Volume 22 | Issue 1 Article 6

2023

Hitting two birds with one emissions-based maintenance stone – a literature review on improving overall productivity of underground diesel fleets

Author(s) ORCID Identifier:
Johannes Deon Swanepoel: 0000-0003-1204-7482
Jennifer Hines: 0000-0001-5429-6212
Vinod Gopaldasani: 0000-0002-0335-5654
Brian Davies: 0000-0002-4437-435X

Recommended Citation

Swanepoel, Johannes Deon; Hines, Jennifer; Gopaldasani, Vinod; and Davies, Brian (2023) "Hitting two birds with one emissions-based maintenance stone – a literature review on improving overall productivity of underground diesel fleets," *Journal of Sustainable Mining*: Vol. 22 : Iss. 1 , Article 6.
Available at: https://doi.org/10.46873/2300-3960.1376

Hitting two birds with one emissions-based maintenance stone – a literature review on improving overall productivity of underground diesel fleets

Abstract

Many industries regard occupational health and safety as a core value and an integral component to maintaining high productivity, and, thus, shareholder value. Diesel fleets' engine maintenance is instrumental in ensuring affected workplaces meet production requirements while controlling health and safety hazards that these fleets introduce to the workplace. This systematic literature review focuses on production and occupational health and safety advantages associated with the implementation and adherence to an emissions-based maintenance (EBM) program. The literature review was conducted across eight databases relevant to workplace health and engineering. To be eligible for inclusion, the publication had to contain maintenance interventions that were informed by diesel engine emissions (DEE) data. Eight publications met the inclusion criteria. The quality of evidence was evaluated by applying the Authority, Accuracy, Coverage, Objectivity, Date, and Significance (AACODS) checklist [1]. There is a paucity in peer-reviewed EBM literature. Available research show evidence for productivity gains such as reduced DEE at the source, reduced fuel consumption, reduced worker exposure, and anecdotal evidence for extended exhaust aftertreatment (EAT) service life. There was no evidence that EBM improved fleet management (measured as fleet availability and reliability) or resulted in reduced underground dilution ventilation delivery.

Keywords

emissions-based maintenance, DPM control, DEE control, productivity gain

REVIEW

Hitting two birds with one emissions-based maintenance stone − A literature review on improving overall productivity of underground diesel fleets

Johannes D. Swanepoel [a,b,*], Jennifer Hines [a,b], Vinod Gopaldasani [a,b], Brian Davies [a,b]

[a] University of Wollongong, Faculty of Arts, Social Sciences and Health, School of Health and Society, Wollongong, NSW, 2522, Australia
[b] Centre for Occupational Public Environmental Research in Safety and Health (COPERSH), Wollongong, New South Wales, Australia

Abstract

Many industries regard occupational health and safety as a core value and an integral component to maintaining high productivity, and, thus, shareholder value. Diesel fleets' engine maintenance is instrumental in ensuring affected workplaces meet production requirements while controlling health and safety hazards that these fleets introduce to the workplace. This systematic literature review focuses on production and occupational health and safety advantages associated with the implementation and adherence to an emissions-based maintenance (EBM) program. The literature review was conducted across eight databases relevant to workplace health and engineering. To be eligible for inclusion, the publication had to contain maintenance interventions that were informed by diesel engine emissions (DEE) data. Eight publications met the inclusion criteria. The quality of evidence was evaluated by applying the Authority, Accuracy, Coverage, Objectivity, Date, and Significance (AACODS) checklist [1]. There is a paucity in peer-reviewed EBM literature. Available research show evidence for productivity gains such as reduced DEE at the source, reduced fuel consumption, reduced worker exposure, and anecdotal evidence for extended exhaust aftertreatment (EAT) service life. There was no evidence that EBM improved fleet management (measured as fleet availability and reliability) or resulted in reduced underground dilution ventilation delivery.

Keywords: emissions-based maintenance, DPM control, DEE control, productivity gain

1. Introduction

Operational productivity and occupational health and safety have an intrinsic duality. There has been an ongoing tug-of-war between these two seemingly opposed disciplines, however, some companies have demonstrated the link between workplace risk reduction, increased production and shareholder value [2−4]. Emissions-based maintenance of diesel fleets has the potential to benefit both production requirements and improving the quality of the work environments, especially in the underground mining industry.

Diesel engines are ideal for freighting heavy loads and are purposefully designed and applied to handle strenuous environments. Unfortunately, it emits carcinogenic DEE [5] that poses a health risk for exposed workers, especially in underground work like mining, where confined work conditions rely on mechanical ventilation to supply fresh air for workers. Diesel engine exhaust is a complex mixture of hundreds of hydrocarbons (HC), polycyclic aromatic hydrocarbons (PAH) [6], submicron diesel particulate matter (DPM) and inorganic gases, most notably carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NO_x) (differentiated as nitrous oxide (NO), and nitrogen dioxide (NO_2)), and sulphur dioxide (SO_2) [5]. Even though there is rationale and momentum for the adoption of electric engines in mining, this process is still in a transition phase, and it is anticipated that diesel engines will remain the mainstay for heavy-load transportation in the immediate future.

On a rudimentary level, the power output of a diesel engine is determined by the amount of fuel that is combusted within the engine cylinders.

Received 8 June 2022; revised 4 October 2022; accepted 30 October 2022.
Available online 11 January 2023

* Corresponding author at:
E-mail address: jds986@uowmail.edu.au (J.D. Swanepoel).

https://doi.org/10.46873/2300-3960.1376

Diesel engines typically operate lean, providing excess air to aid with complete fuel combustion. When the fuel-air ratio is rich − i.e., contains excess fuel with insufficient air for complete combustion − the exhaust gas contains elevated concentrations of CO, DPM and other incomplete combustion products [7]. Gradual engine component wear deteriorates emissions quality over time, resulting in increasing concentrations of DPM, CO and HC [8]. Furthermore, some engine faults may be synergistic in increasing emissions, e.g. intake or exhaust restriction with over-fuelling [8]. The search for means to combat DEE resulted in the focus on six relevant engine systems. These systems are illustrated in Fig. 1: (1) intake air system; (2) engine cooling system; (3) diesel fuel handling and quality; (4) fuel injection system; (5) lubrication system; and (6) exhaust system [7,8]. Appropriate maintenance has been shown to mitigate the degradation in emissions [9].

Maintenance decisions' dual responsibilities are ensuring that a fleets' operation does not create an unacceptable health, safety, or environmental risk, and that diesel fleets are available to meet production needs [10]. Maintenance philosophies are typically divided into two categories: unplanned maintenance and planned maintenance [11]. Unplanned maintenance is considered reactive and is relevant when failure has occurred. The purpose of unplanned maintenance is to restore diesel fleets to functional condition or to prevent an immediate hazardous situation. Planned maintenance, on the other hand, is a proactive approach geared towards either preventing or predicting future faults and failures [11].

Emissions-based maintenance, as part of planned maintenance, is a process that collects engine emissions data to infer an engine's combustion and EAT efficiency compared to its' baseline data or compared to identical engine types and, when needed, to make targeted intervention decisions, to reduce emissions or to prevent against impending engine fault or failure. A statistical method to identify high-emitting engines is to compare individual engine emission data to the mean's 95% upper confidence level of an identical fleet of engines [12]. Engines with emissions that exceed the fleets' 95% upper confidence level should be investigated for deviating from the fleets' emission profile.

The term was initially introduced as "emissions-assisted maintenance" in the 1990s [13]; after the publication of McGinn (2000) [14], the term EBM appeared twice at the 2005 conference of the Mining Diesel Emissions Council [15,16]. Emissions-based maintenance is an emission control tool which requires decisions beyond the original equipment manufacturers' (OEMs) normal maintenance requirements [17]. It includes quantifying raw and treated DEE, pressure differentials across control technologies, and inspection of the six different engine systems previously mentioned [7,8,14]. Emissions-based maintenance has four key procedures: 1) periodic monitoring of engine systems; 2) data-based engine fault diagnosis; 3) targeted maintenance to address the diagnosed fault, and 4) confirmation testing to evaluate the effectiveness of the intervention [18].

The legislation does not use the terminology EBM but it does lay the foundation for its implementation by prescribing a framework of regular emissions monitoring and by prescribing a maximum EAT-out concentration for gases e.g.,

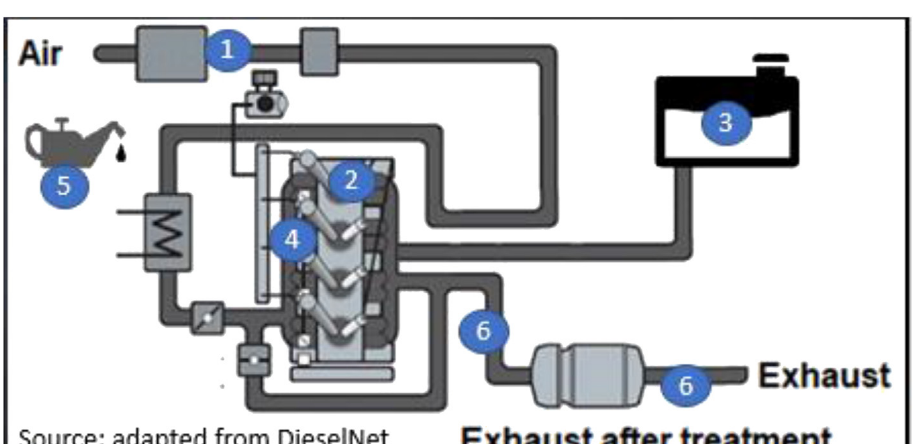


Fig. 1. Illustration of the six-engine system relevant to maintenance and emissions control adopted from DieselNet. Notation: 1) intake air system; 2) engine cooling system; 3) diesel fuel handling and quality; 4) fuel injection system; 5) lubrication system; 6) exhaust system.

CO (1100 ppm [19] – 2500 ppm [20]), and NO_x (1000 ppm), differentiated as 900 ppm and 100 ppm respectively for NO and NO_2 [19]. Legislation furthermore requires the maintenance of engines' operation to not increase the risk to health and safety and to keep particulate emissions as low as reasonably practicable [19,21–24]. This framework includes keeping maintenance and test report records and comparing current emissions data with baseline emissions [19,21]. The recommended variance from baseline is 15% for CO and NO_x greater than 500 ppm and 25% for these gases below 500 ppm. The recommended variance for dirtier and cleaner engines are, respectively, 15% and 30% [20]. Other control strategies for diesel emission exposure, such as EAT technologies (diesel oxidation catalysts, selective catalytic reduction, diesel particulate filters etc.), mine ventilation, and administrative control, are eloquently explained by Bugarski, Schnakenberg [25]. The role of mine ventilation in the context of this paper is to demonstrate that personal exposure to DPM is controlled to below relevant exposure standards, e.g. 0.1 $mg\,m^{-3}$ of elemental carbon (EC) [19].

This literature review focuses on advantages reportedly associated with the implementation and adherence to an EBM program. For the context of this review, productivity gains are defined from a production and occupational health perspective as "any quantifiably positive outcome". Productivity gains are summarised under the following categories: reduced DEE at the source, reduction in fuel consumption, improved diesel fleet management, extended EAT service life, reduced worker exposure, and reduced dilution ventilation delivery underground. Engine-out emissions will be used to refer to exhaust constituents measured at the exhaust manifold, and exhaust aftertreatment-out (EAT-out) emissions to refer to measurements after emission control technology.

2. Materials and methods

A literature search was conducted, searching the following databases: Web of Science, Scopus, Computers and Applied Sciences Complete, Health Business Elite, MasterFILE Complete, CINAHL Plus, Information Science and Technology, and Environment Complete. Four search syntaxes containing Boolean operators were used in alternating trios to create four unique combinations, across all the databases. Each of the four combinations covered a different theme relevant to investigating productivity gains related to EBM. These themes were: diesel engines; maintenance; diesel engine exhaust; and occupational health and safety. As an example, combination one included a search for diesel engines, maintenance, and diesel engine exhaust, while combination two covered diesel engines, diesel engine exhaust, and occupational health and safety. All publications up to 1 March 2022 were considered, including full-text, peer-reviewed publications, and grey literature. A manual search was conducted of all available Mining Diesel Emissions Council (MDEC) conference presentations and the Centres for Disease Control (CDC) and Diesel.net webpages for "emissions-based maintenance" and "emission-assisted maintenance program". Where an author contributed to more than one publication based on the same results, the uniqueness of the reported gains of each publication was determined, and the most relevant publication(s) were included. To mitigate publication bias, grey literature was considered. Limitations to the selected publications were that only English publications were considered.

The quality of the literature was evaluated by applying the AACODS checklist for grey literature critical appraisal [1]. An overall rating – "strong", "moderate", or "weak" – was derived for each publication based on an evaluation of the six AACODS parameters. Productivity gains were evaluated based on evidence for: reduced emissions at the source; reduced personal exposure; improved fuel economy; improved fleet management, e.g., increased engine life and reduced downtime; increased EAT service life; and reduced ventilation requirements.

3. Results

An overview of the publication selection process is displayed in Appendix A: Prisma Diagram. The initial search yielded 4996 documents. After removing duplicates, 2113 documents were screened for applicability. After reviewing abstracts, the full text of 84 documents was reviewed for eligibility. No peer-reviewed publications met the inclusion-exclusion criteria, while eight grey literature publications were included. The eight publications that were included in this review are summarised in Table 1 by the advantages reported, and the quality of evidence reported. Two publications were rated as strong, three as moderate, and three had a weak rating. The majority of the publications are based on in-situ case studies by industry experts and are not peer-reviewed. From the limited available data, data sets that report the effect that specific maintenance had on emissions are small.

Table 1. Summary of productivity gains associated with EBM.

Gains stated	Publication	Sampling methodology	Strength of evidence
Reduced engine-out emissions	i. Hines (2019) [17] ii. McGinn (2000) [14]	Baseline emissions compared to emissions after EBM implementation	i. Strong ii. Moderate
Reduced EAT-out emissions	i. Davies (2004) [12] ii. Davies and McGinn (2005) [15] iii. Forbush (2006) [16] iv. Forbush (2001) [26] v. Hines (2019) [17] vi. McGinn et al. (2002) [27] vii. McGinn (2000) [14] viii. Volkert and Rhiley (2007) [28]	Baseline emissions compared to emissions after EBM implementation	i. Strong ii. Moderate iii. Weak iv. Weak v. Strong vi. Moderate vii. Moderate viii. Weak
Reduced personal exposure	Hines (2019) [17]	Baseline exposure to of DPM and NO_2, compared after EBM implementation	Strong
Reduced fuel consumption	i. Forbush (2006) [16] ii. Hines (2019) [17]	Baseline fuel consumption compared after EBM implementation	i. Weak ii. Strong
Improved fleet management	i. Forbush (2006) [16] ii. Forbush (2001) [26] iii. Volkert and Rhiley (2007) [28]	Not reported	i. Weak ii. Weak iii. Weak
Improved EAT service life	i. Davies (2004) [12] ii. Forbush (2006) [16]	Back pressure monitoring	i. Strong ii. Weak
Reduced dilution ventilation	i. Forbush (2006) [16] ii. Forbush (2001) [26] iii. Volkert and Rhiley (2007) [28]	Not reported	i. Weak ii. Weak iii. Weak

The publications also do not provide information to compare EBM fault diagnosis and OEM-specified planned maintenance.

3.1. Changes in DEE

All publications reported various reduced emissions ascribed to EBM-based targeted maintenance [12,14–17,26–28]. Table 2 is a summary of reported interventions, categorised by air intake-, fuel-, and exhaust system. Intervention on a combination of engine systems often occurs for a single engine.

Three publications reported the identification of deviances in the air intake system requiring maintenance [14,15,27]. This led to various degrees of reduction in measured DEE. Four publications reported reducing maximum fuel delivery to reduce emissions [15,16,26,28]. One publication increased the fuel delivery after another maintenance was completed to regain some of the lost power output [12]. Seven publications reported reduced emission after maintenance was conducted on EAT devices, which included using emission data to identify poor performing EAT devices and to rationalise fitting different EAT devices [12,14,15,17,26–28].

Table 2. Summary of interventions categorised by different engine systems.

Engine system	Intervention(s)
Air intake	Repair system air leaks [14,27] Restore turbo pressure [14] Address restrictions [14,15,27]
Fuel	Reduce fuel [15,16,26,28] Replace injectors [14,15,27] Alter engine timing [14,15,27] Increased fuel [12]
Exhaust	Replace defective EAT [12,14] EAT cleaning [12,14,15,17,27] Repair system leaks [14,17,27] Different technology fitted [26,28]

Table 3 summarises number of scenarios where the publication documented both the effect of targeted maintenance and the resulting emissions' outcome. Replacement of faulty fuel injectors reduced CO and DPM by 18–30% and 40–55% respectively [12]. Chemically treating a blocked water-based conditioning tank (scrubber tank) to reduce high back pressure and fitting a new fuel pump resulted in a 67% reduction in EC and 45% decrease in CO.

Two publications reported reduced engine-out emissions [14,17]. Table 4 amalgamates the effect of targeted maintenance on engine-out DEE.

One publication with a strong rating investigated the effect that an EBM program had on diesel emissions on personnel transportation vehicles (PTV) ($n = 50$) and load haul dumpers (LHD) ($n = 51$). The study was conducted over one year between two underground coal mines – a test site where EBM was to be implemented and a control site without an EBM program [17]. Table 5 is the summary of the changes in emissions based on the median results reported.

Median reported engine-out concentration for NO_2, CO, and EC reduced at the test site, compared

Table 3. Summary of published case studies (n) that reported the effect of specific maintenance on the intake, exhaust, fuel or a combination of engine systems on various EAT-out emissions.

Engine system	Publications				
	Davies (2004) [12]	Davies and McGinn (2005) [15]	Hines (2019) [17]	McGinn (2000) [14]	McGinn et al. (2005) [27]
Air intake	None reported	Reduced DPM ($n = 1$)	None reported	Reduced CO and DPM ($n = 3$)	Effect on emissions not reported
Fuel	Net reduction in CO ($n = 1$)	Reduced CO and DPM ($n = 3$)	None reported	Net reduction in CO and DPM ($n = 1$)	Effect on emissions not reported
Exhaust	Effect on emissions not reported	Reduced DPM ($n = 2$)	Reduced CO and DPM ($n = 6$)	Reduced CO and DPM ($n = 2$)	Effect on emissions not reported
Combination of any two or more systems	Net reduction in CO and DPM ($n = 3$)	Reduced DPM ($n = 3$)	None reported	Reduced CO and DPM ($n = 1$)	Reduced CO and DPM ($n = 3$)

to an increase in these constituents at the control site. EAT-out emissions decreased at both sites, except for a one ppm increase in CO at the test site. The author does not report the confidence interval for these constituents.

3.2. Changes in personal exposure

Two publications reported a reduction in personal exposure to DEE supported by data [12,17]. An analysis of five years of personal DPM exposure data of the Tower Colliery Diesel Research Group [12] found that one of the six collieries had statistically lower exposure to DPM. An intensive planned maintenance program was cited as a significant contributor to the lower DEE exposure.

A personal exposure monitoring campaign using recognised sampling methodologies for DPM and NO_2 exposure, compared baseline exposure to exposure after the implementation of EBM [17]. Personal exposure data were collected from expected medium to high DEE exposure risk occupations based on the test mine's historic DPM exposure data. The same job tasks were sampled at the control site. There was an overall downward trend in EC exposure at the test site, with a statistically significant decrease of 33%, while the median exposure at the control site increased. Oxides of nitrogen exposure data did not indicate a clear trend at either the test or control site. The author recognised that there might be several reasons for the lower exposure at the test site but, based on the reduction in exposure and data variability after the maintenance phase, concluded the most significant factor to be engine and emission control system maintenance.

3.3. Reduced fuel consumption

Four publications reported reduced fuel consumption [16,17,26,28]. From these, two expressed fuel savings as a value, 15% [17] and 23% [26], with one publication substantiating this with quantifiable

Table 4. Summary of specific engine system maintenance and the associated engine-out emission changes.

Engine system	DEE	Net effect
Intake [14]	CO	Decrease
	DPM	Decrease
	NO2	Increase
	NOx	Decrease
Fuel [14]	CO	Decrease
	DPM	Decrease
	NO2	Increase
	NOx	Decrease
Unspecified [17]	CO	Decrease
	DPM	Decrease
	NO2	Decrease
	NOx	Not reported

Table 5. Summary of changes in DEE induced by EBM program [17].

All vehicles (PTV and LHD)			
Engine-out mission changes			
	NO_2	CO	EC
Test site ($n = 101$)	8% decrease	7% decrease	13% decrease
Control site ($n = 13$)	1% increase	23% increase	7% increase
EAT-out Changes			
	NO_2	CO	EC
Test site ($n = 101$)	46% decrease	1% increase	9% decrease
Control site ($n = 13$)	7% increase	2% decrease	60% decrease
Change based on baseline engine-out and post-EBM EAT-out data			
	NO_2	CO	EC
Test site ($n = 101$)	80% decrease	45% decrease	68% decrease
Control site ($n = 13$)	66% decrease	25% decrease	91% decrease

data [17]. The remaining publications did not rationalise this reported gain.

Reducing maximum fuel delivery to compensate for high altitude resulted in a 23% reduction in fuel usage [26]. There is no information on how this value was derived. Strong evidence for fuel saving ascribed to an EBM program reported an overall 15% in fuel saving one year after the baseline measurement [17]. Fuel and vehicle data were collected by site personnel, and data was only included in the analysis if the following was recorded for three testing campaigns: vehicle operating hours, fuel data, and relevant time data. Unfortunately, fuel data could not be collected at the control site. A 20% and 6% reduction in fuel consumption were recorded for LHDs and PTVs, respectively [17].

3.4. Improved EAT service life

Two publications reported on EAT replacement intervals [12,16]. One publication reported an increased average time of 90 h before filters needed change without specifying the filter replacement interval before the implementation of EBM or type of filters used [16]. The other publication reported six disposable diesel exhaust filters (DDEF) of a 21-filter data set were replaced after utilisation of fewer than 5 h within a 24-h period [12]. No strategy for the optimum replacement interval of filters was recommended by either author [12,16].

3.5. Improved diesel fleet management

Three publications noted productivity gains associated with fleet management, framed as reduced downtime, reduced breakdown, increased engine life or improved fleet availability [16,26,28]. One publication reported an improved engine life from 3000 to 10,000 h without providing supportive evidence [16]. Reduced maintenance time was ascribed to the implementation of regular emission testing and subsequent targeted maintenance [26,28].

3.6. Reduced ventilation requirements

No publications provided evidence that a reduction in emissions resulted in reduced dilution ventilation. Relying on ventilation alone to control DPM concentrations is impractical in most coal mines [12].

4. Discussion

This article reviewed the evidence of productivity gains that resulting from the implementation of an EBM program. Publications report different productivity gains, ranging from a single, specific gain, such as reduced EAT-out EC [15], to a broad range of gains, including reduced DEE at the source, improved fuel economy, reduced breakdowns and downtime, extended engine life and improved engine performance, increased EAT life and reduced ventilation requirements [16,28].

All of the publications focused on diesel emissions in underground coal mines. A reasonable rationale is that historically metalliferous mines were not legislated to conduct periodic emissions, testing whereas coal mines are more highly regulated in terms of exhaust emissions monitoring which may incentivise the adoption of EBM. The most cited, and arguably the most accepted gain of EBM, is the reduction in DEE. This can be bifurcated into a reduction of engine-out emission and a reduction of EAT-out DEE. Evidence shows that EBM data can be used to diagnose faults and inform maintenance decisions that reduce engine-out CO and DPM [14,17]. These results are aligned with the expected outcome of reduced CO and DPM when targeted maintenance alters diesel combustion towards lean fuel-air ratios [7]. A granular, albeit small data set shows how EBM data can be used to diagnose engine faults and inform maintenance decisions on the intake- and fuel systems to reduce CO, DPM and NO_x [14]. Although the variance of this baseline data set, and missing DPM data from the investigation limits inference that can be made, the overall conclusion of reduced engine-out emission induced by targeted maintenance is valid. Similar reductions in engine-out CO, DPM and NO_2 were reported from a fleet of 101 diesel vehicles over a year investigation, while a control fleet ($n = 13$) showed an increase in these emissions constituents [17]. Inference from this study is limited by a reduction in available fleet size from baseline ($n = 101$) data collection to post-EBM implementation ($n = 45$), the absence of confidence intervals for means, and the statistical significance of the results. The reported reduction of both NO_2 and DPM is contra-indicative to the literature [7]. Diesel particulate matter and NO_2 have an inverse relationship. When DPM reduces, the combustion temperature increases which results in increased NO_2 formation [7]. It is likely that other publications that reported reducing fuel delivery to the engines [16,26,28], i.e. reducing engine power, resulted in a similar reduction of engine-out constituents.

There is strong evidence that indicates EBM data can inform maintenance decisions of the intake- [14,15,27], fuel- [12,14–16,26–28], and exhaust system [12,14,15,17,26–28], or a combination of these systems, and will result in reduced EAT-out emission. Exhaust after-treatment devices are the last control barrier before emissions are released into the work area. The effectiveness of EAT in reducing emissions varies depending on the selection, configuration [26,28], and maintenance of these devices [12,14,15,17,26–28]. Two important factors of EAT are back pressure and a reduction efficiency. Relatively elementary tasks like unblocking exhaust scrubber tanks can be sufficient to reduce excessive back pressure, increasing the control efficiency and resultant reduced CO and DPM [12,14,15,17]. Addressing exhaust system damage and leakages will also improve EAT reduction efficiency [14,17]. It is reasonable to expect that reducing engine-out CO and DPM contribute towards the reduction of these EAT-out pollutants.

It should be noted, however, that the effect of subsequent targeted maintenance does not inherently follow a perfectly correlated reduction of DEE. To illustrate this, maintaining the intake system to reduce engine-out CO and DPM may be counteracted to various degrees when alterations to the fuel system are made, e.g. increasing fuel [12]. The net reduction in CO and DPM was still noteworthy and indicates that successive testing can be valuable in optimising engine power output while meeting emission targets. Although beyond the scope of maintenance, the reduction in power due to reduced fuel delivery can be compensated for by changing torque converters [16,26].

There is strong evidence that emissions reduction from EBM will reduce personal exposure to DEE, specifically measured as DPM and NO_2 [17]. The test site showed a statistically significant reduction in EC exposure of 33%, compared to a 50% increase in exposure at the control site. There was no clear trend in NO_2 at either site. Differences in mine ventilation delivery between the test and control site were not reported [17]. Consequently, the difference and impact of dilution ventilation or other control measures on exposure control that may occur between the sites cannot be evaluated. Regardless of this limitation, this publication provides strong evidence that controlling emissions at the source will result in reduced personal exposure.

Reported fuel consumption reductions were 15% [17] and 23% [26]. There is evidence that vindicates the association between EBM and reduced fuel consumption for an underground diesel fleet [17]. The control site did not have the means to gather the same detail for individual fuel data. Information was initially collected for the quantity of fuel distributed underground, however due to changes in fuel distribution, this could not be continued throughout the investigation, resulting in a lack of comparable data. The author lists the limitations of the fuel data, including inaccurate bowser registers, human interpretation of what qualifies as a “full tank”, and incorrect or incomplete data collection. Regardless of these limitations, this publication currently presents the most systematic approach to calculating improved fuel consumption as a result of the implementation of an EBM program [17].

A trial that changed DDEF daily yielded a small sample size ($n = 26$) of filters that highlighted the variability of vehicle utilisation during different shifts [12]. Three DDEFs had a service life greater than 24 h without exceeding backpressure of 7.0 kPa. Only two filters' (that were obtained from the same vehicle) backpressure exceeded 7 kPa. These filters were collected on consecutive days, leading to a suspecting of a critical fault in the exhaust system. Although the viable filter sample size was small, these findings suggest that filter service life can be extended, even more so if replacement is based on EBM data as opposed to fixed timeframes [12]. These findings overlap with the general inference that filter life can exceed multiple shifts [16]. A direct comparison between EAT service life reported [12,16] must be approached with caution as the filter technologies referenced in each publication may differ. Although not directly linked to increasing the service life of EAT, three publications indicated that EBM is a useful tool to determine EAT efficiency and address EATs operating below expected efficiency [12,14,17].

There are interactions between productivity gains. For example, reducing back pressure could reduce diesel use, while optimised fuel delivery for lean combustion could reduce CO and fuel consumption. However, to completely explore and rationalise this complex interplay is beyond the scope of this review. The reduction of engine-out CO and DPM [14,17] substantiate statements regarding improved fuel consumption. Lean combustion reduces CO and DPM in DEE [7]. This improved fuel utilisation will result in improved power output per volume of fuel, as more of the fuel combusts, and less unburned fuel enters the exhaust system. The reduction in engine-out EC [14,17] can partly rationalise the extension of filter life. A higher DPM content in the exhaust stream will occlude a filter quicker than a comparatively lower DPM content in an identical system. The higher rate of filter occlusion will inevitably result in an earlier increase in backpressure and subsequent increased filter change.

Aside from the lack of substantiating data to support claims that EBM reduces maintenance cost, it is also unclear what cost factors were included to support such claims. Anecdotal evidence shows that changing fuel injectors based on service time, and not based on emissions data or other indications of injector deterioration, had virtually no effect on emissions [14]. It may be inferred that avoiding unnecessary part replacement will reduce maintenance cost.

There is no evidence that engine faults identified via EBM prevented or delayed catastrophic engine failure. Consequently, there is no evidence that EBM improves vehicle availability or reliability. It is possible that this category of gain is a logical deduction based on the assumption that early identification of engine faults and regular maintenance will prevent catastrophic engine failure. Equipment availability and useful engine life are decreased by a lack of basic maintenance, while engine failures increase [9]. Maintenance, in general, aims to combine increased reliability and hence availability with the lowest cost possible, whether direct or indirect [29]. The use of oil analysis to guide maintenance decisions has been shown to reduce downtime and increase availability in diesel buses in at least one peer-reviewed publication [29]. There is currently no evidence that implementing EBM will have similar productivity gains.

There is no evidence from the included publications that EBM reduced dilution ventilation in an underground mine. Where underground ventilation requirements are based on known high-emitting engines, it is reasonable to expect a reduction in ventilation requirements when emissions are reduced at the source. To control for DPM, it is stipulated that ventilation requirements must dilute exposure to below regional exposure limits, e.g. below 0.1 $mg\,m^{-3}$ EC [19]. It should be emphasised that ventilation quantities underground are also to control heat and other airborne pollutants.

5. Conclusion

From the evidence available, EBM is a tool that can reduce production cost by saving fuel while lowering DEE exposure and associated health risks. Although EBM is currently mostly associated with and employed as a control measure to reduce exposure to carcinogenic DEE, there is evidence that indicates its application can produce other production gains. Its application reduces engine-out [14,17] and EAT-out CO and DPM [12,14–17,27]. This reduction of EAT-out emissions manifests as a reduction in personal exposure to DPM [17]. There is evidence that targeted maintenance informed by EBM results in reduced fuel consumption of the fleet [17].

There is a small body of evidence that indicates DDEF life can be extended by basing change on backpressure measurements rather than fixed intervals [12]. Evidence is lacking to ascertain if EBM improves the service life of other EAT technologies. From the available evidence, no conclusion should be drawn whether EAT service life can be extended for the other emission control technologies. Emissions-based maintenance is crucial in determining the effectiveness of EAT controls. There is no evidence provided to substantiate claims that EBM programs improve fleet management, typically expressed as reduced breakdowns [26], prolonged engine life [16,28], reduced downtime [28], reduced maintenance costs [16] and maintenance time [28] or that a reduction of EAT-out DPM resulted in reduced underground dilution ventilation.

Recommended OEM maintenance suggests planned maintenance, e.g., to replace intake filter, fuel pumps etc., at fixed intervals, however, it is not clear how EBM maintenance correlates with OEM recommended maintenance programmes.

It is currently unclear if EBM will pose the same value for mechanical and electronic diesel engines. The value of EBM on newer Tier engines, e.g. Tier 3 or higher, has not been explored. There is no widely available central database to assist with EBM data interpretation, and currently no single parameter that can be used to trigger targeted maintenance. The consequence is that fault diagnosis is reliant on operator skill, knowledge, and experience. There is great value in the construction of a diagnostic tool based on EBM data to assist relevant personnel with engine fault diagnostics. This aspect is part of the current research program at the University of Wollongong.

Conceptually, EBM as an emission control tool has been proven, but currently, there is a paucity of available peer-reviewed research. It would be valuable to investigate if the successful implementation of an EBM program at an operation has a positive impact on fleet availability and reliability by comparing fleet maintenance records before and after the adoption of such a program. Evidence of fleet management gains could expedite industries to formally implement EBM programs to achieve operational and occupational health gains.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

This research has been conducted with the support of an Australian Government Research Training Program Scholarship and the Occupational Safety and Health Research Alliance (OSHRA).

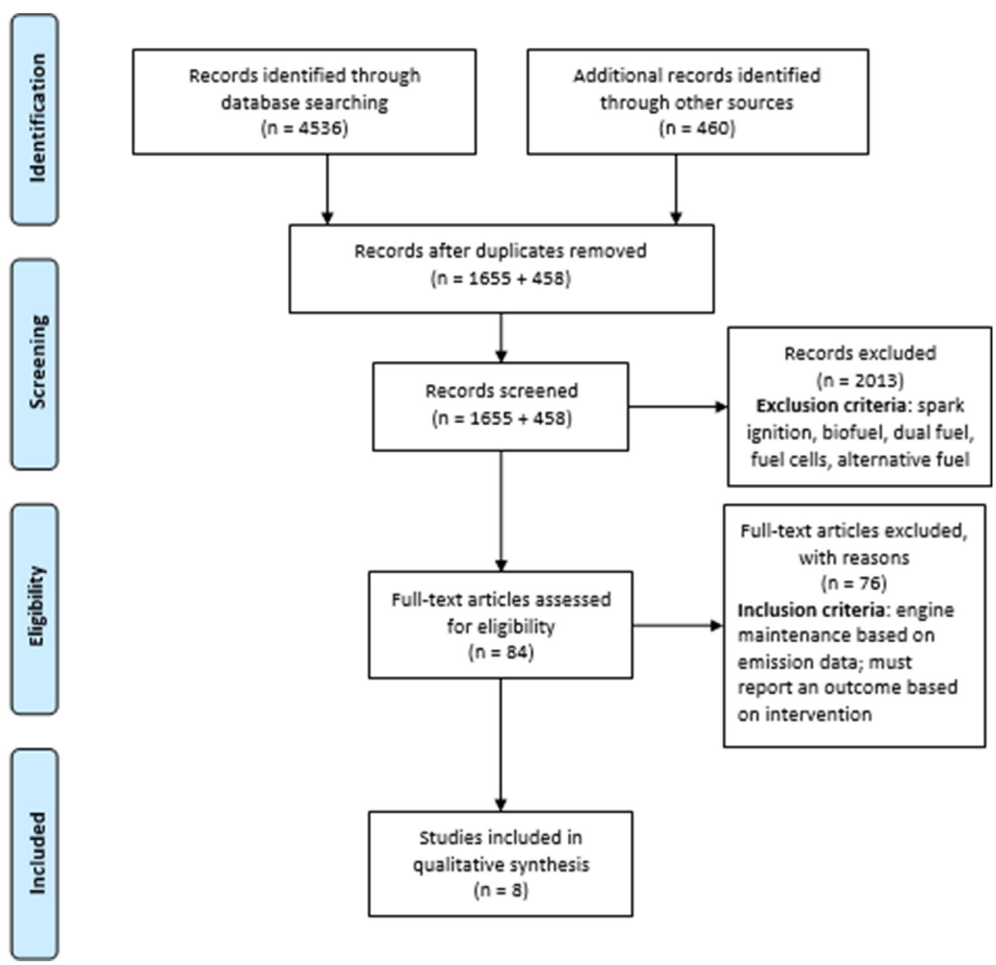
Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Acknowledgements

We acknowledge the team at E-R-P Engineering for providing training and insight into raw engine exhaust monitoring, as well as Christo de Wet and Rehan Badenhorst from D'Sayensi Occupational Hygiene for supporting this endeavour. Special consideration for Francia Swanepoel for assisting with language curation and dotting the i's of this article.

Appendix A. Prisma diagram



References

[1] Tyndall J. AACODS checklist [Internet]. Flinders University; 2010. Retrieved from: https://canberra.libguides.com/c.php?g=599348&p=4148869.
[2] BHP Group Limited. Annual report. 2021. Retrieved from: https://www.bhp.com/investors/annual-reporting/annual-report-2021.
[3] Anglo American. Integrated annual report. 2021. Retrieved from: https://www.angloamerican.com/~/media/Files/A/Anglo-American-Group/PLC/investors/annual-reporting/2022/aa-annual-report-full-2021.pdf.
[4] South 32 Limited. Annual report. 2021. Retrieved from: https://www.south32.net/docs/default-source/exchange-releases/annual-report-2021.pdf?sfvrsn=1ab964e0_2.
[5] International Agency for Research on Cancer (IARC). In: Cancer IAfRo, editor. IARC monographs on diesel and gasoline engine exhausts and some nitroarenes. Lyon, France: WHO; 2012.
[6] United States Environmental Protection Agency (U.S. EPA). Health assessment document for diesel engine exhaust. In: U.S. Environmental Protection Agency OoRaD, National

Center for Environmental Assessment. Washington, DC: Washington Office; 2002. EPA/600/8-90/057F2002.
[7] Holtz JC. Safety with mobile Diesel-powered equipment underground. US Department of the Interior, Bureau of Mines; 1960.
[8] Waytulonis R. In: Interior USDot, editor. The effects of maintenance and time - in - service on diesel engine exhaust emissions. U.S. Bureau Of Mines; 1992.
[9] Waytulonis R. In: Interior USDot, editor. An overview of the effects of diesel engine maintenance on emissions and performance. U.S. Bureau Of Mines; 1992.
[10] Campbell JD, Jardine AK, McGlynn J. Asset management excellence: optimizing equipment life-cycle decisions. CRC Press; 2016.
[11] Kothamasu R, Huang SH, VerDuin WH. System health monitoring and prognostics - a review of current paradigms and practices. Int J Adv Manuf Technol 2006;28.
[12] Davies B. The control of diesel particulates in underground coal mines. Victoria University of Technology; 2004.
[13] Spears M. An emissions-assisted maintenance procedure for diesel-powered equipment. Minneapolis, MN: University of Minnesota; 1997. Contract No.: NIOSH contract No. USDI/1432 CO369004. Retrieved from: http://www.cdc.gov/niosh/mining/eamp/eamp.html.
[14] McGinn S. The relationship between diesel engine maintenance and exhaust emissions. Sudbury, Ontario: DEEP; 2000. Retrieved from: https://mirarco.org/wp-content/uploads/CAMIRO-Archive/mtce_report.pdf.
[15] Davies B, McGinn S. The effect of maintenance of diesel engines on particulate generation. IOHA; 2005. Retrieved from: https://cornettscorner.com/wp-content/uploads/2021/06/diesel-maintenance.pdf.
[16] Forbush S, editor. Emissions-based maintenance program. Taylor and Francis/ Balkema; 2006. Retrieved from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-56249133894&doi=10.1201%2f9781439833391.ch17&partnerID=40&md5=f14cfa9d9caf2ff787ea1103e76588ab.
[17] Hines J. The role of Emissions Based Maintenance to reduce diesel exhaust emissions, worker exposure and fuel consumption. University of Wollongong; 2019.
[18] Bugarski A, Schnakenberg G, Noll J, Mischler S, Crum M, Anderson R, editors. Evaluation of diesel particulate filter systems and biodiesel blends in an underground mine; 2004. Retrieved from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-2942521057&partnerID=40&md5=56f4da529b2784bf8f1ea9d1e783e75c.
[19] New South Wales (NSW) Department of Primary Industries. MDG 29 Guideline for the management of diesel engine pollutants in underground environments Mine Safety Operations Division. 2008. Retrieved from: http://www.resourcesandenergy.nsw.gov.au/__data/assets/pdf_file/0011/419465/MDG-29.pdf.
[20] Mine Safety and Health Administration (MSHA). Mandatory Safety Standards. Underground coal mines. Maintenance of diesel-powered equipment. 1914. Retrieved from: https://arlweb.msha.gov/s&hinfo/deslreg/1914f1.htm.
[21] New South Wales (NSW). Work health and safety (mines) regulation. 2014. Retrieved from: https://legislation.nsw.gov.au/view/html/inforce/current/sl-2014-0799.
[22] Health and Safety Executive (HSE). Control of diesel engine exhaust emissions in the workplace. 2012. Retrieved from: https://www.hse.gov.uk/pubns/books/hsg187.htm.
[23] Canada Occupational Health and Safety Regulations (COHSR). Part X – hazardous substances. 2014. Retrieved from: https://www.canada.ca/en/employment-social-development/services/health-safety/reports/hazardous-substances.html.
[24] Mine Safety and Health Administration (MSHA). Diesel engines intended for use in underground coal mines, 30CFR, Part 7. Subpart E; 1988. Retrieved from: https://www.govinfo.gov/app/details/CFR-2005-title30-vol1/CFR-2005-title30-vol1-part7-subpartE.
[25] Bugarski AD, Schnakenberg JGH, Hummer JA, Cauda E, Janisko SJ, Patts LD. Effects of diesel exhaust aftertreatment devices on concentrations and size distribution of aerosols in underground mine air. Environ Sci Technol 2009;43(17):6737–43.
[26] Forbush S. Diesel emissions reduction program. Mining diesel emissions conference; 7-8 November; Markham, Ontario, Canada. 2001. Retrieved from: https://mdec.ca/2001/S6P4_Forbush.pdf.
[27] McGinn S, Huzij B, Cisyk D. Diesel emissions maintenance training program. Mining Diesel Emissions Council; 25-28 March 2002. Retrieved from: https://mdec.ca/2002/S1P6_McGinn.pdf.
[28] Volkert S, Rhiley T. Practices and principles associated with DPM compliance at Queenstake Resources. Reno, Nevada: DPM Workshop; 24-25 January 2007. 2007 Retrieved from: https://www.cdc.gov/niosh/mining/UserFiles/workshops/dieselreno2007/VolkertRhileyEMPQueenstake.pdf.
[29] Raposo H, Farinha JT, Fonseca I, Ferreira LA. Condition monitoring with prediction based on diesel engine oil analysis: a case study for urban buses. Actuators 2019;8(1).