Field Measurement of Diesel Particulate Matter Emissions

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A primary means to reduce environmental levels of diesel particulate matter (DPM) exposure to miners is to reduce the amount of DPM emission from the engine. A quick and economic method to estimate engine particulate emission levels has been developed. The method relies on the measurement of pressure increase across a filter element that is briefly used to collect a DPM sample directly from the engine exhaust. The method has been refined with the inclusion of an annular aqueous denuder to the tube which permits dry filter samples to be obtained without addition of dilution air. Tailpipe filter samples may then be directly collected in hot and water-supersaturated exhaust gas flows from water bath-cooled coal mine engines without the need for dilution air.

Measurement of a differential pressure (DP) increase with time has been related to the mass of elemental carbon (EC) on the filter. Results for laboratory and field measurements of the method showed agreement between DP increase and EC collected on the filter with R^2 values >0.86. The relative standard deviation from replicate samples of DP and EC was 0.16 and 0.11, respectively. The method may also have applications beyond mining, where qualitative evaluation of engine emissions is desirable to determine if engine or control technology maintenance may be required.

Keywords: diesel exhaust; diesel particulate; direct-reading instruments

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INTRODUCTION

Diesel engines are efficient and economical power sources for mobile equipment used by the underground mining industry. Increasing the size of mining equipment to achieve economies of scale has led to larger engines with increasing exhaust gas volumes. The health effects of most of the inorganic gaseous components of the exhaust are well known. In particular, the carbon monoxide emission levels of diesel vehicles in the US are required to be monitored weekly by a qualified person in the mine (CFR 30, 1978).

The particulate fraction of diesel exhaust, on the other hand, is much more complex in nature and the suspected health effects are not well understood. It is generally accepted that human exposure to diesel particulate matter (DPM) should be minimized because of the designation of DPM as a suspected carcinogen (NIOSH, 1988). Nevertheless, at this time, control technology and monitoring of DPM levels in underground work environments are quite new and governments and industry worldwide are striving to set acceptable limits and monitoring regimes to protect the health of workers.

Exposure of underground workers to DPM can be controlled using three basic approaches. The first approach would be to reduce the DPM emissions at the source by implementing a variety of techniques such as engine maintenance, exhaust filtration and use of reformulated fuels. The second approach would be to assure adequate volumes of dilution air. The third method would be to administratively limit the number and horsepower of vehicles allowed within a given volume of ventilation air (Schnakenberg

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and Bugarski, 2002). Simple methods to know the emission levels would be useful to help minimize exposure of workers to DPM.

Over time, engine use leads to component wear and changing emission levels. Mines, therefore, are typically mandated to measure and keep records of gas emission levels on a weekly basis. Particulate levels could be monitored on a similar basis. Current techniques to monitor raw exhaust gas particulate levels from engines rely on laboratory quality gravimetric measurements of diluted fractions of the exhaust gas stream (ASTM Standard, 2002). Similar quantitative measurements in the field cannot be done without complex instrumentation and extreme control of experimental variables.

Field-worthy techniques to provide a qualitative estimate of DPM emissions each have their limitations. The Bosch smoke method is an optical transmission method whose results vary with load and gives variable results in water-supersaturated environments. The ECOM (ECOM America Ltd, Gainsville, GA, USA) gas analyzer has a built-in filter that blackens with particulate loading. Interpretation of the smoke dot on the filter requires a subjective judgment on the blackness of the filter. Opacity and light-scattering monitors do not work well in water-condensing environments since the water droplets affect the measurement. Some efforts to use a minidiluter with the optical techniques have met with some success but require careful attention to the dilution system. Another field technique that has been used involved a large laboratory-type elemental carbon (EC) analyzer mounted in a trailer (Davies, 2000); however, because of the size and cost, it is not truly a field type of instrument. What would be useful is a small simple device that the mechanics could use during a gas emission-level check to also determine when an engine begins to emit excessive levels of DPM.

One of the challenges of sampling combustion aerosols is the changing nature of the particulate matter as it cools and condenses into the atmosphere. The presence of water as a product of combustion normally precludes collecting aerosols on filters unless heated sampling lines or a quantitative volume of dilution air is provided. The ability to collect a dry filter sample in raw exhaust gas is even more difficult in some engines used in underground coal mining because of the requirement to pass exhaust gas through a water trap to cool and thus prevent possible ignition of mine gas and coal dust.

The chemical and physical complexity of DPM further complicates measurement techniques. The National Institute for Occupational Safety and Health (NIOSH) recommends that EC be the marker for DPM as analyzed by NIOSH Analytical Method 5040 (Birch and Cary, 1996). EC has few interfering chemical species and is the major component of the chemically complex DPM produced by diesel engines. While no one parameter totally describes DPM from an analytical point of view, EC, or a technique that tracks EC, gives a result that is as least as accurate as our current knowledge of the health effects of DPM (NIOSH, 1988).

In an effort to find a mine-worthy particulate monitor that mine mechanics can routinely use to monitor the particulate emission levels of their mining equipment, the Coal Services Health and Safety Trust in New South Wales, Australia, funded a project to measure the effectiveness of various approaches to tailpipe particulate monitoring. Through this effort, the New South Wales Department of Minerals Resources funded the Centers for Disease Control and Prevention/NIOSH/Pittsburgh Research Laboratory (PRL) to test a newly developed differential pressure (DP)-based diesel particulate tailpipe monitor. Testing was conducted in Londonderry's TestSafe Australia diesel dynamometer research laboratory and at various diesel engine shops at underground mines in Australia. The overall study compared various potential portable engine tailpipe monitor devices with the standard American Society for Testing and Materials (ASTM) laboratory particulate measurement instruments whose results will be published elsewhere. The Coal Services Report (2004) compared the Diesel Detective to the full-scale dilution tunnel test and concluded that the Diesel Detective is suitable for measuring DPM from raw diesel exhaust.

The PRL tailpipe monitor system described in this work was developed through a cooperative research and development agreement between SKC, Inc. (Eighty Four, PA, USA), and the NIOSH/PRL. The development was an extension of a Dust Dosimeter that used similar principles to provide a qualitative assessment of workplace-respirable dust levels (Volkwein et al., 2000; Page et al., 2000). This paper describes the relationship of near-real-time DP measurements with the amount of EC deposited on a filter collected from raw diesel tailpipe exhaust. This method is suitable for periodic measurements of DPM emission in field conditions. The results can be used to determine when servicing is necessary to minimize DPM emissions or to determine if a particular engine exceeds normal operating emission levels in coal mine service. Initial laboratory results from NIOSH, results of the Australian laboratory and field testing are presented. A previously presented paper described similar results when using this technique for hot exhaust gas streams exceeding 100°C (Mischler et al., 2005). While the focus of this paper has been toward mining applications, there are considerable applications of tailpipe monitoring in over-the-road and off-road diesel emission monitoring.

DESCRIPTION OF THE DEVICE

This device, known as the Diesel Detective uses two components to determine tailpipe DPM levels. The first component is a detector tube that is placed directly into the exhaust tailpipe and contains a filter, holder and aqueous denuder for control of moisture on the filter. The second component is a handheld programmable pump that is connected to the detector tube. This pump automatically takes a predetermined sample and calculates the difference in pressure across the filter in the tube from the beginning to the end of a sample. The pump currently reports the DP but, if properly calibrated, can provide an estimate of the EC present on the filter.

Detector tube

The detector tube is used to sample the exhaust from an engine used in coal mines, where exhaust is passed through a baffled, water-filled tank, to cool and prevent ignitions of mine gases. These scrubber-equipped vehicles normally have a water vapor-saturated tailpipe temperature of ∼60°C. Similar principles apply to detector tubes sampling hot untreated exhaust streams with the exception that no desiccant is needed, materials that can tolerate higher temperatures are required and temperature measurement for correction of gas volume flow rate is recommended.

The detector tubes for use with scrubbers were constructed from commercially available copper tubing [9.2 cm long, 9.5 mm outer diameter (OD) and 7.6 mm inner diameter (ID)] and nominal 3/8-in. (∼10 mm) brass fittings. The brass fittings were counterbored to create a square-edge shoulder to support a stainless steel backup screen and glass fiber filter compatible with the NIOSH 5040 carbon analysis. A 9.5-mm OD and 6.4-mm ID precision stainless steel washer, placed on the front of the filter, precisely defined the area where the DPM was deposited and the area over which the filter pressure difference occurred. A high-temperature O-ring sealed the area between the washer and copper tube. An annular aqueous denuder within the copper tube consisted of a 7-cm-long cylinder of 5 Å mole sieve desiccant rings with outer and inner diameters of 7.5 and 4.8 mm, respectively. These were used to remove moisture before the DPM deposited on the filter. The denuder design permits an unobstructed path for particulate from the inlet to the filter. Previous testing of this design showed that a flow of saturated steam would be absorbed by the desiccant for a period of 2 min before moisture breakthrough occurred. The filter may then be removed from the tube and sent to a laboratory for analysis of the EC. Figure 1 shows the major components of the detector tube.

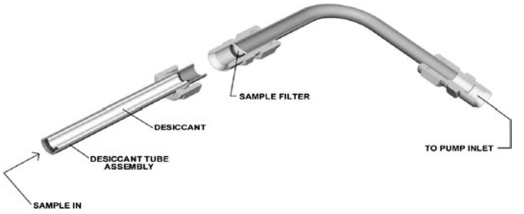

Fig. 1. Principal components of detector tube.

Pocket Pump®

Early stages of testing used a commercially available SKC Pocket Pump® (SKC Inc.). This is a variable low flow rate pump with an integral pressure gauge that monitors filter back pressure. The researcher used a stopwatch to time an initial 20-s period of filter stabilization in the exhaust stream, followed by manually observing an initial pressure, timing a 60-s sample period, quickly observing a final pressure and removing the probe from the exhaust.

Diesel detective pump

The Diesel Detective Pump was developed to simplify the measurement method. It is based on the Pocket Pump® design but operates at a fixed volumetric flow-controlled rate of 250 ml min^{-1}. This new pump also includes improved pressure sensors, improved memory capacity, new programing, automated sampling and rugged case for mine environments.

The sample air (less DPM on the filter) travels from the detector tube through a copper cooling coil where the temperature is reduced to ambient levels. Volumetric flow rate is maintained using a pressure-based flow control device that adjusts pump speed to maintain constant volumetric flow.

The Diesel Detective Pump is unique in that it may be programed to take an automated 80-s sample. The first 20 s is used to acclimatize the filter to the temperature of the exhaust. The pump then marks the initial pressure and continues to sample for an additional 60 s. At the 80-s end point, the pump electronics subtract the initial pressure from the final pressure, display the DP and record the measurement history in memory for later retrieval and analysis.

METHODS

Initial laboratory testing

The first testing of the prototype of the Diesel Detective system took place at the NIOSH/PRL. A 41-kW Isuzu diesel engine was used on a portable laboratory dynamometer with the exhaust run through a water bath scrubber commonly used in mines. The apparatus is shown in Fig. 2. The engine was run at steady state in each of the eight-mode

Fig. 2. Mobile engine dynamometer with exhaust of Isuzu C240 engine connected to stainless steel water bath in foreground used for preliminary laboratory testing at NIOSH/PRL.

Mine Safety and Health Administration (MSHA) diesel engine test points (CFR 30, 1996). For each mode, testing began after a warm-up period and after temperatures of the exhaust gas stream became stable. Three sequential tailpipe DPM measurements were made in each mode. Tests were conducted using the Pocket Pump® and a stopwatch to measure the rate of pressure increase per minute across the filter. The filters were then analyzed by NIOSH Method 5040 for EC mass (NIOSH, 1999). The only modifications to the published method were that the entire filter rather than a punched sample of the larger filter was used for the analysis and the appropriate area calculations were used. The concentration of EC was then calculated using the total pump run time of 80 s and the flow rate of 250 ml min^{-1}.

Australian laboratory testing

Based on the initial NIOSH laboratory results, more extensive testing was conducted at the Test-Safe, Londonderry research facility near Sydney, Australia. The facility uses a state-of-the-art dynamometer with a full-flow exhaust gas dilution system to evaluate both gaseous and particulate emissions. Details of the testing were devised by a committee consisting of engineers and scientists from the mining industry, engine manufacturers and the New South Wales Department of Mineral Resources (Mine Safety Technical Services, 2004). Testing was done by researchers from several organizations coordinated by the Department.

The Diesel Detective and a number of other tailpipe measurement techniques were evaluated in parallel at the Londonderry facility. Three engines commonly used by the underground mining industry were evaluated: a Caterpillar 3306 (72 kW) and a KIA (37 kW), both naturally aspirated engines, and a turbocharged Caterpillar 3126 (133 kW). The exhaust from each of the engines was passed through a water bath-cooling/scrubber system. DPM samples were taken with the detector tubes and Pocket Pump® directly from the undiluted cooled exhaust gas portion of the test apparatus. The Diesel Detective tubes with filters in place were then sent to NIOSH/PRL for EC analysis using NIOSH Method 5040.

While the Pocket Pump® DP versus the EC mass collected on the same filter was being determined, a full-scale dilution filter sample was also collected and weighed. This enabled an analytically determined EC measurement from the undiluted exhaust to be compared with the diluted gravimetric sample collected according to the ASTM Standard (2002). Thus, the determination of the Diesel Detective EC and DP can be compared to the laboratory reference mass. In turn, field measurement of DP alone can be compared to analytically determined EC, a recognized surrogate of DPM. The calculated DP was manually corrected for temperature using Henry's law. Use of the engine dynamometer allowed us to set and monitor steady-state conditions, which enabled triplicate sequential samples to be taken. In place of a standardized engine mode test that used fixed points, this test protocol permitted engine conditions to be adjusted to produce a nearly linear increase in DPM production from idle to full load.

Field measurements

The Diesel Detective Pump was used to conduct field sampling at five mines in New South Wales, Australia, in June and July, 2004. A total of 44 samples were collected from the water-scrubbed exhaust of 21 different machines. The DP reading from the Diesel Detective Pump display was recorded and the sample tubes were sent to NIOSH/PRL for NIOSH 5040 analysis. Because DP varied with load, it was essential that a consistent procedure be used to create similar load conditions for each test.

Field test procedures consisted of bringing the mine machines' engines to operating temperature then, while the machine was at idle, the detector tube was inserted into the tailpipe while simultaneously starting the Diesel Detective Pump sample. An initial pump pressure was recorded 20 s into the measurement. About 30 s into the sample, a torque converter stall condition was created by accelerating the engine while loading either the vehicle's transmission or hydraulic system with a dead load. This loaded condition was held for ∼20 s and the engine was brought back to idle until the Diesel Detective Pump cycle was completed—at a time equal to 80 s. Not all machines could achieve torque converter stall, but some form of acceleration and load was substituted in those cases. An important part of this test procedure was that the initial pressure measurement at 20 s and final pressure measurement at 80 s be taken at approximately the same engine RPM. The DP per minute reported by the Diesel Detective Pump was recorded, and the tubes were sent to NIOSH/PRL, where filters were analyzed for EC content using NIOSH 5040 analysis.

Statistical analysis

Data were examined using regression analysis to determine the coefficient of determination R^2, of the DP and EC determinations from each test group. The limit of detection and limit of quantification were determined from the standard deviations (SDs) of the triplicate blank filter measurements.

RESULTS AND DISCUSSION

NIOSH Laboratory

The scatter plot of DP versus EC that resulted from the eight-point MSHA test is shown in Fig. 3. Because the instrument reports the pressure as inches of water (where 1 in. H_2O = 249 Pa) that notation will be used in all figures. In general, the correlation between DP and EC was linear. However, Test Mode 5 called for lugging the engine under full load at an intermediate speed and resulted in the triplicate measurements showing a large concentration of EC and corresponding high DP. The exact functional form of this relationship was difficult to define because of the lack of data between the lowest and highest levels of emissions. Based on these preliminary results, however, it was apparent that the DP measurement alone had potential to predict EC levels on the filter. More detailed testing was required.

Australian laboratory testing

Detailed results from the Londonderry testing are reported in Coal Services report 04/0884 (2004). A subset of the data is presented in Fig. 4. These results show the undiluted exhaust EC concentrations measured by the Diesel Detective filters and corresponding diluted exhaust diesel particulate mass measurements. These data are from laboratory tests of three engines commonly used in mines and all using water bath scrubbing. The slope of the regression of 0.63 is in agreement with previous data which indicate that EC composes 0.6–0.8 of the total DPM of raw diesel emissions (Birch and Cary, 1996). The relationship between DP and dilution tunnel filter concentration shows similar correlation to that of

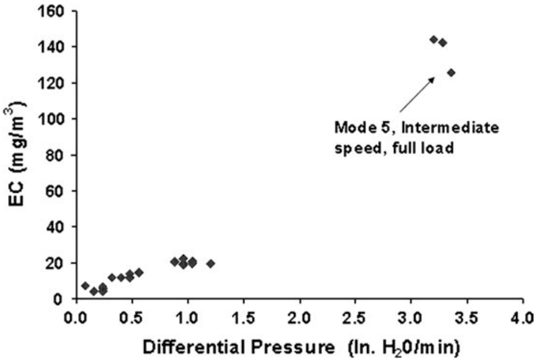

Fig. 3. Scatter plot of preliminary portable dynamometer water bath data following MSHA eight-point testing protocol (1 in. water-gauge = 249 Pa).

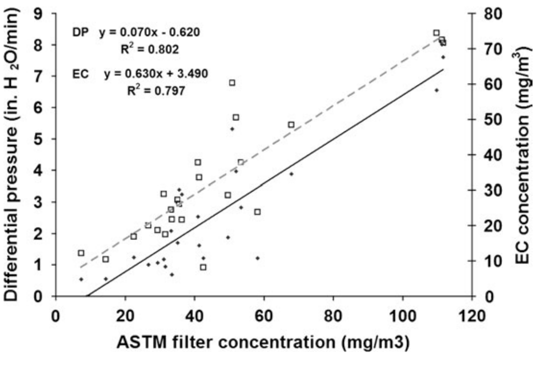

Fig. 4. Laboratory dynamometer-diluted mass concentration compared to undiluted DP and EC from the Diesel Detective (dilution tunnel filter concentrations courtesy of Coal Services 2004) (1 in. water-gauge = 249 Pa). DP: upper line and open squares; EC: lower line and diamonds.

EC. Thus, the measurement of DP in the field would be expected to relate to laboratory dilution tunnel mass measurements.

Figure 5 shows the coefficient of determination between DP and EC from the undiluted exhaust in the Londonderry Diesel Dynamometer Laboratory testing. Exhaust gas temperatures were ∼60°C at the filter and 25°C at the pump. The data were well distributed over a range of EC concentration levels from ∼8 to 110 mg m^{-3} of EC. The data have an R^2 value of 0.91.

The error bars on Fig. 5 represent 1 SD and are an estimate of the precision of the triplicate measurements of both the DP and EC measurements. Because the DP and EC results are from the same filter, systematic errors in sampling are likely to result in similar SDs. A large SD appearing in one parameter and not in the other is most likely a result from a measurement or analysis error of that parameter.

For the laboratory experiments, the limit of detection, as defined by the mean filter blank mass value plus 3 SDs for EC, was 0.50 mg m^{-3}. The limit of quantification, defined by the mean filter blank mass plus 10 SDs for EC, was 1.30 mg m^{-3}. The laboratory relative SD of the triplicate DP and EC measurements was 0.15 and 0.11, respectively.

Field measurements

Field results using the Diesel Detective Pump are shown in Fig. 6. These results have a somewhat improved R^2 value over the laboratory data that used the Pocket Pump. This may be partially due to the improved pressure transducer and electronics of the newer Diesel Detective Pump. Four of the initial samples were voided during the analysis process due to obvious water spots on the filter. The source of the water was attributed to samplers ingesting a large stream of liquid water that water bath scrubbers occasionally emit. While the aqueous denuder works well at removing supersaturated water vapor, it can be overwhelmed by a significant stream of liquid water. Careful attention to probe placement can minimize this event.

Field precision results were similar to the laboratory precision results. The field average precision estimated by the relative SD from 12 samples (ranging from 2 to 5 replicates) for DP and EC was 0.16 and 0.11, respectively. Because the precision of the method determined with the Pocket Pump was similar to the precision based on the Diesel Detective Pump, the small difference in precision could not be attributed to the new pump design.

Overall results

When data from the laboratory and field testing are combined in Fig. 7, the resulting R^2 value drops slightly to 0.86, perhaps a reflection of the Pocket Pump versus the Diesel Detective Pump. Note the *y* intercept of 6.54 mg m^{-3} EC is interpreted as part of the bias of the technique which is subject to further investigation. The regression equation in Fig. 7 was calculated from Sigma Plot software which enables calculation of confidence intervals. Inclusion of the ±95% confidence limits shows a number of data points outside of this limit, suggesting that the Diesel Detective is best suited as a survey quality measurement of engine particulate emission. If no design

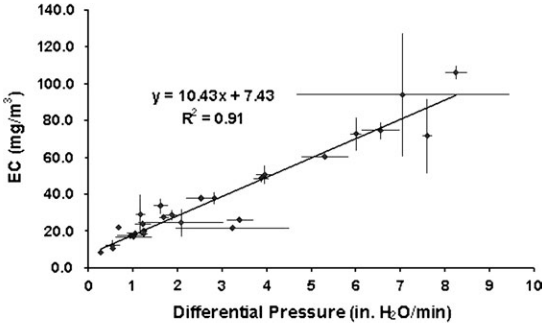

Fig. 5. Laboratory dynamometer results of Diesel Detective. Error bars represent 1 SD (1 in. water-gauge = 249 Pa).

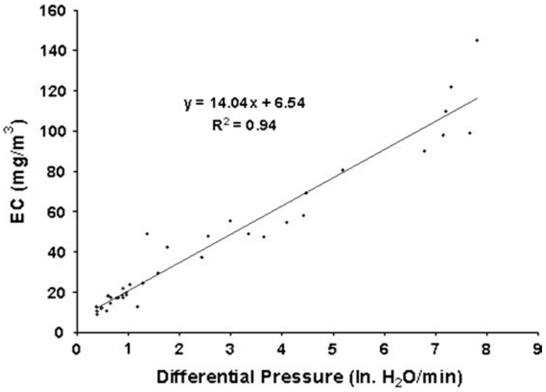

Fig. 6. Field results from Australian mine equipment (1 in. water-gauge = 249 Pa).

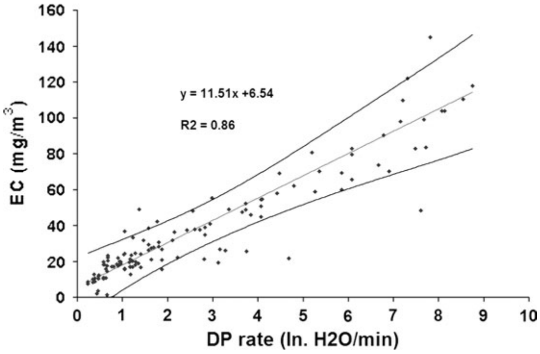

Fig. 7. Combined laboratory and field data with ±95% confidence limits (1 in. water-gauge = 249 Pa).

Table 1. Example of pre- and postmaintenance testing

Vehicle type	Premaintenance in H_2O	Postmaintenance in H_2O	Maintenance performed
Eimco	13.9	4.1	New injectors
SMV 5076	5.9	3.2	Retard timing, cleaned intake system, reduced fuel
PJB 107	17.5	6.4	Cleaned intake, reduced fuel
PJB 15	12.5	5.9	Changed air cleaner

changes occur with the filter holder, the data in Fig. 7 could be used to create a calibration factor for the pump to convert from DP rate to EC concentration. Any design change to the filter holder would require recalibration since the measurements are sensitive to the precise area of the filter sample. In the interim, the DP reading reported by the device can always be used as a relative measurement of engine EC emission.

Given the wide variety of emission characteristics of diesel engines and the difficulty of establishing an accurate correlation of any measurement method in the field, the comparison of an engine to itself is perhaps the best solution. Monitoring the emission history or the pre- and post-maintenance of a particular engine would then indicate the appropriate time for maintenance to control DPM. Table 1 shows the results of a pre- and post-maintenance test of some engines using the Diesel Detective. Another suggested way to use this instrument would be to survey the fleet of engines in regular mine use to establish a baseline, perhaps by engine type, and to then select a target maximum pressure allowed for a specific vehicle type before maintenance is required. This would, in effect, enable mechanics to target repairs toward the worst DPM-producing engines, thereby providing the largest reduction in ambient DPM levels per maintenance hour.

CONCLUSIONS

A direct method to measure tailpipe DPM emissions can be made by placing a filter directly into the hot and even extremely wet exhaust gas flow without need for dilution. The inclusion of an annular aqueous denuder to the tube permits dry filter samples to be obtained. A rise in DP in the tailpipe filter samples correlates well with corresponding EC on those filters which is a measure of the engines DPM emission. Because EC is the predominate component of the black soot emitted from diesel engines, using this DP method, data from this instrument can help a mechanic immediately and clearly identify which engines in a vehicle fleet are producing EC at a greater rate than other engines. Focusing cleaning, tuning and maintenance on these high-emission engines will produce the greatest efficiency for the reduction of fleet DPM emissions.

This technique offers a survey-type quality measurement of DPM. It provides an inexpensive, hand-held and rugged device for everyday use in mines. Another version of the technique for hot exhausts that do not pass through a water bath scrubber may be used to spot-check DPM emissions on over-the-road vehicles. This approach would provide both immediate feedback on the relative emission of a vehicle and a filter sample for subsequent analysis of the results. Calibration of DP to EC concentration is certainly possible, but additional data are required before the accuracy of such a relationship can be determined.

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