Published in final edited form as:

Min Eng. 2013 October ; 65(10): 42–49.

Portable instruments for measuring tailpipe diesel particulate in underground mines

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Abstract

There is a need for direct tailpipe sampling of diesel vehicles in mines in order to determine the effects of an emissions-based maintenance program, evaluate control technologies such as diesel particulate filters and identify the worst diesel particulate matter (DPM) emitters in a fleet of vehicles. Therefore, this study examined the performance of three portable instruments: a personal dust monitor (PDM) manufactured by Thermo Scientific, a prototype elemental carbon monitor (Airtec) manufactured by FLIR and a prototype AE91 instrument from Magee Scientific. These instruments were evaluated on the basis of their ability to provide direct reading tailpipe analysis for DPM. It was determined that the average bias of the tailpipe results from the PDM and the Airtec were 3±12% and 4±20%, respectively, when compared to the standard method of determining tailpipe particulate concentrations from a diluted exhaust. It was also determined that the AE91 instrument correlated with the standard method.

Introduction

Diesel particulate matter (DPM) has been classified as a potential occupational carcinogen by the U.S. National Institute for Occupational Safety and Health (NIOSH) and as likely to be carcinogenic to humans by the U.S. Environmental Protection Agency (EPA) (NIOSH, 1988; EPA, 2002). Therefore, the U.S. Mine Safety and Health Administration (MSHA) promulgated a rule to limit the DPM exposures of metal/nonmetal underground miners (MSHA, 2001; 2005).

To comply with the MSHA rule and lower the DPM exposures of underground miners, mines are implementing a variety of control technologies. Some mines have implemented emissions-based maintenance programs, where adjustments or repairs are performed on the engine to lower the particulate emissions (McGinn, 2000; Anyon, 2008). As part of a maintenance program, a method to directly measure tailpipe particulate emissions is needed to determine the effectiveness of certain engine adjustments and repairs, identify the

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Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications by Jan. 31, 2014

vehicles emitting the most DPM and detect an increase in emissions resulting from normal wear.

The MSHA method, which is similar to the American Society for Testing and Materials (ASTM) and EPA methods for determining tailpipe particulate concentrations (TPC), requires diluting the exhaust before collecting a sample (MSHA, 2009; EPA, 1998; ASTM, 2002). Under this protocol, the exhaust is diluted with clean air and the particulate sample is then collected onto a 90-mm filter at a face velocity no greater than 100 cm/s at temperatures lower than 52° C (125.6° F) (MSHA, 2009). The mass of the particulate is then determined gravimetrically. This mass, along with the dilution ratio and flow rate, is used to calculate the concentration of particulate from the engine (MSHA, 2009). This method, as well as the associated laboratory instruments, can be bulky and time-consuming, and the logistical requirements (electrical outlets, etc.) make it unfeasible in many areas of an underground mine.

As an alternative to the bulky laboratory instruments, a portable instrument that measures tailpipe particulate in real time would be beneficial for determining the effectiveness of a maintenance program, since the effectiveness of engine adjustments can rapidly be determined regardless of vehicle location in the mine. Furthermore, this type of instrument could also be used to evaluate the integrity of control technologies—e.g., by quickly determining the presence of a leak in a diesel particulate filter (DPF).

One portable sampling method smoke dot test (Bugarski et al., 2004). This method entails passing a certain volume of exhaust through a strip of paper forming an exhaust deposit spot. A number is then assigned to the spot depending on its darkness. Although this method is effective in providing a qualitative assessment of the particulate output, it relies on the judgment of the tester to assign a subjective number to classify the darkness of the spot and, thus, does not provide actual exhaust DPM concentrations.

Several studies have published data evaluating the use of different instruments to obtain a quantitative measurement of particulate matter being emitted from a diesel engine, and each study has demonstrated limitations (Anyon, 2008; Mine Safety Technical Services, 2004; Volkwein et al., 2008; Mischler and Volkwein, 2005; Miller et al., 2007). In a study in Australia, a light-scattering method was reported as providing good correlation (R^2 of 0.87) with a filter gravimetric method, but the tailpipe stream needed to be diluted due to interference from water vapor (Anyon, 2008; Mine Safety Technical Services, 2004). Additionally, in the Australian study (as well as several others), a differential pressure method for determining tailpipe emissions showed potential for use in measuring TPC, but the method is not yet commercially available and requires further development (Mine Safety Technical Services, 2004; Volkwein et al., 2008; Mischler and Volkwein, 2005). A limited evaluation of a light-scattering instrument resulted in data showing acceptable correlation with the gravimetric measurement, when the data was corrected for humidity and a specific calibration factor was employed (Miller et al., 2007). However, additional evaluation of this instrument is necessary since the protocol did not include testing different engines, measuring directly from the tailpipe or collection of a statistically sufficient number of data points.

All of the instruments mentioned above have some limitations based on what could be considered the desired criteria for a portable instrument that measures TPC in underground mines. These criteria include: accurate particulate measurement, ability to measure directly from the tailpipe without dilution or supplementary measurement (such as relative humidity), portability and ability to operate on battery power. This study identified three instruments with the potential to meet the above criteria, and each was evaluated to determine its ability to measure TPC on vehicles in underground mines. There may be other instruments that could also potentially meet the criteria; for example, the MAHA MPM-4 was not part of this paper. The three instruments investigated in this paper are the personal dust monitor (PDM 3600) manufactured by Thermo Scientific, a prototype elemental carbon (EC) monitor (Airtec) manufactured by FLIR, and a prototype Magee Scientific AE91 tailpipe instrument.

The Thermo Scientific PDM 3600 uses a tapered element oscillating microbalance (TEOM) technology to measure particulate mass. Currently used to measure real-time dust concentrations in underground coal mines (Page et al., 2008; Volkwein et al., 2004; Volkwein et al., 2006), the PDM was chosen as a potential tailpipe monitor because it is wearable (easy to carry), durable (used continuously in a mining environment) and it accurately measures mass concentrations.

The Airtec EC monitor measures real-time EC concentrations via laser absorption and is currently used in an underground mining atmosphere (Janisko and Noll, 2008; Noll and Janisko, 2007). EC is used as one of the surrogates for determining DPM exposures in underground mines, because EC represents a major portion of DPM; therefore, it can be used as a surrogate in tailpipe analysis (Noll et al., 2006; Kittelson, 1998; Pierson and Brachaczek, 1983). In fact, an advantage of measuring tailpipe EC concentrations is that this approach will allow for direct comparison of tailpipe concentrations with ambient compliance data. The Airtec was chosen for this study because it is wearable and durable, and it provides accurate real-time EC particulate concentrations.

The AE91, which uses technology much like the Aethalometer (Hanson et al., 1984) instrument from Magee Scientific, is a prototype instrument designed to collect tailpipe particulate samples and determine the concentration of black carbon via laser absorption. The black carbon concentration should correlate to EC from DPM measurement, because EC is the only source of strong laser-absorbing aerosols emitted from the tailpipe. This instrument could potentially be a good tailpipe emission monitor since it is handheld and provides real-time EC results.

Methods

In order to evaluate the effectiveness of these instruments for measuring tailpipe particulate concentrations, the results from the instruments were compared to results from methods established in other experiments for tailpipe analysis (MSHA, 2009; EPA, 1998; ASTM, 2002). The established methods entailed collecting particulate samples from a diluted exhaust similar to the approach used by MSHA, ASTM and EPA. These methods all dilute the exhaust to avoid the influence of water vapor, pressure and temperature and to simulate atmospheric particle mixing and formation (MSHA, 2009; EPA, 1998; ASTM, 2002). The TEOM 1400 was selected for determining mass concentrations in the diluted exhaust, since it correlates to the filter-based gravimetric method used by the EPA for determining particulate mass concentrations (Chan and He, 1999; Kelly and Morgan, 2002; Clark and Gautam, 2001; Gilbert and Clark, 2001; Bugarski et al., 2006). One concern with using the TEOM, however, was that in several studies, even though the two methods always correlated for each study, the difference between the TEOM and the filter-based gravimetric method ranged from 3 to 30%, depending on the conditions of the experiment, such as flow rate and the temperature of the TEOM (Chan and He, 1999; Kelly and Morgan, 2002; Clark and Gautam, 2001; Gilbert and Clark, 2001; Bugarski et al., 2006). However, a few studies have shown that under the conditions used for the current study (TEOM flow rate of 1.7 L/ min/ 0.4 gpm and temperature of 47° C/ 117° F), the TEOM results were within about 10% of a gravimetric filter-based method (Clark and Gautam, 2001; Gilbert and Clark, 2001; Bugarski et al., 2006). EC concentrations in the diluted exhaust were determined by collecting particulate onto quartz fiber filters and analyzing the filter using NIOSH method 5040—the standard method for determining occupational EC concentrations in underground metal/nonmetal mines (Birch, 2004). Filter-based methods for chemical analysis on a diluted exhaust stream are used by MSHA and the EPA (MSHA, 2009; EPA, 1998; ASTM, 2002).

Prior to sample collection by the instruments, it was necessary to remove the water vapor from the exhaust to avoid potential interference. The AE91 has a built-in probe for this purpose, and NIOSH constructed a probe made from copper tubing (Fig. 1) for the Airtec and PDM to cool the engine exhaust to the temperature used in EPA and MSHA exhaust particulate sampling methods (<52° C; <125.6° F) (MSHA, 2009; EPA, 1998; ASTM, 2002).

After the samples were collected, the direct readings from the instruments were compared to concentrations measured via the TEOM and NIOSH method 5040 in the diluted exhaust multiplied by the dilution ratio. The dilution ratio was calculated from gas concentrations collected in the tailpipe and in the diluted exhaust. Table 1 provides a summary of the samples taken for each instrument and engine. Though at least two tailpipe samples were attempted for each condition, sometimes only one sample was acceptable because of various experimental errors such as a flow fault in the pump. More specific information related to each sampling instrument and technique and the sampling procedures are provided in the following sections.

Direct tailpipe samplers

PDM – personal dust monitor—Prior to sampling, the PDM required a 30-minute warm-up period. The PDM, operating at a flow rate of 2.2 L/min (0.6 gpm), was then attached to the sampling probe (Fig. 1) and the probe was placed into the tailpipe as described in section labeled “Testing.” Currently, the PDM does not calculate a mass concentration from a one-minute sample. Therefore, in order to determine the mass collected by the PDM during the one-minute sample, the data had to be downloaded, after which the mass at the start of the sampling period was subtracted from the mass at the end of the sampling period. The resulting mass was then inserted into the following equation to calculate the tailpipe mass concentration:

$$\text{Mass concentration}\left(\frac{\text{mg}}{\text{m}^3}\right)=\frac{\text{mass(mg)}}{(\text{flow rate(L/min)}\times\text{time(min)})}\times 1,000 \quad (1)$$

The results from subtracting the final mass from the initial mass using a TEOM to determine mass concentrations have been shown to be within 10% of a filter-based gravimetric method in a previous study (Bugarski et al., 2006). If this instrument proves to be viable as a tailpipe monitor, the software can be adjusted to provide a one-minute mass concentration.

Airtec—The Airtec, operating at a flow rate of 1.7 L/min (0.4 gpm), was attached to the sampling probe (Fig. 1) and the probe was placed into the tailpipe as described below. Like the PDM, the Airtec currently does not calculate a 30-second or one-minute mass concentration; therefore, the initial and final voltages over the sampling periods were recorded and were used to calculate the collected mass. The absorption (−log(final voltage/ initial voltage)) was multiplied by the established calibration factor (Noll and Janisko, 2007) for this instrument to determine the milligrams of EC collected. The following equation was used to calculate the tailpipe mass concentration:

$$EC\text{concentration}\left(\frac{\text{mg}}{\text{m}^3}\right)=\frac{EC\text{mass(mg)}}{(\text{flow rate(L/min)}\times\text{time(min)})}\times 1,000 \quad (2)$$

AE91 prototype—The AE91 was specifically designed to collect tailpipe samples with a probe incorporated into the instrument to cool the exhaust. This instrument calculates black carbon mass concentrations.

Testing

Safety precautions—During this evaluation, safety precautions were implemented and vehicles were blocked to prevent movement while sampling. In addition, testing was performed in well-ventilated areas to prevent concentrations of contaminants higher than the permissible exposure limit (PEL). To further avoid exposure to the exhaust, researchers collected samples upstream from the direct exhaust using a probe. If the concentration of the contaminants ever exceeded the PEL where the researchers were located, respirators were available.

Lake Lynn Facility—The instruments were evaluated in the D-drift of the experimental underground limestone mine at the Lake Lynn NIOSH facility (Bugarski et al., 2010). The use of the D-drift as a laboratory for evaluating various control technologies is explained in detail elsewhere (Bugarski et al., 2010). In summary, a 150-kW dynamometer with an associated Isuzu C240 engine (using ultra-low sulfur fuel) was positioned in an enclosed section of the mine. The air flow to this section was controlled and measured employing an auxiliary fan and a venturi tube.

The particulate samples in the diluted exhaust were collected on a sampling grid positioned 61 m (200 ft) downstream of the engine. Three EC and TC samples for NIOSH method 5040 analysis were collected using the apparatus setup described by Bugarski et al. (2010) This apparatus used five SKC cassettes spread out uniformly across the sampling grid, plumbed into one quartz fiber filter, and operated at 11 L/min (2.9 gpm) via critical orifices. In addition to the NIOSH method 5040 samples, tubing attached to the sampling grid was connected to a TEOM 1400 to measure DPM mass. Using Eq. (1), the mass concentration was determined by subtracting the initial mass from the final mass measured via the TEOM 1400. Real-time CO_2 concentrations were measured using a GM70 handheld monitor (Vaisala Inc.) positioned on the grid, and another GM70 was positioned upstream of the engine to collect background CO_2.

Once the particulate concentration at the sampling grid reached a steady state, the downstream samplers were turned on, and then tailpipe samples were collected. A PDM in sampling mode was attached to a probe with conductive tubing. The probe inlet was inserted into the tailpipe perpendicular to the engine exhaust flow for one minute and then removed. This process was then repeated using the Airtec. Two to three measurements were taken for each type of tailpipe sample (one of the three PDM measurements at the I100 mode was eliminated because of a flow fault shown after the data was downloaded). While the tailpipe samples were being collected, tailpipe CO_2 concentrations were measured via a California Analytical CA600 analyzer.

The downstream samplers were operated long enough to collect at least 3 μg/cm^2 EC on the quartz filter, resulting in time periods between 40 and 60 minutes. The dilution ratio for these samples was calculated by dividing the tailpipe CO_2 concentration by the CO_2 concentration downstream minus the background.

The above sampling procedure was performed at three engine modes:

R50: RPM 2950 Torque: 41 ft/lb – light load

I50: RPM 2100 Torque: 51 ft/lb – light load

I100: RPM 2100 Torque: 102 ft/lb – heavy load.

Table 1 lists the experiments that were performed

NIOSH Pittsburgh Laboratory—The instruments were also evaluated at the NIOSH laboratory in Pittsburgh, PA. A Kubota V1200-B diesel four-cylinder engine (using ultra-low sulfur fuel) equipped with a resistance bank to apply a load to the engine was used to provide diesel exhaust to a Marple chamber (Noll et al., 2005). The Marple chamber dilutes the exhaust with filtered air and passes it through a honeycomb system to uniformly distribute the diesel particulate across the chamber. A full description of the Marple chamber and laboratory setup have been previously given by Noll et al. (2005).

Three-piece SureSeal cassettes containing quartz fiber filters were placed into the Marple chamber and used to collect EC and TC samples in a diluted exhaust. These samples were collected at a flow rate of 1.7 L/min (0.4 gpm), which was controlled using critical orifices and a vacuum pump. The samples were analyzed for EC and TC mass using NIOSH method 5040. The EC and TC concentrations were calculated according to Eq. (1). Mass and carbon monoxide (CO) or nitrogen monoxide (NO) concentrations were measured inside the chamber using the TEOM 1400 and ECOM KL portable gas monitor, respectively.

To start the experiment, the engine was operated at idle for at least 10 minutes, and part of the exhaust was directed into the chamber. The remainder of the exhaust was vented outside, and this is where the tailpipe samples were collected. After the warm-up time, the samplers inside the chamber were turned on. Next, measurements taken directly from the tailpipe (as described in Section 2.2.2) were collected with the Airtec (30-second sample) and the PDM (one-minute sample). In addition, tailpipe samples were collected with the AE91 for 15 seconds, and an ECOM was used to measure the CO or NO in the tailpipe. Again, after the samplers in the chamber collected about 3 μg/cm^2 EC, they were turned off. The dilution ratio, calculated by dividing the tailpipe CO or NO concentration by the CO or NO concentration in the diluted airstream, was higher than the minimum dilution factor of four used by MSHA (Table 1). The setup in the laboratory was designed to produce a consistent load being applied to the engine, resulting in steady concentrations of DPM in the tailpipe and also in the diluted airstream. The TEOM 1400 monitored the concentration of diluted particulate inside the chamber to ensure that the engine emissions remained consistent so that the particulate concentration in the chamber could be compared with the shorter tailpipe measurements. This procedure was repeated for 25%, 50% and 80% engine load scenarios (Table 1).

Data analysis

The error in the dilution method was determined by performing a propagation of error for multiplication and quotient (Skoog and West, 1986). The manufacturer-recorded error for the gas analyzer was used for the error of the gas measurements used for the dilution ratio. As mentioned earlier, a coefficient of variation (*CV*) of 10% was used as the error for the TEOM. A *CV* for each duplicate and triplicate sample of NIOSH method 5040 samples in the diluted airstream was calculated, and then each experiment was pooled to determine an overall *CV* for the experiment. The precision of the tailpipe samples with the PDM and Airtec were determined by pooling the *CV* for each experiment (Skoog and West, 1986).

Least squares regression analysis, using Sigma Plot 12.0, was performed by comparing the concentrations from the direct tailpipe instruments with the standard method for determining tailpipe concentrations. In Sigma Plot, the Shapiro Wilks test was used to test for normality. The R^2 value was used to determine correlation. The slope and intercept were used to determine agreement (Miller and Miller, 1991). If the two analytical methods completely agree, the slope of the least squares regression analysis would be one and the *y*-intercept would be zero. A *y*-intercept different from zero indicates a constant systematic error between methods, usually occurring when there is interference in the assay, inadequate blanking or bad zero calibration. The amount of slope beyond unity provides the proportional systematic error between the two methods. The 95% confidence intervals for the slope and intercept were determined by multiplying the *t*-value (with *n*-2 degrees of freedom) by the standard error (Neter et al., 1996). In addition to linear regression, a paired *t*-test was performed using Sigma Plot 12.0 to test for agreement.

The bias between the standard method and the direct readings from the portable instruments was calculated using the equations found in Kennedy et al. (1995). The 95% confidence interval for the bias was determined by multiplying the *t*-value by the standard deviation and dividing by the square root of the number of samples (Bartley et al., 2007; Skoog and West, 1986).

Results and discussion

PDM

The data in this study illustrates that PDM may have the capability to collect direct tailpipe readings. The direct tailpipe PDM readings demonstrated agreement within experimental error with measurements from a diluted airstream (standard method). As seen in Fig. 2, the regression comparing the PDM and the established method displays a good correlation between the two datasets (R^2 of 0.967). In addition, the 95% confidence interval of the slope overlaps 1, and the 95% confidence interval of the intercept overlaps 0, indicating agreement between the two methods (Miller and Miller, 1991). The paired *t*-test (p=0.795) showed that the difference between the results from the two methods is not statistically significant.

The direct tailpipe PDM readings were within 16% of diluted airstream measurement in most cases. The average bias of the direct reading PDM results when compared to the reference method (Table 2) was 3 ± 12%, which is within the NIOSH accuracy criteria for overall average bias (less than 10%) (Kennedy et al., 1995). For all but one sample, the direct tailpipe readings with the PDM were within 16% of the diluted exhaust measurements. It is not known at this time why one measurement had a 37% bias.

Airtec monitor

The results of this study also illustrated a potential for the Airtec to be used as a direct tailpipe monitor. The data seems to be normally distributed according to the Shapiro Wilks test (p = 0.804). As can be seen in Fig. 3, the regression shows a strong correlation between the Airtec and the reference method, with an R^2 of 0.982. In addition, the 95% confidence interval overlaps 0 for the intercept and overlaps 1 for the slope, demonstrating agreement between the two analytical methods within experimental error. The *t*-test (p = 0.307) also showed that the difference between the two methods is not statistically significant.

The average bias between the two methods was 4±20 percent (Table 2), which is within the NIOSH accuracy criteria for overall average bias (less than 10%). In all but one case, the bias was within 25% and, in most cases, within 14% of the established method of measuring EC via NIOSH method 5040 in a diluted exhaust. It is not known at this time why one measurement had a 69% bias.

One observation to be aware of when using the Airtec is that when measuring the EC in the tailpipe for one minute at the lower engine loads (idle and 25%) with the Kubota engine, the Airtec at times had a positive bias (as high as 33%) compared to the NIOSH method 5040 results. While operating the Kubota engine at lower engine loads, water droplets were observed on the cassettes; therefore, the sampling time was decreased from one minute to 30 seconds. The water vapor could have interfered with the laser light, thus causing the high bias. The bias could also be the result of high concentrations of organic carbon, which are present at low loads. These results were excluded from the data analyses due to the deviation from the standard procedure. Water vapor was not observed when sampling the Isuzu engine for one minute.

AE91

When comparing the readings from the AE91 to the EC concentrations via the diluted exhaust stream times the dilution factor (Fig. 4), a strong correlation between the two values was observed, as seen by an R^2 of 0.999; however, the AE91 overestimates the tailpipe EC mass. The overestimation is probably because the AE91 is calibrated for black carbon and not for EC from DPM, and the absorption coefficient could possibly be different between black carbon and EC. Due to the strong correlation, the AE91 potentially could determine EC concentrations in the tailpipe once calibrated for EC. Additional data are needed before conclusions can be drawn.

Conclusion

Results suggest that quantitative measurements of exhaust emissions may be accurately determined using direct reading monitors. There was agreement (within experimental error) between the direct tailpipe readings from the PDM and Airtec instruments when compared to the reference method for tailpipe analysis (measuring in a diluted exhaust). The average bias between the direct reading measurements of the PDM and Airtec and the diluted airstream were 3±12 and 4±20 percent. The large 95% confidence limit for the Airtec readings could be the result of the influence of one data point with a large bias (69%). The AE91 measurements demonstrated strong correlation with the reference method. This type of measurement would allow tailpipe concentrations to be measured in any location in the mine in order to quantify the effects of engine repairs and adjustments and identify the highest DPM-emitting vehicles.

There were some limitations with this data. In order to avoid interferences, samples using the Airtec should be collected for only 30 seconds when operating at low loads on the engine. Also, the PDM will provide total DPM mass while the AE91 and Airtec can be used to provide EC concentrations. A limited number of data points and engines were included in this study; therefore, additional data could be beneficial as more engines and testing facilities become available. Larger engines could produce a different air flow in the exhaust and need tested, and more data points could help strengthen the statistical power. Future work should also entail determining how the instruments measure lower concentrations of tailpipe particulate, such as when a DPF is used.

Acknowledgments

The authors thank Jason Driscoll and Nicole Shamitko for their contributions in taking tailpipe samples and analyzing samples for this project.

Disclosure

Mention of a company name or product does not constitute an endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH.

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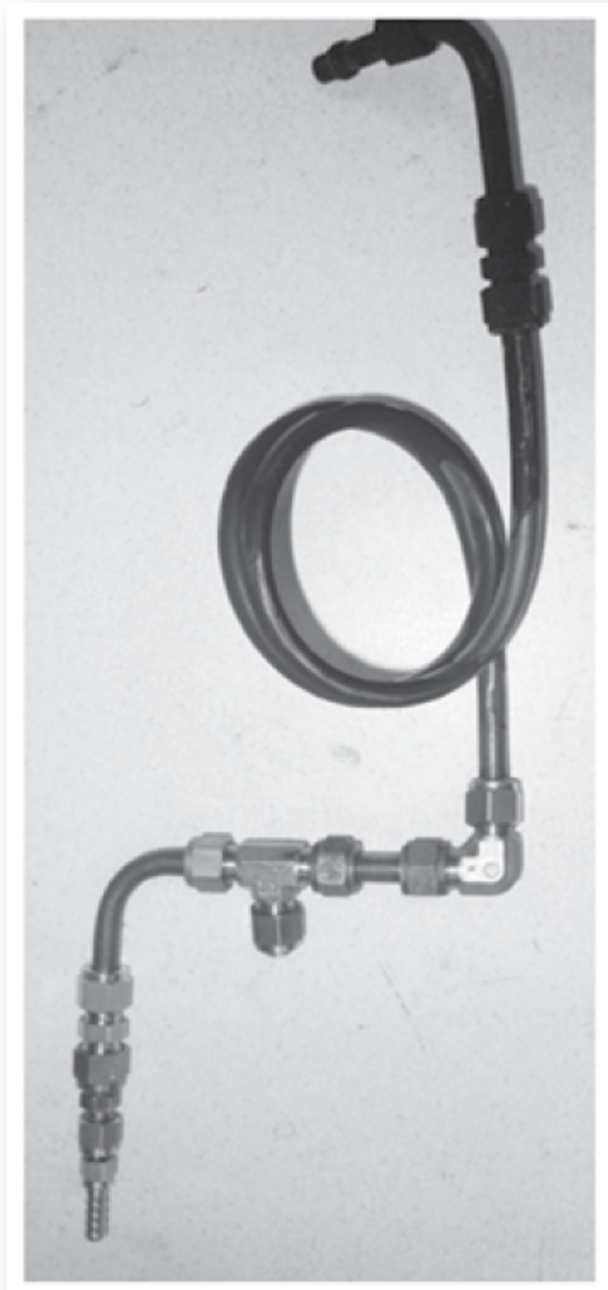

Figure 1.
The copper probe, used to remove water vapor from the exhaust and attached to the Airtec and PDM instruments to sample tailpipe particulate.

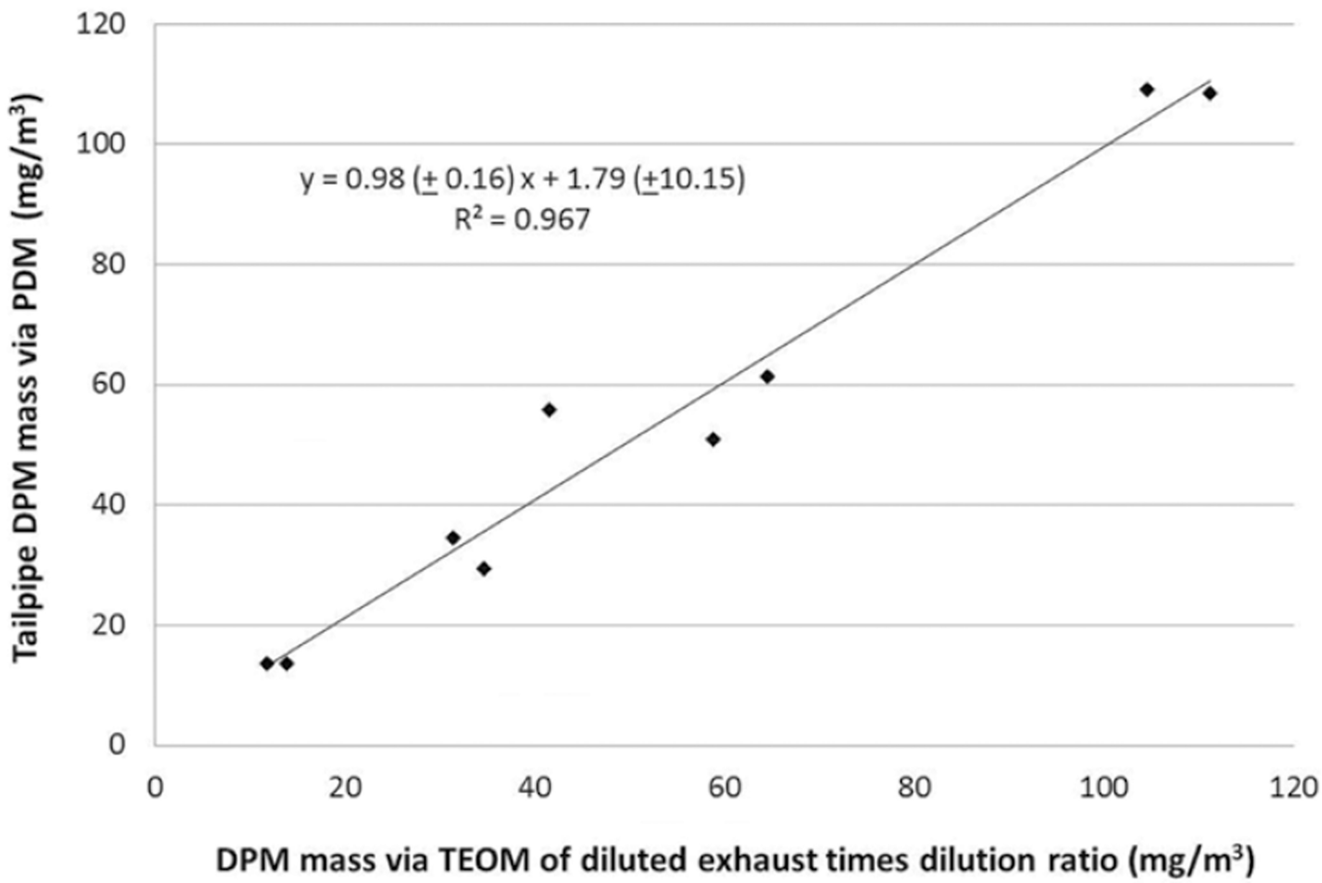

Figure 2.

A graph comparing tailpipe DPM mass via the PDM with the DPM mass via the TEOM in the diluted exhaust multiplied by the dilution ratio.

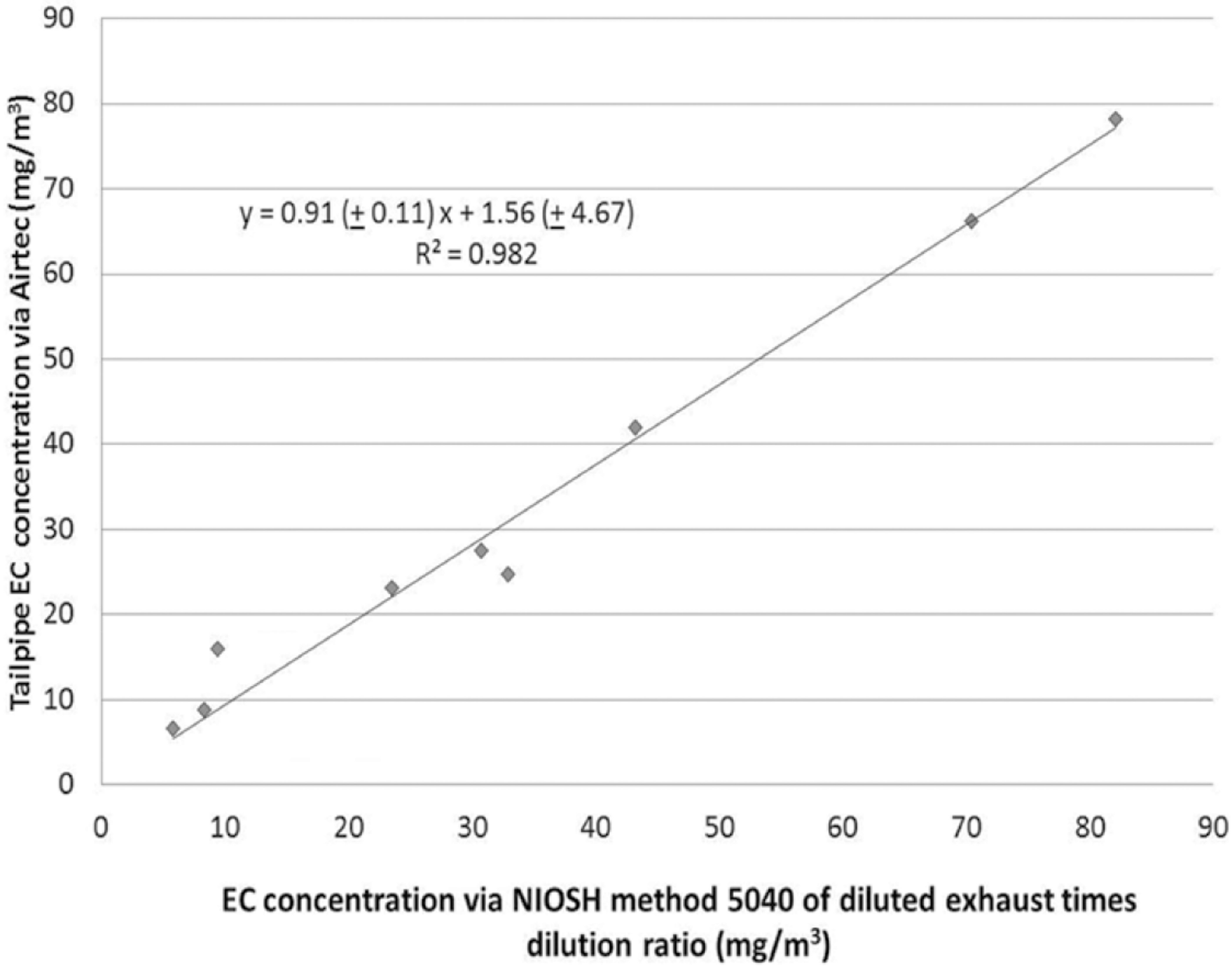

Figure 3.

A graph comparing the tailpipe EC concentrations via the Airtec monitor with the EC concentrations via NIOSH method 5040 in the diluted exhaust and multiplied by the dilution ratio.

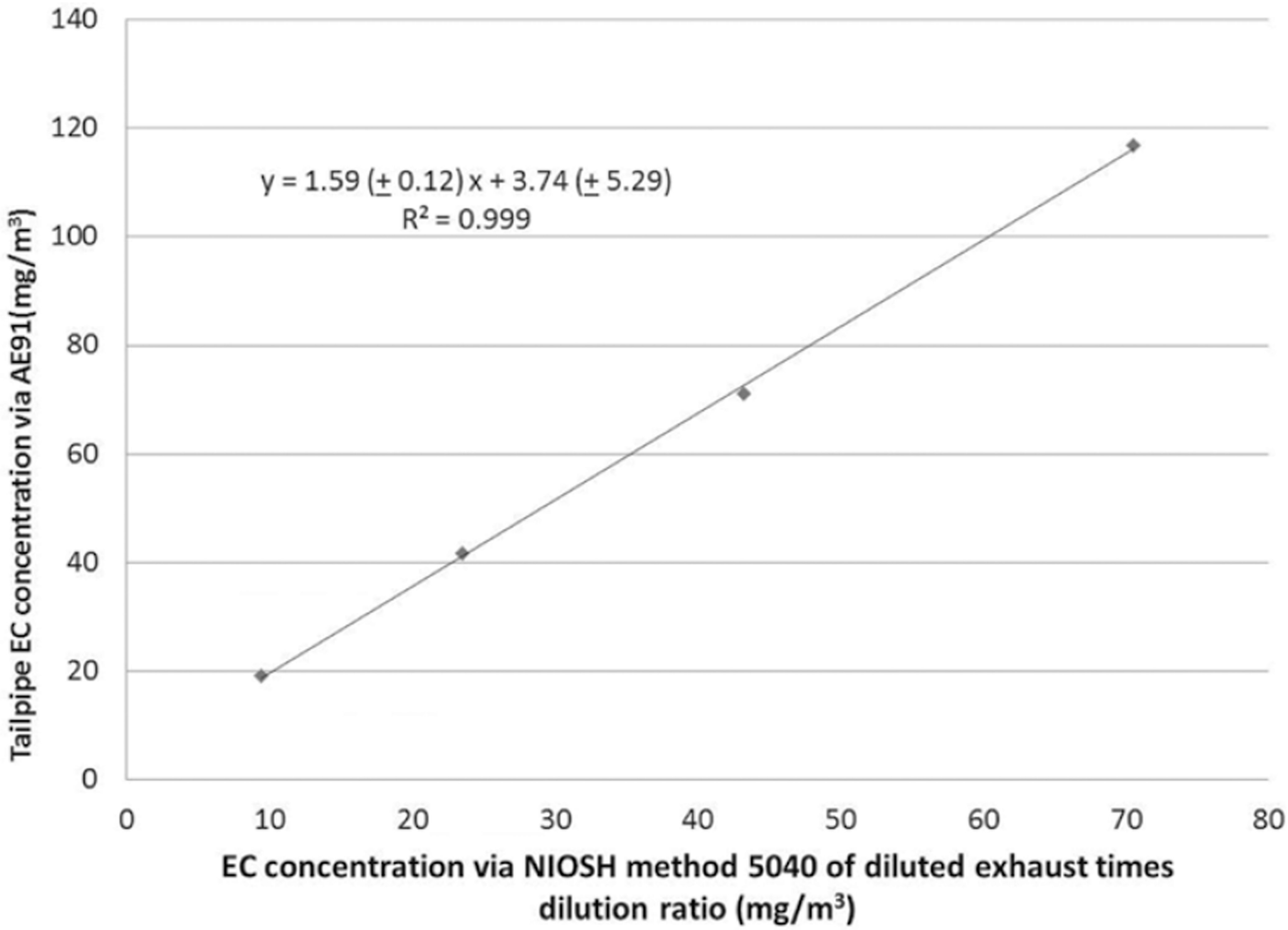

Figure 4.

Graph comparing the tailpipe black carbon concentrations via the AE91 with the EC concentrations via NIOSH method 5040 of the diluted exhaust times the dilution ratio.

Table 1

Summary of samples collected.

Engine	Load	Number of tailpipe samples				Number of diluted exhaust samples		Dilution ratio
		PDM	Airtec	AE91	NIOSH method 5040	TEOM	NIOSH method 5040	
Isuzu C240	R50	3	2	NA	NA	1	3	131
Isuzu C240	I50	3	2	NA	NA	1	3	185
Isuzu C240	I100	2	2	NA	NA	1	3	175
Kubota V1200-B	25%	2	1	NA	NA	1	2	13
Kubota V1200-B	80%	2	2	NA	NA	1	1	11
Kubota V1200-B	idle	1	2	2	2	1	2	15
Kubota V1200-B	25%	1	2	2	2	1	1	31
Kubota V1200-B	50%	1	2	2	2	1	1	27
Kubota V1200-B	80%	2	2	2	2	1	2	19

NA - not applicable.

Table 2

Comparison of PDM and Airtec readings from tailpipe with diluted exhaust results.

		Mass (mg/m^3)			EC (mg/m^3)		
Engine	**Load**	**Tailpipe concentration via PDM**[a]	**Diluted exhaust concentration via TEOM times dilution ratio**[b]	**% bias**	**Tailpipe concentration via EC monitor**[c]	**Diluted exhaust concentration via NIOSH method 5040 times dilution ratio**[d]	**% bias**
Isuzu C240	R50	13.7	11.8	16	6.6	5.8	14
Isuzu C240	I50	13.6	13.9	−2	8.8	8.3	5
Isuzu C240	I100	29.3	34.7	−15	24.8	32.9	−25
Kubota V1200-B	25%	57.1	41.5	37	27.4	30.8	−11
Kubota V1200-B	80%	109.1	104.6	4	78.1	82.1	−5
Kubota V1200-B	idle	50.9	58.8	−13	16.0	9.5	69
Kubota V1200-B	25%	34.6	31.4	10	23.2	23.5	−1
Kubota V1200-B	50%	61.4	64.5	−5	41.9	43.2	−3
Kubota V1200-B	80%	108.4	111.3	−3	66.2	70.5	−6
Average				**3**			**4**

[a]Pooled CV-11% for Isuzu C240 testing and 16% for Kubota testing.

[b]Propagation of error - CV - 11% for Isuzu C240 testing and 10% for Kubota testing.

[c]Pooled CV - 6% for Isuzu C240 testing and 10% for Kubota testing.

[d]Propagation of error - CV - 8% for Isuzu C240 testing and 4% for Kubota testing.