Field Evaluation of Diesel Particulate Matter Using Portable Elemental Carbon Monitors

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ABSTRACT: Regulations on worker exposure to diesel particulate matter (DPM) are becoming increasingly stringent in the mining industry. Due to the complexity and unpredictability of this aerosol, there is a need for new tools to help mines develop an effective strategy to reduce DPM concentrations. To address these needs, NIOSH has developed a portable elemental carbon monitoring device for use in underground mines. This instrument is compact and capable of monitoring EC concentrations in real time. The information that it provides is useful when planning new DPM curtailment strategies or when measuring the effectiveness of existing DPM controls. The following paper discusses a variety of ways that this instrument has been used to help lower DPM concentrations and exposure to DPM in active mines.

1 Introduction

In May, 2008, the Mine Safety and Health Administration significantly lowered the permissible exposure limit of underground mine workers in the U.S. to diesel particulate matter (DPM). The new regulation states that "a miner's personal exposure to diesel particulate matter in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 160 micrograms of total carbon per cubic meter of air (160 TC µg/m^3)", where TC is the sum of elemental carbon (EC) and organic carbon (OC) (MSHA, 2005). This adjustment is a substantial reduction from the 2007 interim limit of 350 TC µg/m^3.

In order to comply with this regulation, most mines must employ one, or a number of combined control strategies to lower DPM concentrations. Some options available to mines include: improved vehicle maintenance programs, increased or re-routed ventilation, upgrading fleet to newer engines, use of alternative fuels such as biodiesel, the addition of diesel particulate filters (DPFs) to key vehicles, changes to truck traffic and other administrative controls. Because these strategies vary greatly in the amount of reductions attainable and the costs of implementation, it is important to have a thorough understanding of the DPM emissions within the mine so that the most effective control strategy can be utilized. Obtaining a clear understanding how individual DPM sources impact the transient concentrations of DPM within a mine is a difficult task, but recent advancements in measurement techniques have made this goal more feasible.

1.1 Real-time Monitoring

Currently, there are no instruments available to the mining industry for measuring DPM concentrations that are portable and field-worthy. The traditional method for measuring DPM in underground mines is based on the NIOSH 5040 method (Birch and Cary, 1996; Birch, 2002). Although this procedure may be the most accurate method for collecting and measuring compliance samples of DPM, the time and cost involved in the process make it a less practical method for mines that are looking to monitor the effectiveness of DPM controls. In addition, the NIOSH 5040 method is a one-dimensional measurement, meaning that it provides an average DPM exposure measurement over a given time period without recording critical information pertaining to the cause of the overexposure. To address these issues, NIOSH has developed a portable instrument that is capable of indicating the concentration of DPM in near real-time. By tracking the changes in laser beam transmittance through a particulate matter collection filter over time, the instrument is able to measure the rate of EC deposition on the filter based on previous calibration against the NIOSH 5040 method. This combined data set (time and sensor rate of change) correlates with EC concentrations within the tested location (Noll & Janisko. 2007). If desired, an optional EC to TC ratio can be set within the instrument settings to correlate this value to TC, however caution is advised when utilizing this method (see section 1.2). Using this process, the instrument provides charted outputs of recorded EC and calculated TC concentration changes over time. Because these concentrations are often transient in nature, understanding this data will help mine operators obtain a clearer picture of how DPM levels are affected by mining activity and how well they respond to different control strategies. This data can provide valuable information on the effectiveness of ventilation, vehicle-specific emissions, DPF failures, miner-specific exposures, and the effectiveness of cab filtration systems. The following is a discussion on how real-time monitoring technology can be used to evaluate DPM problem areas and aid in the selection of effective DPM control strategies.

1.2 Capabilities, Limitations and Interferences

The instruments used for real-time assessment of DPM are beta prototypes supplied by ICx technologies (Figure 1).

These devices rely on a rolling average to evaluate EC levels[1]. Therefore, when used as an area sampler or a personal sampler, they provide an indication of the average concentrations of EC over the previous five, ten and fifteen minutes as well as the time-weighted average exposure value (TWA) for an eight hour shift. All of these calculated values are updated once per minute. The lower limits of quantification of the instrument are as follows; 18 ug/m^3 EC for TWA, 110 ug/m^3 EC for five minute rolling averages, 62 ug/m^3 EC for ten minute rolling averages, and 54 ug/m^3 EC for fifteen minute rolling averages. The instruments show an approximate error within 10% EC of the NIOSH 5040 method in controlled laboratory tests and within 15% EC in field tests (Noll & Janisko, 2007; Janisko *et al*., 2008)

Figure 1 A photograph of the ICx DPM Monitor beta prototype showing the instrument, sampling line and size selector.

As with most technologies, the information that the DPM monitors provide is subject to certain limitations and interferences. First, the monitors use EC as a surrogate to estimate DPM and, therefore, do not perform any direct measurement of TC. This means that, in countries without an EC standard (such as the United States), an EC to TC ratio must be set on the instrument in order to convert EC measurements to TC. Research on specific conversion factors in underground mines has been presented in previous investigations (Noll *et al.*, 2007). For compliance sampling, MSHA requires that a simultaneous conversion factor be obtained from an area sample collected in the main exhaust and downstream of the exposed mineworker (MSHA, 2008). Although it is encouraged that the instruments be utilized primarily for the measurement of EC, if TC estimations are desired, it is suggested that mines obtain EC/TC ratios in a manner similar to the MSHA compliance method.

When used as directed, mineral dust will not interfere with the monitor's reading in metal/non-metal mines. However, when the monitors are exposed to drastic changes in temperature from cold to hot, condensation can build up on the sampling cassette within the instrument and cause false overestimations of EC concentration. This interference has been seen primarily in cold climates and lasts for only a short duration. Typically, it occurs when traveling from a warm section of the mine to the intake. After a short time, the system will equilibrate and the monitor will begin functioning properly. This interference is recognizable in the data as large abnormal spikes that correlate with times when the monitor was exposed to drastic changes in temperature (07:50-08:15 of Figure 2). Another method for detecting this interference is to analyze a chart of the sensor output throughout a test. Under normal conditions, the sensor voltage will decrease or remain constant throughout the testing period. If the signal ever rises (as it does around 08:07-08:15 of Figure 3), this is a good indicator that a temperature interference has occurred. In Figure 2, the data before and after the interference would still be accurate.

2 Methodology and Results

2.1 Sampling Techniques

The following tests were performed at active mines. Depending on the nature of the test, DPM concentrations were either read directly from an LCD screen on the instrument at the time of testing or downloaded from the internal memory of the instrument after the testing period.

2.2 Measuring the Effectiveness of Ventilation in an Area

Adjusting the mine's ventilation system can be one of the easier and more cost effective solutions when combating DPM emissions. However, it is important to understand how successful these ventilation increases will be before committing to this control strategy. The DPM monitors may be used to measure the adequacy of ventilation in an area (in terms of DPM flushing) and to estimate the point at which further increases become inefficient when weighed against the increased cost and complexity of such a solution.

Figures 4 & 5 show data that was collected in two active metal/non-metal mines in 2009. In the first case, data was collected at the main exhaust for approximately six hours. The monitor was left unattended during the test period. As shown, the concentration of EC built slowly, but steadily, throughout the test. This is a "fingerprint" trend which indicates that a ventilation increase might be successful at lowering DPM concentrations.

[1] A further technical description of the operation of the instrument is provided in previous publications: Janisko *et al.*, 2008; Noll & Janisko, 2007.

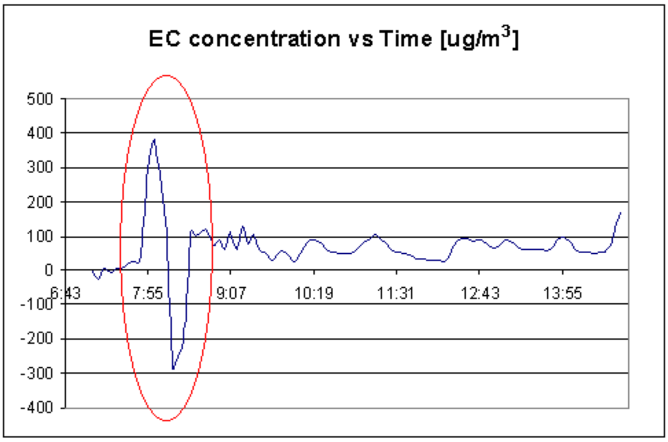

Figure 2 A chart of EC concentration vs. time, showing temperature interference at 07:50-08:15.

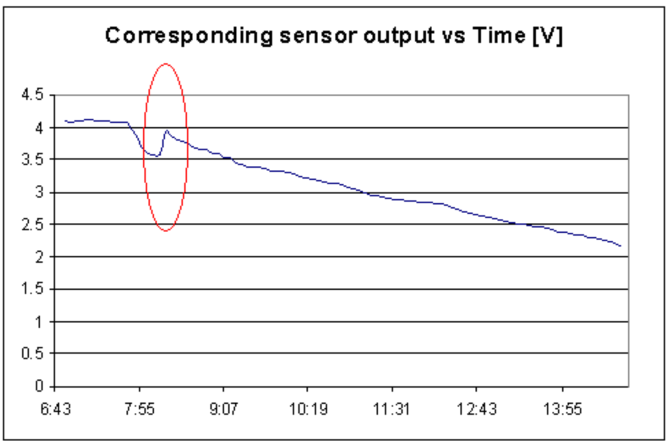

Figure 3 A corresponding chart of sensor output showing an increase in signal at 08:07

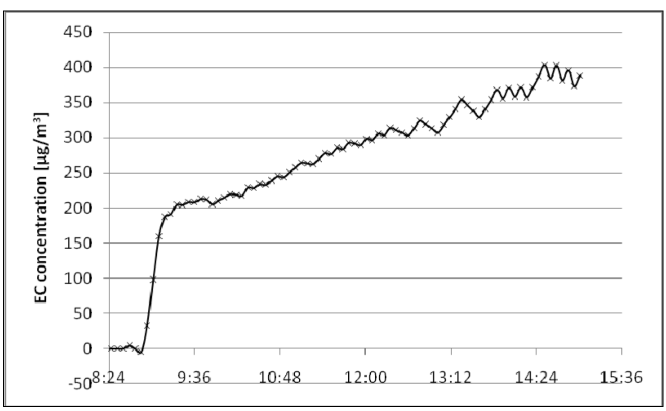

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Figure 4 A chart showing a steady increase in recorded EC concentration from 200 to 400 ug/m^3 throughout a six hour time frame.

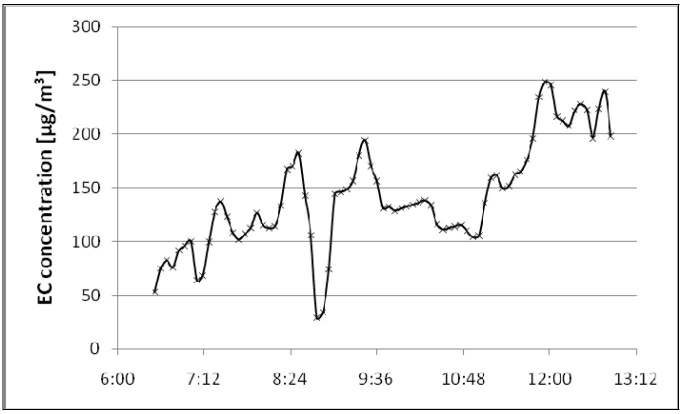

Figure 5 A chart showing a fluctuating, but overall increase in recorded EC concentration from 75 to 200 ug/m^3 throughout a six hour time frame.

Often times, attaching the DPM monitors to the exterior of a vehicle is a superior method of collecting data in an area because it can be collected near the center of the entry and directly within the working zone. Figure 5 shows a case where area measurements were collected on a mucker (an LHD, or load haul dump vehicle) during its working cycle. Although these types of measurements are more prone to fluctuation from localized activity, a similar trend can still be found in the data (Figure 5).

Both of these examples highlight the advantages of real-time monitoring as well as full-shift sampling when analyzing DPM conditions in an area. Without a long-term, real-time measurement of EC transients, increases in DPM concentrations throughout the shift may have gone undetected.

Although not available at the time, a good method for assessing the effectiveness of ventilation changes to that area would be to increase the air flow to that section of the mine without changing any other parameters that would influence DPM concentration levels (truck traffic, changes in work flow, etc.). From this, some measure of how much additional air flow equals a particular reduction in DPM concentration could be derived.

2.3 Monitoring Vehicle-specific Contributions to DPM

When choosing a DPM reduction solution, it is often assumed that diesel particulate filters are the preferred method for controlling particulate emissions. Although these filters have shown the potential to drastically reduce DPM emissions (Bugarski *et al*., 2007; McGinn *et al*., 2002), they can present additional up-front costs and maintenance demands (US EPA, 2007) as well as concerns over increased NO_2 emissions in catalyzed systems (Czerwinski *et al*., 2007; Mogenson *et al*., 2009). For these reasons, it is not uncommon to find cases where it would be more efficient to single out the major contributors to DPM emissions within a mine's fleet and outfit those vehicles with particulate filters while attacking the rest of the fleet with other methods such as enhanced maintenance programs, administrative controls or alternative fuel blends. In these cases, it would be beneficial to know the individual contributions of particular vehicles to total DPM emissions throughout the mine (i.e., the vehicle-specific emissions) so that the most effective plan could be developed.

2.3.1 *Isolated zone testing for vehicle-specific emissions*

A good technique available for measuring vehicle-specific DPM contributions is an isolated zone analysis. When performing these tests, a vehicle is operated in an inactive section of the mine which is as free from DPM interference as possible (i.e. the isolated zone) (McGinn *et al*., 2002; Bugarski *et al*., 2005, 2006). The goal is to mimic the typical loading cycle of that engine under normal operating conditions. This is accomplished by running the machine through a simulation of its working cycle within the isolated zone throughout the length of the testing period. The benefit of this type of analysis is that it more closely replicates engine transients than other forms of vehicle-specific testing. The primary limiting factors are the ability to maintain prevailing ventilation conditions and accurately simulate working cycles. For a detailed description of isolated zone methodology, the reader is referred to: "Performance Evaluation of Diesel Particulate Filter Technology in the Underground Environment", McGinn *et al*., 2002, and "Evaluation of Diesel Particulate Filter Systems and Biodiesel Blends in an Underground Mine", Bugarski *et al*., 2005.

Figure 6 shows real-time measurements that were taken during an isolated zone test in a metal mine in 2009. In this experiment, a mucker was operated within the isolated zone, moving ore with the air flow, from the upstream end to the downstream end in a continuous cycle. Two breaks in testing occurred at 11:32 and 13:47. DPM monitors were placed both upstream and downstream of the isolated zone to record changes in concentration throughout the test. In this case, because the entry was not much larger than the vehicle itself, the vehicle acted like a piston within the isolated zone –flushing DPM downstream when traveling downwind and partially pulling DPM against the ventilation when traveling

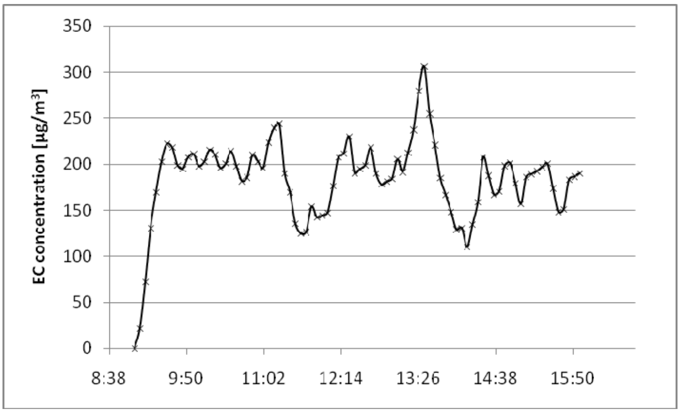

Figure 6 A real-time trace of recorded EC taken downstream during an isolated zone test. The chart shows concentration oscillations ascribed to the movement of the vehicle throughout the test.

upwind. This type of cycling can be observed in figure 6, although the data shows some clipping due to the response times of the monitors.

In this case, the DPM monitor indicated an average concentration of 180 ug/m^3 EC at the prevailing ventilation rate and a time-weighted average of 172 ug/m^3 EC over the testing period. The upstream measurements were below the limits of quantification of the instrument, and were therefore not corrected for.

In order to make use of this data, the other vehicles in the fleet should be analyzed in a similar manner, and the contributions to DPM emissions compared proportionally. The time that a particular engine spends within the mine during a given shift and its location(s) as well as instances when the vehicle is idling all need to be factored into this analysis. Once this process is completed, vehicle emissions can be combated on a priority basis in order to enhance the effectiveness of DPM control strategies and potentially reduce implementation costs.

2.3.2 *Tailpipe monitoring for vehicle-specific emissions*

A proposed method for estimating vehicle-specific emissions is to perform tailpipe sampling of EC with the instruments. Although still under investigation, this type of testing would involve forcing engines into different operational modes and taking short samples of EC concentration from the exhaust exit. This would allow for an estimation of vehicle-specific contributions which is free from outside sources of DPM interference. In addition such a method may provide a beneficial approach towards monitoring changes in diesel particulate filter efficiencies over time and recognizing failures within the exhaust filtration systems. The difficulties involved in properly simulating transient loading cycles, removing water and temperature interferences, and accounting for leaks within the exhaust system as well as crankcase gas emissions are all areas of on-going research.

2.3.3 *Area sampling for vehicle-specific emissions*

A third, and fairly crude method for measuring vehicle specific contributions using the DPM monitors is to select a strategic location for area sampling throughout a shift and assess the fluctuations in real-time concentration over time. Matching the time-stamped data from the monitors with the times when an individual vehicle has passed the sampling location can provide a basic look at which vehicles are the largest emitters in that area of the mine. Although easier to perform than an isolated zone study, in terms of vehicle-specific emissions, this method may only useful to identify which vehicles are the major emitters of DPM in that area and is not practical for quantifying individual vehicle contributions.

2.4 Measuring Miner-specific Exposure to DPM

The DPM monitors are not recognized as an alternative to compliance sampling, but the instruments can be used in a similar manner to obtain an informative assessment of individual worker exposures. For compliance sampling, MSHA requires that a shift-weighted measurement of EC and TC exposure be taken (via the NIOSH 5040 method) from a mineworker's breathing zone. To do this, a mine worker is outfitted with a sampling train consisting of a pump, flexible tubing and an integrated cyclone/impactor/filter assembly. The DPM monitors were designed to mimic this system and therefore use many of the same components.

The monitors are capable of providing both shift-weighted EC and calculated TC exposures in real-time and, in addition, they can monitor changes in EC exposures throughout the entire shift. In some cases, it may be useful to ask the mineworker to record events that might affect DPM readings, such as times when the instrument was removed or unexpected changes in location. Coupling these records with the real-time values of EC and information on affective factors such as truck traffic, working conditions and ventilation rates can be useful when trying to pinpoint the cause of overexposures during a working shift. It is often the case that administrative controls can be implemented to limit these overexposures to DPM.

2.5 Measuring the Effectiveness of Cab Filtration Systems

Environmental cabs can be an effective means for limiting mineworker exposure to DPM. However, simply leaving the window open or periodically opening the door can introduce enough DPM into the cab to cause an overexposure. Placing DPM monitors on the inside and outside of a cab throughout a shift can provide a relatively easy assessment of the effectiveness of the cab filtration system.

In a previous study (Noll & Janisko, 2007), it was shown that this method can identify situations when a cab filtration system has failed, as well as identify occurrences where open windows or open doors are causing avoidable overexposures. In a properly functioning system, the monitor within the cab will indicate only small concentrations of EC throughout the shift, regardless of the exterior concentrations. An open door is characterized by a large spike in concentration that gradually falls to near-zero as DPM is flushed from the cab over time. A prolonged increase in DPM concentration within the cab that matches the exterior values is associated with instances where the cab window was left open. In some cases, simple administrative controls are all that are needed to remove these hazardous situations.

3 Conclusion

This paper provides a practical approach to using real-time EC monitoring for the selection and evaluation of effective DPM controls. The ability to perform well-executed tests and to interpret the information that real-time monitors provide is an essential part of understanding the cause of DPM exposure.

In particular, the information provided in charts of concentration changes over time is of great value. This data offers a novel way of understanding the factors that influence DPM exposure and drive concentration transients in an underground environment. In addition, it provides mine operators with a legitimate resource to aid in the reduction of DPM concentrations to meet the U.S. MSHA 2008 exposure limit of 160 ug/m^3 TC.

It is the expectation of the authors that, as with all new technologies, a number of uses for these instruments have yet to be conceptualized. Therefore, the methods outlined in this paper should not be considered a comprehensive list, but rather as an initial guide to a number of novel techniques for assessing DPM concentrations in an underground environment.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

Mention of any product or company does not constitute an endorsement by NIOSH.

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