Real-time Measurements of Diesel EC and TC in a Nevada Gold Mine With Photoacoustic and Dusttrak Instruments: Comparison With NIOSH 5040 Filter Results

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ABSTRACT: This paper presents real time photoacoustic measurements of diesel-soot black-carbon (BC or EC) and Dusttrak nephelometer total carbon (TC) concentrations in a Nevada gold mine. Comparisons with time-integrated filter-based measurements of EC and TC accomplished using the NIOSH 5040 method were found to be 50% smaller than the integrated real time measurements. This work was initiated primarily as a demonstration project for the usefulness of photoacoustic instruments in measuring BC in the mine environment. Real time black carbon measurements are very useful for determining miner exposure, for providing feedback in mine ventilation systems, and for quantifying machine specific emission rates to understand the operating conditions for specific machines that produce greatest black carbon concentrations. This paper reports real time measurements of DPM from a loaded and empty hauler as it is operated in a drift with a 12% grade. The photoacoustic instruments were demonstrated to be satisfactory for BC measurements in the mine environment.

1 Introduction

Underground mines typically use many different types of diesel-powered machines. Occupational exposure to diesel particulate matter (DPM) in underground mines is regulated for health reasons. DPM is composed of elemental and organic carbon (EC and OC) that is collectively referred to as TC, and smaller amounts of inorganic species.

New standards for DPM limits in underground mines come to effect in May 2008 as stated in the U.S. Title 30 code of federal regulations §57.5060 "*Limit on exposure to diesel particulate matter*" (MSHA 2008). This new standard is specifically stated as "Effective May 20, 2008, a miner's personal exposure to DPM in an underground mine must not exceed an average eight-hour equivalent full shift airborne concentration of 160 micrograms TC per cubic meter of air (160TCμg/ m3)." Part of this regulation states that "the mine operator must install, use, and maintain feasible engineering and administrative controls to reduce a miner's exposure to or below the DPM limit established in this section. When controls do not reduce a miner's DPM exposure to the limit, controls are infeasible, or controls do not produce significant reductions in DPM exposures, controls must be used to reduce the miner's exposure to as low a level as feasible and must be supplemented with respiratory protection ...".

The first standard implemented in 2006 was stated as an EC standard. The 2007 standard was stated as a TC standard with an equivalent EC standard. It is anticipated by MSHA that the 2008 TC standard will also be stated equivalently as an EC standard as well, likely due to the fact that the NIOSH 5040 measurement method is actually stated as an EC standard (Birch 2003). The reason EC standards are used is that the OC component of TC is subject to interferences due to cigarette smoke and carbonate rocks (Birch 2003).

This paper demonstrates real time photoacoustic measurements of black carbon (denoted by BC) and total scattering particulate matter with submicron size (denoted by dPM1) in a Nevada gold mine. Real time measurements allow for rapid feedback to mine operators for understanding conditions that give rise to high emissions so that appropriate operational procedures can be put into place to achieve compliance with miner exposure standards. By contrast the NIOSH 5040 method involves first depositing particulate from a 1 or 2 hour in-mine air sample on 37 mm quartz-fiber filters. Then the filter is sent to an analytical laboratory for analysis, with a typical turn-around time of 1 or 2 weeks. Real time BC and dPM1 are akin to EC and TC measured by the NIOSH 5040 method, respectively. Accurate and precise real time measurements allow for continuous quantification of mine EC and TC for immediate feedback control to mine operation and ventilation. One ultimate goal of the effort described here is to seek equivalency between real time measurements and the NIOSH 5040 method so that mines may rapidly achieve and demonstrate compliance with miner hygiene standards.

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2 Mine Measurement Site Description

The mine site has been described extensively (Osei-Boakye, Mousset-Jones et al. 2008). Briefly, filter samplers and continuously measuring instruments were placed at two site in a declining drift. The drift dimensions are 15' wide by 17' high. Drift ventilation is achieved by use of a duct of diameter 48" placed at the top of the drift. The ventilation air is blown to the end of the drift and it returns under negative pressure to the center of the mine where it is exhausted upwards to the next level in the mine. Ventilation is provided by a main auxiliary fan and an inline booster fan. Each blower is a 1750 RPM 200-HP axi-vane-Fan. The ventilation amount is on average 82,000 CFM. A schematic of the drift is shown in Fig. 1.

The diesel-fuel powered vehicle used in these test was operated downhill and back uphill in the drift. It was a haul truck, DUX TD-26, powered by a Cummins QSM11, 400 HP, 6-cylinder, 4-cycle, ESC Scrubber Model B12-0025. The number of engine hours on this truck was unavailable. The travel distance between the sites was 1,800 feet. A photograph of the truck in operation, along with the instruments, is shown in Fig. 2. One set of test results were obtained when the vehicles was operated fully load with rock, and a second set after it was unloaded.

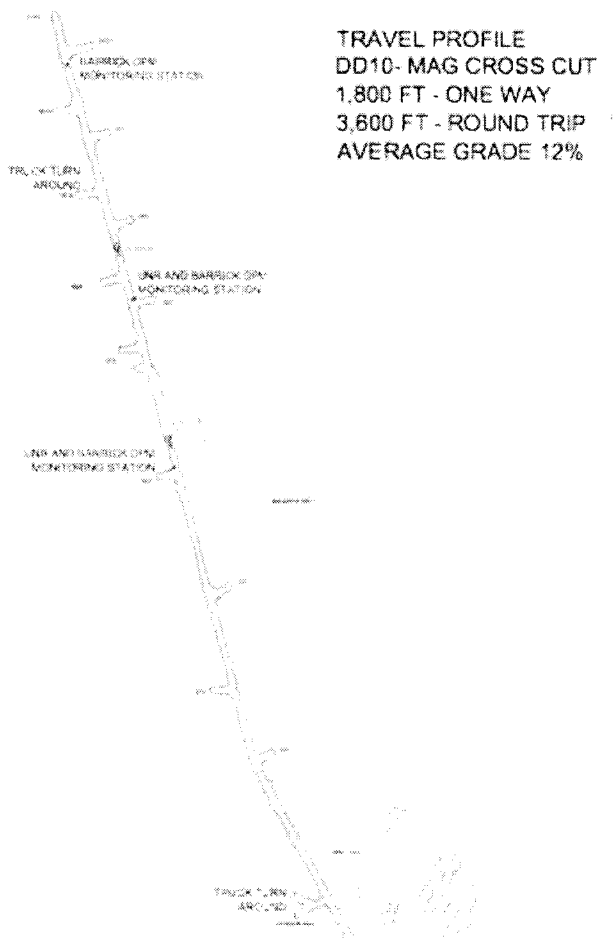

Figure 1. Schematic of the Banshee drift.

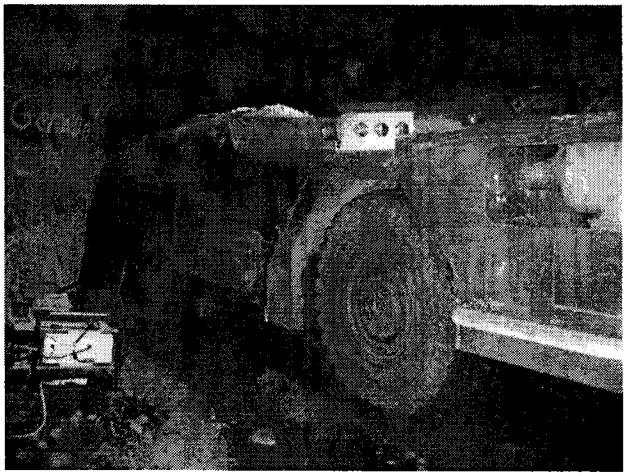

Figure 2. Photograph showing the haul truck in operation along with the air quality samplers. The photoacoustic EC instrument is housed in the vanilla colored box on the equipment rack and the Dusttrak nephelometers are in blue. The filter samplers are up on the wall immediately to the right of the blue writing on the wall. The sample inlet for the photoacoustic instrument can be seen draped over the top of the laptop computer.

3 Instruments

3.1 Filter Samples by the NIOSH 5040 Method

The NIOSH 5040 method (Birch 2003) describes a procedure for measuring DPM as EC. In this method, mine air is sampled onto a 37 mm diameter quartz-fiber filter. A size selective sampler is often used to restrict particle sizes to be less than 1 micron aerodynamic diameter. One or two hour samples are usually obtained to provide enough, but not too much, DPM loading on the filter for accurate measurements. The total sample volume as determined from the flow rate and the sample time needs to be measured accurately.

The filter is sent to Sunset Laboratories for measurement. Measurement turn-around time is usually 2 weeks. At the laboratory, a 1.5 cm^2 punch is used to sample part of the quartz filter. This punch is placed in a carbon aerosol analysis laboratory instrument. The instrument measures EC and OC by use of a small oven, a laser beam transmittance measurement across the filter, a carbon sensor, and helium or helium plus oxygen gas mixtures. Starting from room temperature, the filter punch is brought to 820 C in a helium atmosphere. OC and carbonate related carbon are measured during this phase that lasts for 6 minutes. The oven temperature is lowered to about 600 C. Then 1 part oxygen and 9 parts helium are introduced and the dark pyrolitic carbon (PC) is measured as it combusts, due to the oxygen, from the filter. All of the PC is accounted for when the laser transmittance through the filter is back to the value it was in the beginning. PC is added to the OC measured during the helium stage for determination of the total OC. The oven temperature is then ramped to 860 C and the EC is measured from the carbon combusted off the filter. The entire measurement takes about 14 minutes (Birch and Cary 1996; Birch and Cary 1996).

3.2 Real Time DPM TC Meaurements with a Dusttrak Nephelometer

The use of a Dusttrak nephelometer to infer DPM TC from light scattering measurements has been extensively described (Moosmüller, Arnott et al. 2001; Moosmüller, Arnott et al. 2001; Rogers, Arnott et al. 2004; Osei-Boakye, Mousset-Jones et al. 2008). This instrument is a nephelometer with such a large truncation angle issue that is misses the forward diffraction peak all together. We have investigated this issue using Mie scattering theory, and have shown that such a nephelometer would be useful (Moosmuller and Arnott 2003). The Dusttrak responds both to DPM and to any mineral dust that might be in the fine mode (Rogers, Chow et al. 1998).

3.3 Real Time Photoacoustic Measurements of Black Carbon

Photoacoustic instruments have been used extensively to measure BC concentrations from gasoline and diesel-powered machines. These photoacoustic instruments have a very large dynamic range, are simple to operate, need little or no maintenance, are very accurate and precise, and provide data as fast as 1 measurement per second (Rogers, Arnott et al. 2004; Arnott, Zielinska et al. 2005; Fujita, Campbell et al. 2007; Fujita, Zielinska et al. 2007). These instruments are very robust, being useful also in demanding environments such as use on meteorological aircraft to measure BC aloft (Arnott, Walker et al. 2006).

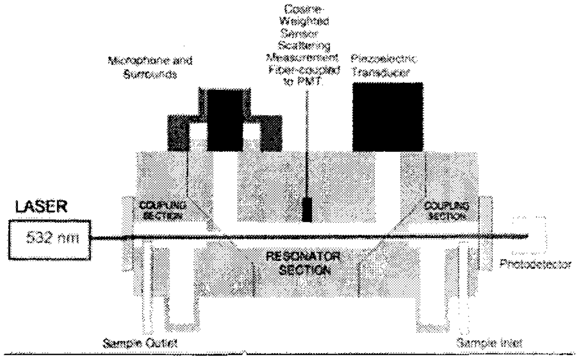

Figure 3. Schematic of the photoacoustic instrument when operated with a single 532 nm laser. Light absorption by particles transfers heat to the surrounding air, and because the laser beam power is modulated at the acoustic frequency a sound wave is created. Holes in the resonator are placed at the pressure nodes, and are ports for the laser beam and sample air. The microphone and calibration source piezoelectric transducer are located at pressure antinodes. The scattering sensor is placed in the center of the acoustic resonator section.

Light absorption related to BC is measured by the photoacoustic method (Arnott, Zielinska et al. 2005), and the reciprocal nephelometer method is used for the light scattering measurement, with a sensor that is placed in the center of the photoacoustic resonator (Rahmah, Arnott et al. 2006). The scattering sensor responds to all particles just as with the Dusttrak instrument. An instrument schematic is shown in Fig. 3. Both 532 nm and 870 nm instruments were used in this campaign.

4 Results

4.1 Real Time Measurements of EC and TC

Real time measurements from the MLC and DD sites are shown in Figs. 4 and 5 for tests 1 and 2. The Dustrak TC and photoacoustic EC are plotted in such a way that they can be directly compared. The TC is plotted on the left axis and the EC is plotted on the right axis, with a different scale on each. The peaks in the TC and EC are due to passages of the haul truck at each site. The haul truck moves faster than the ventilation air. The haul truck fills the drift with DPM and it takes some time for ventilation to remove the DPM from the drift volume.

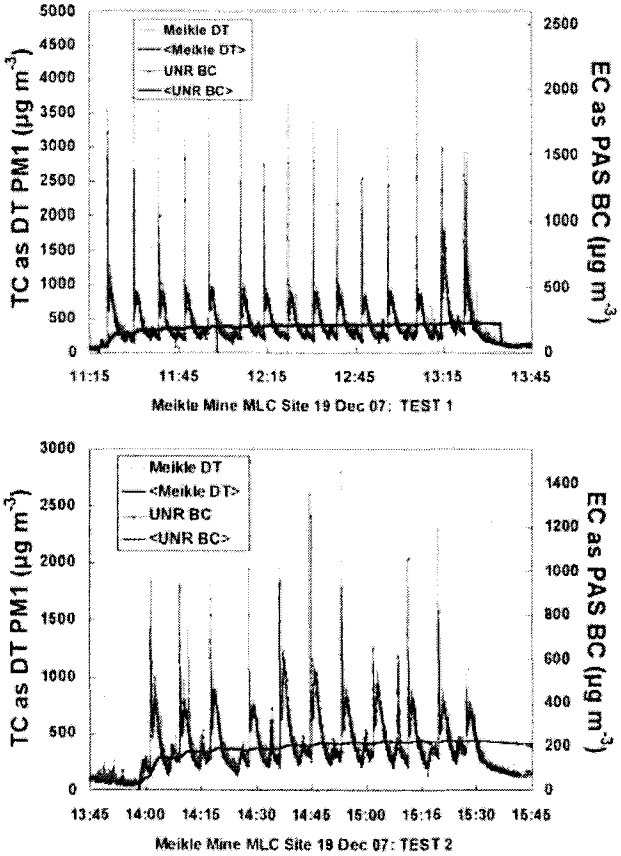

Figure 4. Real time measurements of optical TC (red and left axis) and EC (blue and right axis) during test 1 when the haul truck was fully loaded, and during test 2 when it was unloaded. Thicker black and blue curves are the

average value of the EC and TC as they develop during the tests. This data is from the MLC site.

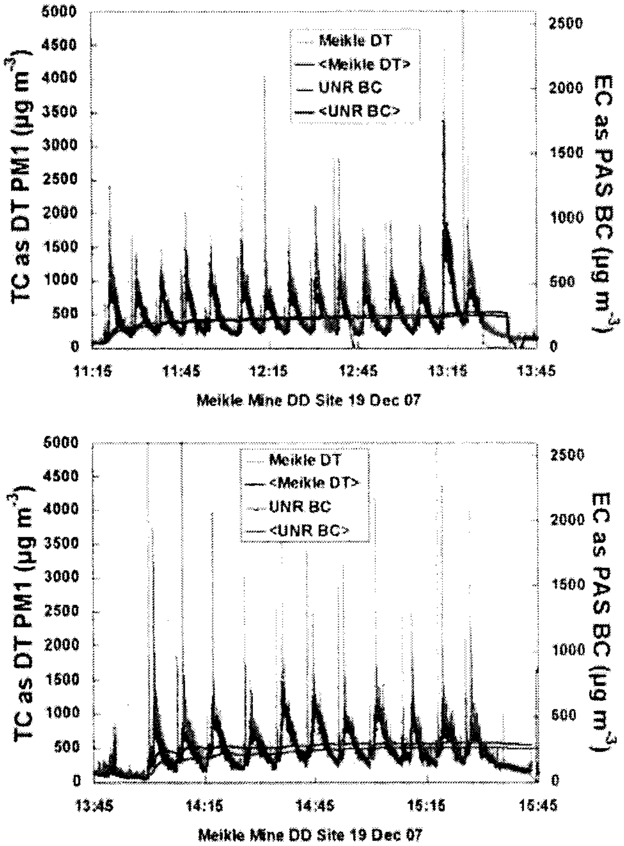

Figure 5. Real time measurements of optical TC (red and left axis) and EC (blue and right axis) during test 1 when the haul truck was fully loaded, and during test 2 when it was unloaded. Thicker black and blue curves are the average value of the EC and TC as they develop during the tests. This data is from the DD site and an 870 nm instrument.

The real time measurements in Figs. 4 and 5 show large, brief spikes of EC and TC. The spikes are due to the passage of the haul truck and its associated direct exhaust.

It is interesting to note that the MLC site is further downwind of the DD site, leading one to expect that the EC and TC readings would be higher at the MLC site. The difference in measurements between these sites should be related to the amount of DPM added by the haul truck as it passes from the DD site to the MLC site, minus any DPM that is lost to the walls of the mine during ventilation. However, both the average data and the the real time data in Figs. 4 and 5 don't show that the MLC site TC and EC are larger than that at the DD site. Most of the DPM is apparently coming from the operation of the haul truck downwind of even the DD site so that the differential amount of DPM coming from the haul truck between the DD and MLC sites does not make a large signal. It is possible that a fraction of the DPM becomes deposited on the drift wall.

From a regulatory perspective the most useful graphics are the average TC and EC as a function of time shown as the heavy curves in Figs. 4 and 5. A mine operator could schedule diesel operations in a way to keep the shift averaged DPM TC and/or EC within regulations.

4.2 Comparison of Time Integrated Results

Here are the average values for EC and TC from the filter and real time measurements for all tests and all sites.

	Filter Method	Real Time	Real Time / Filter (% larger)
TC (ug m^{-3})	338	479	42%
EC (ug m^{-3})	155	231	49%
EC/TC (%)	46%	48%	

Real time values of TC and EC are 42% and 49% larger than those from filter samples. The ratio of EC/TC is similar for both methods. The total EC and TC is a sum of that coming from the operating truck plus that from the ventilation air coming in.

Filter and continuous measurements may be different due to the different placement of their inlets. The filter samplers were on the walls of the drift while the continuous instruments were in the flow closer to the ground. Closer examination of the instruments in a laboratory setting should be done to further analyze these differences.

The real time TC measurements were from the Dusttrak instrument. The Dusttrak would respond to any mineral dust that ends up on the fine mode (Rogers, Chow et al. 1998). The size distribution of DPM varies with vehicle operation and condition (Rogers, Sagebiel et al. 2003), and the Dusttrak does have some sensitivity to particle composition and size (Moosmüller, Arnott et al. 2001; Rogers, Arnott et al. 2004). Previous measurements in a Nevada gold mine indicated that on average 8% of the PM2.5 is associated with rock dust, with as much as 22% at times (McDonald, Zielinska et al. 2003). However, the Dusttrak had a PM1 sharp size cut inlet that likely reduced the rock dust below these previous measurement values.

The real time EC measurements are larger than the NIOSH 5040 method values by about 50%. We have seen this same result in comparison of photoacoustic BC measurements with NIOSH 5040 EC measurements from ambient air measurements in Las Vegas Nevada during the winter 2003. The reason for this is likely that the real time photoacoustic measurements of light absorption are converted into equivalent BC concentration by comparing with thermal optical measurements of EC accomplished using the IMPROVE protocol (Arnott, Zielinska et al. 2005) rather than the NIOSH protocol. The NIOSH protocol is known to give EC values 50% lower than those from the IMPROVE protocol (Chow, Watson et al. 2001). It can be argued that the mass absorption efficiency factor used for the relation of EC by the IMPROVE protocol and the light absorption by the photoacoustic instrument is correct (Fuller, Malm et al. 1999). However, it is common that the EC fraction found by NIOSH and IMPROVE protocols correlate well because they are due to the same source, even if the actual numerical values are different (Chow, Watson et al. 2001; Fujita, Zielinska et al. 2007). The basic problem with EC analysis is that it is not based on a fundamental physical or chemical property, but instead is operationally defined (Chow, Watson et al. 2001). Therefore, the results in the table can be thought of as generating a 'calibration' of the photoacoustic BC measurements so that they conform to the NIOSH 5040 method values.

5 Summary and Conclusion

Photoacoustic EC measurements are well defined and are known to be more accurate than TC measurements by optical methods such as the Dusttrak. It has been shown that real time measurements of TC in DPM by the Dusttrak instrument are about 50% larger than those obtained by the NIOSH 5040 method, and a similar result was found for the photoacoustic EC measurements when compared with NIOSH EC. Other studies have shown excellent correlation of EC measurements by these methods, even though the amount of EC and TC was different. Therefore, it is recommended that in-mine analysis of real time EC and TC measurement using photoacoustic and Dusttrak instruments be calibrated to provide the same results as an equivalent EC and TC measurement by the NIOSH 5040 method for compliance applications.

Figures 4 and 5 demonstrate that the photoacoustic instruments can handle the DPM EC loads typical in mines. MSHA regulations for miner workplace health are likely to be stated both in terms of TC and equivalent EC values. The mining industry has a requirement to comply with MSHA regulations, and could deploy photoacoustic instruments for EC measurements.

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