12th Underground Operators' Conference 2014

Paper Number: 80

CONTINUOUS REMOTE EMISSIONS MONITORING - THE LYNCHPIN FOR AIR QUALITY MANAGEMENT

F.I. Cox[1], T. Bodisco[2,3] and D. Peeler[4]

1.
COO, Peak3 Pty Ltd, Address: P.O. Box 4004, Loganholme DC, Qld 4129, Australia, Email: fcox@peak3.com.au

2.
Researcher in Business, Peak3 Pty Ltd, Address: P.O. Box 4004, Loganholme DC, Qld 4129, Australia, Email: tbodisco@peak3.com.au

3.
Research Fellow, Queensland University of Technology, Address: 2 George St., Brisbane, Qld 4000, Australia, Email: timothy.bodisco@qut.edu.au

4.
CEO, Peak3 Pty Ltd, Address: P.O. Box 4004, Loganholme DC, Qld 4129, Australia, Email: dpeeler@peak3.com.au

ABSTRACT

Diesel particulate matter (DPM), in particular, has been likened in a somewhat inflammatory manner to be the 'next asbestos'.

From the business change perspective, there are three areas holding the industry back from fully engaging with the issue:

1. There is no real feedback loop in any operational sense to assess the impact of investment or application of controls to manage diesel emissions.
2. DPM are getting ever smaller and more numerous, but there is no practical way of measuring them to regulate them in the field. Mass, the current basis of regulation, is becoming less and less relevant.
3. Diesel emissions management is generally wholly viewed as a cost, yet there are significant areas of benefit available from good management.

This paper discusses a feedback approach to address these three areas to move the industry forward. The six main areas of benefit from providing a feedback loop by continuously monitoring diesel emissions have been identified:

1. Condition-based maintenance. Emissions change instantaneously if engine condition changes.
2. Operator performance. An operator can use a lot more fuel for little incremental work output through poor technique or discipline.
3. Vehicle utilisation. Operating hours achieved and ratios of idling to under power affect the proportion of emissions produced with no economic value.
4. Fuel efficiency. This allows visibility into other contributing configuration and environmental factors for the vehicle.
5. Emission rates. This allows scope to directly address the required ratio of ventilation to diesel emissions.
6. Total carbon emissions - for NGER-type reporting requirements, calculating the emissions individually from each vehicle rather than just reporting on fuel delivered to a site.

INTRODUCTION

Diesel emissions have become established as a significant health and safety risk in modern industry. A host of findings have come out in recent times, such as the results of the NIOSH trial published in 2012 (Attfield et al, 2012), the declaration by WHO's International Cancer Council of diesel emissions as a Group 1 carcinogen (IARC, 2012) and a range of scientific papers on the epidemiology of nano and ultra-fine diesel particulates.

The current literature show diesel particulate matter (DPM) is an effective dosing pathway for toxic hydrocarbons adsorbed onto their surface, into the human body via the lungs (Pope, 2000; Oberdürster, 2000; Ristovski *et al*, 2012). All indicate that the problem is real. The consensus in the current literature is that the problem is real and that the health effects should be addressed, particularly in an industrial setting (Pöschl, 2005; Ris, 2007; Sangkapichai *et al*, 2010).

In addition, regulators aside, the broadening public knowledge of the risks diesel emissions present, especially in captive airspaces, provides a common law exposure to any operator and its principals for not providing a safe workplace. They must be able to show they are doing everything practicable to mitigate such risks for their employees and contractors.

There are two key conundrums facing industry in relation to effective management of this business risk:

- While the application of increasingly tough emissions standards, led by Europe and the US, has been very effective in reducing the gross amount of carbon mass released as diesel particulates, the particle sizes now produced are below the measurement threshold of most monitors used in the field (Fierz *et al*, 2011), (as examples, MAHA-4 Specifications: http://www.pm-tech.com.au/content/technical-specifications and Dust Trak Specifications: http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Manuals/8530-8531-8532-DustTrak_II-6001893-web.pdf Page 69). This leads to an impression that there might be no or very little DPM being generated by a diesel machine, where the numbers of nano and ultra-fine particulates could be very high. It is difficult for regulators to prescribe DPM limits for vehicles where they cannot be measured practically in the field. Additional to this issue, technology to mitigate diesel particulates (diesel particulate filters and diesel oxidation catalysts) have variable performance and many do not filter particles smaller than 100 nm. Therefore, with the current emission monitoring technology employed to regulate diesel emission the effectiveness of the filtration cannot be assured (Caroca *et al*, 2010; Barone *et al*, 2010).

- The second is that the smaller particulates are readily ingested through the human lung and the smaller the particulate, the deeper they penetrate, to the point that they can cross the lung membrane directly into the bloodstream (Neer and Koylu, 2006; Nel *et al*, 2006; Ristovski *et al*, 2012). This has the effect that regulatory guidance currently provided around DPM mass does not regulate on the basis of the health and safety risk to those exposed. As fuel atomisation gets finer and exhaust DPM get smaller, this disconnection between the basis of regulation and health risk continues to grow.

WHERE IS MONITORING UP TO?

There are two broad categories of diesel emissions monitoring in this context.

Ambient Monitoring

For ambient monitoring, there are reasonable options available for the major exhaust gases, particulate mass and even particle size and count profiles. The particulate monitors, however, are laboratory grade, expensive ($5,000 to $20,000 as a guide) and are not made for routine use or permanent installation in a harsh environment. For personal monitoring, there are practical and lower cost sampling pumps that mainly measure elemental carbon on a time-weighted average basis. In industry, static continuous atmospheric monitoring is not all that common underground (other than for methane in coal mining), but rather tends to be occasional and oriented to role-based exposures.

Diesel Engine Monitoring

For source monitoring, periodic tailpipe monitoring is the current mainstay of the industry. This generally comprises using an exhaust gas analyser and DPM mass monitor with emissions measured under some combination of high idle and peak load testing. Best case, a heavy diesel's tailpipe emissions might be evaluated once every three months. For many fleets, they still may not be measured at all.

Missing is an on-board, continuous monitoring function for the vehicles themselves. In some cases, there are vehicle-mountable monitors available for individual gases but currently there is no robust mobile DPM monitor available on the market.

CONTINUOUS ON-VEHICLE MONITORING

The underlying mass balance means that for a certain amount of fuel and air going into an operating engine, there is a matching amount of emission as a combination of gases and DPM. Therefore there are base relationships, but since carbon, for example, can be exhausted as CO_2, CO, hydrocarbons or DPM, there are clearly many other factors required to predict with any accuracy the individual emissions. These include temperature (intake and exhaust), humidity, fuel type and quality, engine speed, throttle position, engine load and so on.

Fortunately many of these variables are continuously measured or calculated by the engine control system. Adopting these into the calculation allows some instantaneous compensation or normalisation of the emissions per litre of fuel. Adding to that, some time-compensated numbers from sensors in the raw exhaust gas flow and you are starting to build an informative model of the true emission on a continuous basis.

The algorithms are somewhat transportable across engine package types and applications, however, it is clear that they will be steadily improved as more data is captured, especially in relation to fuel pressure and rate of change (typical work-state) both of which have a large bearing on DPM size distribution and aggregate mass.

For a specific engine, at a particular engine condition, there will be a characteristic distribution of particle sizes produced for that engine, so that the total mass of DPM will be spread across this distribution. If the engine is over-fuelled, for example, fuel is less completely burnt, and the average particle size distribution moves upwards. Movements in NO_X production is a useful indicator of this kind of particle change, owing to the particulate/NO_X trade-off (Lähde *et al*, 2010). If a DPM mass monitor was available for the vehicle, the nature and change of particle sizes and counts could not be estimated without reference to other engine data, applied instantaneously.

Peak3 is currently undertaking a wide trial to collect further data that includes one surface fleet and four underground fleets, covering most of the common vehicle classes found in the Australian fleet. These include: Logan City Council, MMG Dugald River, Anglo Sunrise Dam, Western Areas Flying Fox, and Goldfields Agnew. The underground sites share the same heavy diesel contractor, Barminco.

The benefits of on-vehicle monitoring

Australian fleet operators have largely not developed the thinking, strategies and practical deployments that could capitalise on continuous vehicle-borne monitoring of diesel emissions. This is simply because there has been no practical service in view to connect to. This is beginning to change. However, it does require an intentional plan and methodology to harvest each component of the value proposition.

Condition-based maintenance.

Emissions are a direct consequence of engine operation and condition (Jones and Li, 2000; Burgarski et al, 2010). A change in the engine condition will therefore provide an immediate change in the emissions. This needs to be detected through the normal variability in emissions as engine operation changes. The simplest way is to start by detecting significant changes in emissions – to avoid false positives. This mainly requires an operational protocol where both maintenance staff and operators know that a vehicle must be recalled from operational duty when certain alerts are received.

The aim, obviously, is to reduce further engine damage by addressing the engine issue quickly. Where there is a catastrophic component failure this won't help, but for the many circumstances where a significant wear point is reached or a component starts to degrade, there is scope for intervention to be scheduled in a timely-enough manner to avoid in-service failures. It also serves to reduce over-servicing where many components are simply replaced on an interval basis regardless of actual condition, to avoid such failures. Anecdotal comments from fleet operators have indicated that such a combined system – oil, lubes and filter replacement by schedule and further maintenance-on-demand – could reduce maintenance budgets by 25%.

There is scope to develop this further by defining the nature of the condition change, grading the severity and even finally dynamically compensating on the operating vehicle for some kinds of factors. Queensland University of Technology and Peak3 are currently investigating options in relation to profiling each cylinder's contribution of power intra-cycle, to provide diagnostics and compensation avenues not currently available (Lin *et al*, 2013).

Operator performance

Emissions are at their worst relative to the work done by the engine when the engine is in transition (Giakoumis and Alafouzos, 2010). This means that the operator is one of the biggest variables in the emissions produced by a particular vehicle. Rate of throttle change, frequency of throttle change, frequency of gear shift, lugging and over-revving are all examples of driving behaviour that adversely affects emissions production, stresses engines and drive trains and wears components out before their time.

Anecdotal investigations at a site have indicated that from the worst performing to the best performing driver, on the same machine doing the same work, fuel consumption can vary by 18% in a shift. In crude terms, 18% more fuel consumed means 18% more diesel emissions. In addition, the over-fuelling which is the common by-product of poor driver behaviour leads to inefficient combustion and therefore tends to produce more DPM mass. Cummins documentation indicates driver impacts on fuel consumption can reach 30% (Cummins, 2013).

Most drivers are professional in attitude and when a feedback system is provided as to their performance, their behaviour and discipline will improve.

Vehicle utilisation

Most underground sites and many open-cut sites have an issue with excessive idling. For underground, a common reason that drivers keep engines running to run the air conditioning against high ambient temperatures and to operate cabin-filtration protection from high concentrations of diesel particulates in the immediate areas where the vehicles congregate. Some sites that queue for loading or dumping may exceed 40% of their engine hours idling.

Since the idling vehicles add to the high ambient temperatures and contribute significantly to the ambient air quality through their exhaust, they materially add to their own problem. In addition, these idling emissions typically occur at the edges of the ventilation system where it is most difficult to dilute them. Against that, excessively restarting large engines also puts stress on starting components and could increase the incidence of mechanical failure. Operating hours achieved, ratios of idling to under power, even distance travelled from park-up to workplace, all directly affect the value that can be extracted from a vehicle asset, and the proportion of its use that produces emissions but no economic value. Through effective cost balancing and management, utilisation can be optimised to save fuel and improve ambient air quality without significantly effecting the maintenance cycle of the vehicles.

Differences in site arrangements make setting an idling policy and administering target vehicle utilisation rates complex, but without a measurement and feedback system it is impossible. Achieving regular reporting on a shift basis and aggregating to longer periods provides a means to test operational changes and evaluate productivity versus wastage. Utilisation can also extend to proportions of time in the target power range and can discriminate between travel (time spent on a decline, for example) and fully loaded activities. It opens up the means to evaluate logistics, dispatch, routing, traffic light and intersection performance, and so on.

Fuel efficiency

Many sites refuse to really consider fuel efficiency. This can be because production goaling maybe very one-dimensional (e.g. tonnes at the dump point, ounces of production or metres of development). It may also be because the mine owner purchases the fuel and feels disconnected from how it is used, and the fleet contractor naturally feels less responsible where they do not see or pay the bills.

Yet the quantum is high. RIO indicated recently a rough annual fuel consumption, in Australia alone, of 2 billion litres. At that scale, a 5% overall sustainable improvement in fuel consumption would be of sufficient weight to vary the share price! The gains are there to be had. Every maintenance engineer could tell you most of the factors that make fuel efficiency worse: low tyre inflation, blocked air filters, dirty fuel, back pressure from exhaust treatments, sub-optimal EGR, partially-blocked injectors; to name a few. What has been missing is the quantitative assessment of each one’s effect, and the practical procedural means to capture the benefit and sustain it.

This simply will not happen without good quality frequent monitoring with alerts for material changes provided directly to the maintenance team.

Emission generation rates

Most international jurisdictions have guidelines defining minimum ventilation rates for diesel gas emissions and DPM. In Australia, NSW Mines Department’s MDG29 (2008), which is also referenced consistently in other states, requires:

> The minimum ventilation quantity should also consider the total number and power of diesel engines operating in the same ventilation current at any one same time. For a newly developing mine, good practice is to provide 0.1 m^3/s/kW of diesel engine power to overcome, diesel emissions (gaseous, particulate) and heat stress.
>
> 4.3.1 Gaseous Emissions
> For gaseous emissions the minimum ventilation quantity (volume of air) in each place where a diesel engine operates shall be such that a ventilation current of not less than;
> a) 0.06 m^3/s/kW of maximum capacity of the engine, or
> b) 3.5 m^3/s,
> which ever is the greater is directed along the airway in which the engine is operating. If more than one diesel engine is being operated in the same ventilating current the diesel engine rated kW shall be added.
>
> 4.3.2 Particulate Emissions
> For particulate emissions the minimum ventilation quantity (volume of air) in each place where a diesel engine operates should not be less than those quantities specified by the diesel engines particulate signature. Refer 5.2.3.2 Diesel Particulate Signature (QDP(min)).

By way of a worked example, the sum of the kW mix for a typical (real) underground fleet of heavy diesels of 25 vehicles was 9030 kW. These vehicles ranged from MT6020 haul trucks rated at 580 kW to Mercedes 904 Shotcreters at 175 kW. If all these vehicles were underground together, the required ventilation rate would be 903 m^3/s. Even using the particulate index approach to de-rate the ventilation, the required rates are problematic, to say the least.

The capital cost for ventilation starts at $3 million per 300 m^3/s per year. Clearly, the ability to match air to kW is going to be a major cost factor in the performance of the mine. Too much air (unlikely) and money is just blowing away. Too little, and the mine is at risk of a breach, or production is curtailed.

In practice, the ventilation officer has limited influence over vehicle deployment systems, and mine operations in general do not try to manage kW underground in any serious fashion. Tag boards or their simple electronic equivalent are more about knowing where people are from a safety standpoint than trying to avoid kW exceedances in relation to available air.

This leaves on the table significant opportunities for cost minimisation and improvements in mine efficiency.

1. While at the macro level, providing enough air might be problematic within the mine network, the problem becomes much more tactical and tractable at the micro level. Some areas will have more air available than others and some air zones will be fresher than others. Being able to route and ramp air flows to meet variable pollutant loads is both possible and highly cost effective.
2. Air ventilation suppliers would like to sell air by the ‘cube’ and by the hour. They want to be able to use their expertise to provide variable demand systems that tailor air to pollution demand.
3. The ability to modify down the pollutant index for a vehicle and therefore the lowering amount of diluting ventilation required should reward fleet operators with high maintenance standards and/or who adopt higher tier engine package options.

All of these require the amount of diesel emission being created by each vehicle, and the mine-zone location of each vehicle, to be provided as a feed to a ventilation control system and as feedback to a vehicle dispatch system. The more continuous the feed of data, the more effective the control to maximise production where air can be made available and avoid localised exceedances where it isn’t.

Total carbon emissions

Carbon counting is not going away. Pressure will grow to account for what we do and to spread the cost and responsibility to its producers. National Greenhouse Emissions Reporting (NGER) will remain a requirement and will progressively be pushed to into every level of our lives. Like taxation, corporates should pay what is due but no more. Understanding where and how much carbon you disinter opens the way to ensuring you pay only what is due, and allows you to focus on the efficient minimisation of its production.

Assessment of emissions can be based crudely on the consumption of fuel. This is inherently inaccurate as it takes no account for accuracy in the supply chain:

- How much fuel is delivered compared to what is invoiced?
- How much fuel is dispensed for the business’s purpose? (e.g. a recent audit at one major site showed that an unmetered pump was being freely used by contractors for vehicle fills and work not benefiting the fuel owner.)
- Which vehicles used a disproportionate amount of fuel for the work done?

A better alternative is to capture the actual fuel used per vehicle. Summing the emissions individually from each vehicle gives a strong alternative to just reporting on fuel delivered to a site and that links carbon emitted to the actual production.

CONCLUSIONS

An open-ended system suffers from not associating change in the source with changes in the effect. This inevitably means that the relationships between cause and effect are not closely understood and the ability to optimise is not developed. Making matters worse is the fact that DPM mass is the only thing easily measured in the workplace but the available instrumentation tapers off in sensitivity below about 100 nm. Modern diesel engines with high-pressure fuel systems exhaust most of their DPM as particles well under this size.

The nano and ultra-fine DPM are more easily ingested by personnel and more richly coated with toxic hydro-carbon compounds. Even if a vehicle-borne, continuously monitoring DPM mass sensor were to be developed, in isolation, it is effectively measuring the wrong endpoint, from a risk perspective.

1. Condition-based maintenance.
2. Operator performance.
3. Vehicle utilisation

4. Fuel efficiency
5. Emission rates
6. Total carbon emissions

On the positive side of the ledger, there are material benefits in characterising the moment-by-moment emissions since they provide access to measure and control costs and reduce waste that otherwise are roughly acknowledged but not actively managed in modern mining.

Pressure is on to better manage the risk of diesel emissions anyway. To provide a mechanism that also allows addressing ubiquitous areas of cost and waste, makes a compelling reason to investigate continuous, vehicle-borne, diesel emissions monitoring. Operators are already utilising other data off vehicles and combining it with other data sources in an embryonic 'big data' approach. Some surface operators have full weather stations on their haul trucks. Adding real time emissions data allows for informed operational decision-making not previously available, in relation to hazard, regulatory compliance, vehicle utilisation and condition.

ACKNOWLEDGEMENTS

The authors would like to acknowledge funding from AusIndustry through the Clean Technology Investment Program (CTIP) and from the Department of Industry through the Researcher in Business scheme. Thanks also to Dr Payam Mousavioun and Dr Richard Brown for their assistance and input. This paper was developed with permission from Peak3 Pty Ltd. Thanks to CTIP participants: Barminco, MMG Dugald River, Logan City Council, Western Areas Flying Fox, Gold Fields Agnew and Anglo Gold Sunrise Dam.

REFERENCES

Attfield, M D, Schleiff, P L, Lubin, J H, Blair, A, Stewart, P A, Vermeulen, R, Coble, J B and Silverman, D T, 2012. The diesel exhaust in miners study: a cohort mortality study with emphasis on lung cancer, *J Natl Cancer Inst* 104(11):869-883.

Barone, T L, Storey, J and Domingo, N, 2010. An analysis of field-aged diesel particulate filter performance: particle emissions before, during, and after regeneration*, J Air Waste Manage Assoc* 60(8):968-976.

Cummins, 2013. Cummins MPG guide: secrets of better fuel economy, the physics of MPG [online]. Available from: <http://cumminsengines.com/uploads/docs/cummins_secrets_of_better_fuel_economy.pdf> [Accessed: 12 October 2013].

Caroca, J C, Millo, F, Vezza, D, Vlachos, T, de Filippo, A, Bensaid, S, Russo, N and Fino, D, 2011. Detailed investigation on soot particle size distribution during DPF regeneration, using standard and bio-diesel fuels, *Ind Eng Chem Res* 50(5):2650:2658.

Fierz, M, Houle, C, Steigmeier, P and Burtscher, H, 2011. Design, calibration and field performance of a miniature diffusion size classifier, *Aero Sci Technol* 45(1):1-10.

Giakoumis, E G, Alafouzoz, A I, 2010. Study of diesel engine performance and emissions during a transient cycle applying an engine mapping-based methodology, *Appl Energy* 87(4):1358-1365.

International Agency for Research on Cancer, World Health Organization, 2012. IARC: diesel engine exhaust carcinogenic [online]. Available from: <http://www.iarc.fr/en/media-centre/pr/2012/pdfs/pr213_E.pdf> [Accessed: 12 October 2013].

Jones, N B, Li, Y, 2000. A review of condition monitoring and fault diagnosis for diesel engines, *Tribotest* 6(3):267-291.

Lähde, T, Rönkko, T, Virtanen, A, Solla, A, Kyto, M, Söderström, C and Keskinen, K, 2010. Dependence between nonvolatile nucleation mode particle and soot number concentration in an EGR equipped heavy-duty diesel engine exhaust, *Envir Sci Tech* 44(8):3175-3180.

Lin, T, Tan, A, Lin, M and Joseph, M, 2013. Estimating the loading condition of a diesel engine using instantaneous angular speed analysis, in *Engineering Asset Management 2011: Proceedings of the Sixth Annual World Congress on Engineering Asset Management* (ed: L Jay) pp 259-272 (Duke Energy Center: Cincinatti, Ohio).

Neer, A and Koylu, U, 2006. Effect of operating conditions on the size, morphology, and concentration of submicrometer particulates emitted from a diesel engine, *Combustion and Flame* 146(1-2):142-154.

Nel, A, Xia, T, Mädler, L and Li, N, 2006. Toxic potential of materials at the nanolevel, *Science* 311(5761):622-627.

New South Wales Department of Primary Industries, 2008. Guideline for the management of diesel engine pollutants in underground environments, MDG 29, produced by the Mine Safety Operations Division, New South Wales Department of Primary Industries.

Oberdürster, G, 2000. Toxicology of ultrafine particles: *in vivo* studies, *Phil Trans Roy Soc Lond A*, 358(1775):2719–2740.

Pope, C A, 2000. Epidemiology of fine particulate air pollution and human health: biologic mechanisms and who's at risk?, *Envir Health Perspect*, 108(4):713-723.

Pöschl, U, 2005. Atmospheric aerosols: composition, transformation, climate and health effects, *Angewandte Chemie, Int. Ed.* 44(46):7520-7540.

Ris, C, 2007. U.S. EPA health assessment for diesel engine exhaust: a review, *Inhalation Toxi* 19(1):229-239.

Ristovsk, Z D, Miljevic, B, Surawski, N, Morawska, L, Fong, K M, Hog, F and Yang, I A, 2012. Respiratory health effects of diesel particulate matter, *Respirology*, 17(2):201-212.

Sangkapichai, M, Saphores, J, Ogunseitan, O, Ritchie, S, You, S and Lee, G, 2010. An analysis of the health impacts from PM and NOx emission resulting from train operations in the Alameda Corridor, CA, University of California Transportation Center Research Paper No. UCTC-FR-2010-10.