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Evaluation of Diesel Exhaust Continuous Monitors in Controlled Environmental Conditions

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Abstract

Diesel exhaust (DE) contains a variety of toxic air pollutants, including diesel particulate matter (DPM) and gaseous contaminants (e.g., carbon monoxide (CO)). DPM is dominated by fine (PM_{2.5}) and ultrafine particles (UFP), and can be representatively determined by its thermal-optical refractory as elemental carbon (EC) or light-absorbing characteristics as black carbon (BC). The currently accepted reference method for sampling and analysis of occupational exposure to DPM is the National Institute for Occupational Safety and Health (NIOSH) Method 5040. However, this method cannot provide in-situ short-term measurements of DPM. Thus, real-time monitors are gaining attention to better examine DE exposures in occupational settings. However, real-time monitors are subject to changing environmental conditions. Field measurements have reported interferences in optical sensors and subsequent real-time readings, under conditions of high humidity and abrupt temperature changes. To begin dealing with these issues, we completed a controlled study to evaluate five real-time monitors: Airtec real-time DPM/EC Monitor, TSI SidePak Personal Aerosol Monitor AM510 (PM_{2.5}), TSI Condensation Particle Counter 3007, microAeth AE51 BC Aethalometer, and Langan T15n CO Measurer. Tests were conducted under different temperatures (55, 70, and 80 °F), relative humidity (10, 40, and 80%), and DPM concentrations (50 and 200 µg/m³) in a controlled exposure facility. The 2-hour averaged EC measurements from the Airtec instrument showed relatively good agreement with NIOSH Method 5040 ($R^2=0.84$; slope= 1.17 ± 0.06 ; $N=27$) and reported ~17% higher EC concentrations than the NIOSH reference method. Temperature, relative humidity, and DPM levels did not significantly affect relative differences in 2-hour averaged EC concentrations

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obtained by the Airtec instrument versus the NIOSH method ($p < 0.05$). Multiple linear regression analyses, based on 1-min averaged data, suggested combined effects of up to 5% from relative humidity and temperature on real-time measurements. The overall deviations of these real-time monitors from the NIOSH method results were 20%. However, simultaneous monitoring of temperature and relative humidity is recommended in field investigations to understand and correct for environmental impacts on real-time monitoring data.

Keywords

Diesel Exhaust; Diesel Particle Matter; Real-time Monitor; Environmental Conditions

INTRODUCTION

Diesel fuel is used in many industrial operations, as well as in motor vehicles. The resultant diesel exhaust (DE) contains a variety of toxic air pollutants, including particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2).^(1–4) The PM portion, commonly called diesel particulate matter (DPM), is dominated by fine particles ($\text{PM}_{2.5}$, defined as particulate matter less than 2.5 μm in diameter) and ultrafine particles (UFP, defined as particulate matter less than 0.1 μm in diameter).⁽²⁾ Exposure to DPM has been associated with a variety of acute and chronic human health effects.⁽²⁾ DPM was classified as a human carcinogen (Group 1) by the International Agency for Research on Cancer (IARC) in 2012. DPM is a complex mixture of substances that can be split into two groups by its thermal-optical refractory: organic carbon (OC) and elemental carbon (EC). OC represents the species that are either combustion products or unburned diesel constituents, for example, polycyclic aromatic hydrocarbons (PAHs). EC is the carbon soot in DPM remaining after combustion and can be estimated as black carbon (BC) by its light-absorbing characteristics. While EC and BC are not identical, their ratio is usually close to 1, ranging from 0.7 to 1.3 for 70% of inter-comparison studies in wide range of environments.⁽⁵⁾ Thus EC and BC have been extensively used as a marker for exposure to DPM in occupational^(6–8) and epidemiological^(9–11) studies.

The currently accepted reference method for sampling and analysis of occupational exposure to DPM is the National Institute for Occupational Safety and Health (NIOSH) Method 5040, which uses a sampling pump to collect DPM in a filter cassette that is later sent to a laboratory for analysis. However, there is an inherent lag time between collecting samples and obtaining DPM results from a laboratory when using this method. To overcome this problem and more accurately assess acute health effects from occupational exposure to DPM, continuous monitors that can be carried and measure DPM levels in real time are an attractive option. Unlike integrated DPM sampling methods, continuous measurements can identify where and when peak exposures occurred. However, these real-time monitors can be affected by environmental conditions. Previous studies observed biases in real-time readings with abrupt changes in temperature and relative humidity (RH) for optical instruments such as nephelometers and particle counters.^(12–13)

Temperature and relative humidity have the potential to affect the readings of light-scattering and electrochemical sensors. McMurry et al.⁽¹⁴⁾ discussed issues in aerosol measurement using optics by referring scattering effects of hygroscopic species in sampled air. The concentration reported by any light scattering aerosol instrument increase with relative humidity, due to the increase in the average particle size associated with condensational growth of hygroscopic components of the aerosol.⁽¹⁴⁾ This measurement error is an issue at a relative humidity above 60% because the error increases exponentially.⁽¹⁴⁾ Miller et al.⁽¹⁵⁾ showed the effect of relative humidity was substantial for direct real-time reading of PM when relative humidity levels were above 50%, and demonstrated a good correlation ($R^2=0.97$) between real-time PM data (adjusted with relative humidity and corrected by a calibration factor) and the integrated EC measurements by the NIOSH 5040 method. Rapid changes in temperature and relative humidity when measuring BC with a portable real-time aethalometer may also result in false positive and negative peaks^(16–17) or noisy high-time resolution measurements^(18–19). In addition, the recommended operation temperature range for a condensation particle counter in the field is 50–95 °F.⁽²⁰⁾ However, the issue of relative humidity on the performance of particle counter has not been systematically addressed elsewhere. Electrochemical sensors, used for measuring CO, are known to have thermal effects that affect the sensor output. Thus, corrections are suggested when measurements are made at temperature higher/lower than 68 °F.⁽²¹⁾

Research to investigate the impact of environmental conditions on real-time measurements is necessary, especially for underground mine settings, where abrupt changes in temperature and relative humidity occur frequently. We designed a study in the controlled exposure facility (CEF) of Environmental and Occupational Health Sciences Institute (EOHSI) to evaluate the impacts of environmental conditions on five real-time monitors: FLIR Airtec real-time DPM/EC Monitor, TSI SidePak Personal Aerosol Monitor AM510 (PM_{2.5}), TSI Condensation Particle Counter (CPC) 3007, microAeth AE51 BC Aethalometer, and Langan T15n CO Measurer. We compared two EC sampling/analysis methods: the reference NIOSH 5040 method and a real-time monitor (Airtec DPM/EC Monitor). Then we characterized the performance of the continuous monitors for side-by-side tests in conditions of different temperatures (55, 70, and 80 °F), relative humidity (10, 40, and 80%), and DPM concentrations (50 and 200 µg/m³ of PM_{2.5}).

METHODS

Study Overview

All tests were conducted in the EOHSI's CEF. The CEF includes a 25 m³ stainless steel chamber in which temperature, relative humidity, and air-exchange rate can be constantly monitored and controlled during a study. A consistent set of environmental conditions for the intake air are established in the CEF by using a series of conditioning processes including cooling/heating and humidification/dehumidification. Activated carbon and high efficiency particulate air (HEPA) filters remove ambient PM and organics in supply air prior to being delivered to the CEF. Eight small brushless fans were installed in the CEF to mix the inside air.

Based on the range of concentrations suggested by the NIOSH 5040 method (23–240 $\mu\text{g}/\text{m}^3$) as well as previous human exposure studies conducted in the EOHHSI's CEF^(22–23), we selected two DPM levels: low ($\sim 50 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$) and high ($\sim 200 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$), respectively, to evaluate the continuous monitors' performance. The chosen $\text{PM}_{2.5}$ level was monitored during the exposure session using a real-time $\text{PM}_{2.5}$ monitor (TSI SidePak AM510), which was calibrated at the manufacturer. If necessary, the DPM concentration was adjusted by changing the volumetric air flow into the CEF. We varied temperature and relative humidity to evaluate the monitor under nine different environmental conditions: low (55 °F), medium (70 °F), and high (80 °F) temperature, and low (10%), medium (40%), and high (80%) relative humidity. Temperature and relative humidity were continuously monitored and controlled from the CEF control room. The experiment at each environmental condition was repeated three times. Therefore, a total of 27 experimental test sessions were completed to achieve the study objectives. Three temperature conditions at constant relative humidity were evaluated over the course of 8–9 hours (equivalent to 480–540 measurements considering a one-minute sample interval) on each experiment day. The selection of the specific relative humidity level for a given day was determined by local outdoor meteorological conditions on the date of the experiment (e.g., 80% RH was tested on rainy days). Prior to the start of the experiments a one-day pilot test was conducted with three sessions to evaluate the study protocols.

Real-time Monitors

We utilized a variety of real-time monitors for this study. Besides the Airtec Real-time DPM/EC Monitor we included a BC real-time monitor (microAeth Model AE51, AethLabs, San Francisco, CA), a CO real-time monitor (T15n, Langan Products, Inc., San Francisco, CA), a $\text{PM}_{2.5}$ real-time monitor (AM510 SidePak Personal Aerosol Monitor, TSI Inc., Shoreview, MN), and condensation particle counting real-time monitor (CPC 3007, TSI Inc. Shoreview, MN). In addition, a real-time Temp/RH logger (HOBO U12, Onset Corp., Bourne, MA) was placed side-by-side with other devices to simultaneously monitor temperature/relative humidity inside the CEF during an exposure session. To evaluate the temporal variability of the real-time measurements, we used a logging interval of 1 min for all real-time monitors. In addition, the clocks for all monitors were synced with a computer located in the CEF prior to conducting each exposure session. The manufacturer specifications for the real-time monitors used in this study are summarized in TABLE I.

The Airtec Real-time DPM/EC Monitor uses a laser light and sensor to provide real-time EC measurements (hereafter referred as $\text{EC}_{\text{realtime}}$).⁽²⁴⁾ In brief, the air is drawn to the monitor after passing through a cyclone and impactor to remove particles greater than 0.8 μm in diameter. Then particles are deposited onto a Teflon filter cassette, which constantly monitors the optical transmittance of the filter by a laser and sensor. As the particles accumulate on the filter, the laser's transmittance will decrease. The software for the monitor converts this decrease in transmittance into a real-time concentration of EC in the air.

The microAeth Aethalometer AE51, pocket-sized real-time BC monitor, measures the rate of change in absorption of transmitted light due to continuous collection of aerosol deposit

on the Teflon-coated borosilicate glass fiber filter.⁽²⁵⁾ The optically-absorbing black carbon component of aerosol particles is measured by the light-emitting diode (LED) source at the wavelength of 880 nm and photo diode detector. The attenuation of the particle deposition spot is measured relative to an adjacent reference portion of the filter. The gradual accumulation of optically-absorbing particles leads to a gradual increase in attenuation from one period to the next. BC concentrations are calculated based on the controlled airflow rate and the increment of the attenuation value during each time using the known optical absorbance per unit mass of BC material.

The TSI SidePak Personal Aerosol Monitor AM510 uses light scattering to determine mass concentration in real-time.⁽²⁶⁾ An aerosol is drawn into the sensing chamber in a continuous stream. One section of the aerosol stream is illuminated with a small beam of laser light. The strength of scattered light is linearly associated with the mass concentration of the aerosol in the air stream. The real-time PM_{2.5} mass concentration is determined by this linear response of scattered light to aerosols in the air stream screened by a PM_{2.5} impactor.

The TSI Condensation Particle Counter 3007 uses a laser, a detector, and isopropyl alcohol (working fluid) to determine real-time particle number concentration (PNC), represented as number of particles per cubic centimeter in a particle size between 0.01 and 1 µm, in the sampled air.⁽²⁰⁾ Air is continuously drawn into a heated saturator (~95–104 °F), in which alcohol is vaporized and diffused into the air stream. Then, the aerosol sample and alcohol vapor pass into a cooled condenser (~50 °F) where the alcohol vapor becomes supersaturated and condenses onto particles present in the air stream. Particles grow quickly due to condensation and are counted by the optical sensor. While optical counters cannot measure particles less than 50 nm, this condensed particle counter can measure particles as small as 10 nm.^(27–28)

The CO monitor uses an electrochemical sensor to measure electrical current, generated by the chemical reaction of CO to carbon dioxide (CO₂). Changes in electrical current are converted to CO concentration, after a temperature correction based on a sensor in the monitor.^(21,29)

Integrated EC Sampling Method

During each session, integrated air samples were collected on quartz-fiber filters (Pallflex® Tissue quartz 2500QAT-UP) for EC analysis using NIOSH's reference 5040 method (hereafter referred as EC_{NIOSH}). The quartz filters were pre-cleaned at EOHSI with baking out at 800 °C for 2 hours and housed in a 3-piece cassette with a support pad (cellulose). The filter samples were analyzed by Sunset Laboratory (Tigard, OR), a certified laboratory for EC analysis using a NIOSH reference method (5040).

Diesel Emission Delivery System

A one-time purchase of forty gallons of ultra-low-sulfur diesel (ULSD) fuel was made at a gas station in Highland Park, NJ. Each session required ~4 gallons of ULSD fuel. The single diesel generator (YDG E5500, YANMAR Inc., Adairsville, GA) is permanently located in the penthouse of EOHSI and was used to generate diesel emissions. The generator has also been used in several exposure studies conducted by the EOHSI scientists to investigate

health effects and toxicological mechanisms associated with exposure to petroleum diesel emissions.^(22–23)

The particle mass and number distribution for the generated DPM was characterized using the CEF in EOHSI. A real-time eight-channel optical particle counter (LASAIR Model 1002, Particle Measuring Systems Inc., Boulder, CO) was used to measure size distributions of the particles delivered to the CEF. The particle size distributions of the optical instrument are: 0.1–0.2, 0.2–0.3, 0.3–0.4, 0.4–0.5, 0.5–0.7, 0.7–1.0, 1.0–2.0, and >2.0 μm in diameter. A real-time ultrafine particle counter (TSI CPC 3007) was simultaneously used to measure ultrafine (<0.1 μm in diameter) particle counts. The result showed the ultrafine particles constituted the majority of the DPM delivered to the CEF (Supplemental Figure 1). The greatest number of particles was those with 0.01–0.1 μm in aerodynamic diameter, whereas the greatest mass of DPM was composed of particles with an aerodynamic diameter of 0.1–0.2 μm .

Quality Assurance and Quality Control

To ensure data quality assurance and quality control, all real-time monitors were calibrated using the methods described in manufacturer's manuals and underwent background and flow checks prior to conducting each experiment. The filters used for Airtec EC and microAeth BC monitors were replaced at each change in environmental conditions to avoid filter overloading. The operation of real-time monitors followed the manufacturer-recommended protocols. The integrated EC sampling followed QA/QC procedures described in NIOSH Method 5040.

Real-time Data Acquisition and Data Processing

The 1-min averaged data were downloaded from each monitor using software provided by the manufacturers and compiled for further data analyses. However, especially in low DPM exposure case, the raw $\text{EC}_{\text{realtime}}$ measurements did not change in several minutes, due to poor resolution of concentrations reported by the Airtec real-time monitor. Thus, to make the $\text{EC}_{\text{realtime}}$ measurements comparable to other data sets, $\text{EC}_{\text{realtime}}$ measurements were post-processed using an Excel spreadsheet provided by the manufacturer. The spreadsheet provided 1, 5, 10, and 15-minute rolling averages of $\text{EC}_{\text{realtime}}$ measurements. The temporal pattern was improved by averaging more than 10 minutes. Therefore, we selected 15-min rolling average as the representative $\text{EC}_{\text{realtime}}$ data for the study. Data obtained by other real-time monitors (i.e., TSI SidePak Personal Aerosol Monitor AM510, microAeth AE51 Aethalometer, TSI CPC 3007, Langan CO Measurer) were not post-processed.

Data Analysis

Descriptive statistics ($\text{AVG} \pm \text{SD}$) for each session were obtained for all monitors and environmental conditions. All statistical analyses were completed using SAS v9.4 (SAS Institute Inc., Cary, NC, USA).

Three-way ANOVA Test of Relative Differences by Comparing Airtec to NIOSH Reference Method—To compare the Airtec real-time monitor to more established measurements, we calculated the relative difference (RD) between Airtec measurements

(EC_{realtime}) and the NIOSH reference method (EC_{NIOSH}) for each exposure session using equation (1):

$$RD = \frac{(EC_{\text{realtime}} - EC_{\text{NIOSH}})}{EC_{\text{NIOSH}}} \quad (1)$$

where, RD is a difference of real-time EC measurements relative to the NIOSH reference method at each exposure session,

EC_{realtime} is an arithmetic average of EC measurements conducted by the Airtec real-time monitor at each exposure session, and

EC_{NIOSH} is an EC concentration determined by the NIOSH reference method (5040) at each exposure session.

Then, a three-way ANOVA test of the relative differences was conducted for the factors of temperature, relative humidity and DPM levels. In addition, an interaction effect (i.e., temperature*relative humidity) was examined in the ANOVA test. The three-way ANOVA model was tested using the equation (2):

$$Y_{i,j,k} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha \cdot \beta_{i,j} + \varepsilon_{i,j,k} \quad (2)$$

where, $Y_{i,j,k}$ is calculated relative differences,

μ is a common effect for the whole test,

α_i is a fixed effect of categorical temperature levels (i.e., low (55 °F), medium (70 °F), and high (80 °F)),

β_j is a fixed effect of categorical relative humidity levels (i.e., low (10 %), medium (40 %), and high (80 %)),

γ_k is a fixed effect of categorical DPM levels (i.e., low (~50 $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$) and high (~200 $\mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$),

$\alpha \cdot \beta_{i,j}$ is an interaction effect of temperature and relative humidity, and

$\varepsilon_{i,j,k}$ is a random error of the regression model.

Correlation Analysis of Real-Time Monitors—To examine associations among the collected real-time monitoring data across the overall 30 exposure sessions, the 1-min averaged data were pooled and Spearman correlation coefficients (r_s) were calculated. If a Spearman correlation coefficient was greater than 0.8 and significant ($p < 0.05$), the result suggested that the two variables were strongly associated. If the correlation coefficient was less than 0.5, the association was considered weak.

Multiple Linear Regression Analysis of Environmental Condition Effects—To evaluate the impacts of environmental conditions on each real-time monitor, a multiple linear regression model was developed for the 1-min averaged monitoring data using categorical DPM levels (i.e., high/low) and continuous temperature and relative humidity data. Continuous 1-min averaged data (i.e., real-time monitoring and temperature/relative

humidity data) were directly used in SAS's REG procedure. Categorical DPM levels were coded as dummy variables: 0 if DPM level was low (i.e., $\sim 50 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$) and 1 if DPM level was high (i.e., $\sim 200 \mu\text{g}/\text{m}^3$ of $\text{PM}_{2.5}$), and imported to the SAS program. The partial r -squared and standardized estimates were obtained for each regression model to provide information on how much each variable contributed to the overall variability as well as to compare how much of each parameter yielded the changes of predicted levels within the model. Multicollinearity issues among predicting variables were examined by calculating variance inflation factor (VIF) for each predicting parameter in the model. The potential issue of autocorrelation was examined by conducting a Durbin-Watson test on the criteria of 1.64–2.36 (Durbin-Watson lower statistics with $n > 200$ and 3 parameters). A multiple linear regression model was established using the equation (3):

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \quad (3)$$

where, Y_i is the 1-min averaged real-time DE concentrations,

X_{i1} is the categorical DPM levels (0 and 1 if DPM level is low and high, respectively),

X_{i2} is 1-min averaged temperature data,

X_{i3} is 1-min averaged relative humidity data,

β_0 – β_3 are parameters of the model, and

ε_i is an error term for the model.

RESULTS AND DISCUSSION

Evaluation of the Airtec DPM/EC Monitor by Comparison to the NIOSH Reference Method

We completed a total of 30 experiments (TABLE II). Since the pilot experiment was completed for three sessions without DPM collection using the NIOSH 5040 method, a total of 27 temperature-humidity pairs were available for the direct comparison between real-time and NIOSH methods of measuring EC. The relationship between $\text{EC}_{\text{realtime}}$ and EC_{NIOSH} was established by a simple linear model without an intercept, showing an agreement of approximately 84% between the pairs (FIGURE 1). The Airtec real-time monitor reported higher EC levels compared to the EC concentrations measured by the NIOSH reference method. The slope of the regressed line between $\text{EC}_{\text{realtime}}$ and EC_{NIOSH} was 1.17, indicating EC concentrations monitored by the Airtec real-time monitor were elevated by approximately 17% when compared with the NIOSH filter-based method. In addition, the deviation of other real-time monitors was estimated $< 20\%$ for in comparison between each monitor and the NIOSH reference. The calculated slopes ranged from 1.08 ($\text{PM}_{2.5}$) to 1.20 (PNC) against EC_{NIOSH} .

Evaluation of the Airtec Real-time DPM/EC Monitor under different Temperature/RH/DPM Conditions

The relative differences among the three variables (Temperature, RH and DPM) are displayed in FIGURE 2. These are shown in FIGURE 2a for temperature, FIGURE 2b for relative humidity and FIGURE 2c for DPM levels. The three-way ANOVA test results

showed that the three independent categorical variables as well as an interaction effect (FIGURE 2d) had no significant effect on the relative differences between EC_{realtime} and EC_{NIOSH} for the tested environmental conditions ($p=1.00$ for temperature; $p=0.09$ for RH; $p=0.15$ for DPM; and $p=0.49$ for temperature*RH)..

Filter Overloading Issue for MicroAeth BC Aethalometer

The BC monitor reported a decreasing trend in real-time BC concentrations during the first 60 minutes during our low DPM exposure experiment (FIGURE 3), even though the other four realtime monitors were relatively constant over the same time period. Previous studies reported biases in real-time BC measurements using an aethalometer.^(30–32) Factors and associated correction schemes were discussed for filter loading effect⁽³³⁾, sensitivity in high-time resolution data⁽¹⁸⁾, or effects from humidity and vibration⁽¹⁶⁾. In our case, filter overloading may have caused a more abrupt drop in BC concentrations than real-time measurements from other monitors. Thus, due to its inaccurate readings, the BC monitor was not employed in all test conditions and the collected BC data were not used for subsequent data analyses (i.e., correlation and multiple linear regression analyses).

Correlations among the Continuous Monitors

All pairs of Spearman correlations were strongly correlated ($r_s = 0.83–0.88$; TABLE III). Among the four pollutants measured, EC had the highest correlation coefficient of 0.88 with both PM_{2.5} and PNC data, and 0.86 with gaseous CO concentrations. Considering diesel exhaust is abundant in particulate phase, the strongest correlations among EC, PM_{2.5} and PNC was expected in these experiments. The results indicate that the four real-time monitors respond similarly to the changes of diesel emissions across the tested temperature and relative humidity conditions.

Evaluation of Continuous Monitors' Performance in Environmental Conditions

In this controlled chamber study, all four tested real-time monitors could be affected by environmental conditions with the most important being the high humidity (~80%). The final regression models for each monitor are provided in TABLE IV. All regression models were significant ($p<0.01$ for all four models) and the model R^2 values ranged from 0.54 (EC) to 0.71 (PM_{2.5}). No significant multicollinearity and autocorrelation issues were found. The categorical DPM level (i.e., low and high) was the most dominant variable (partial R^2 between 0.50 and 0.68) in all of the four developed models. This was expected from positive and strong correlations ($r_s>0.8$) for continuous monitors with diesel emissions observed in previous correlation test. Therefore, we focus only on the effects of environmental conditions on real-time diesel exhaust measurements in each regression model. In general, relative humidity contributed more to the model R^2 than temperature. However, the effect varied by monitor type.

Optical sensors in the EC and PM_{2.5} monitors were more sensitive to changes in relative humidity than temperature. For EC and PM_{2.5} regression models, relative humidity was significant ($p<0.01$) and more influencing (standardized estimates of 0.23 for EC and 0.20 for PM_{2.5}) than temperature. For these EC and PM_{2.5} models, temperature was either not significant ($p=0.48$ for EC) or less influential than the relative humidity (for PM_{2.5}). If there

is a 10% change in relative humidity (e.g., from 60% to 70%) then the real-time EC monitor reading would change by $27.2 \mu\text{g}/\text{m}^3$ at constant temperature and DPM level. Similarly, the reading of real-time $\text{PM}_{2.5}$ monitor would change by $8.4 \mu\text{g}/\text{m}^3$, if relative humidity is changed by 10% and temperature and DPM levels are held constant. For the 10°F change in temperature (e.g., from 60°F to 70°F), the reading of real-time $\text{PM}_{2.5}$ monitor would change by $-3.9 \mu\text{g}/\text{m}^3$ at constant relative humidity and DPM level. These results are consistent with field observations. Janisko and Noll⁽³⁴⁾ reported erroneous real-time EC readings if condensation occurs after abrupt changes of temperature or humidity. Wallace et al.⁽³⁵⁾ also remarked elevated real-time PM measurements under high humidity conditions (e.g., $\text{RH} > 80\%$) due to the increasing the volume of hygroscopic particles. Some studies have corrected this relative humidity effect in collected PM data.^(36–37)

For the real-time PNC data, the regression model suggested the variable of relative humidity was significant ($p < 0.01$) and a stronger contributor (standardized estimate of -0.09) than temperature ($p = 0.09$; standardized estimate of -0.02). However, the parameter estimate for relative humidity was negative in the model, indicating a possibility of growing hygroscopic particles at higher RH and subsequently lowering particle counts, especially in ultrafine particle size range between 0.01 – $0.1 \mu\text{m}$, due to a reduction in agglomerates.⁽³⁸⁾ The readings of real-time PNC monitor changed by $-4,640 \text{ particles}/\text{cm}^3$ (10% change in relative humidity) and $-3,460 \text{ particles}/\text{cm}^3$ (10°F change in temperature), respectively.

In the CO regression model, relative humidity and temperature had similar effects on real-time CO measurements. Standardized estimates were 0.11 for relative humidity and 0.09 for temperature ($p < 0.01$ for both). If there are changes in relative humidity (10%) and temperature (10°F), the readings of real-time CO monitor would change by $0.3 \text{ mg}/\text{m}^3$ and $0.9 \text{ mg}/\text{m}^3$, respectively. The temperature effect was expected, as a consequence of the temperature-dependent nature of the sensor.⁽²⁹⁾ However, as demonstrated by the regression analysis, we found the impact of relative humidity was also significant in real-time CO measurements. More tests are needed to verify study findings.

Study Limitations and Future Research

This study has a few limitations in implementation and interpretation of study results. First, the range of tested temperature (55 – 80°F) is narrower than the relative humidity (10 – 80%). Therefore, the temperature effect may be underestimated. Second, the tested DPM level was not constant over the exposure session, due to inadvertent changes of generator cycles, air flows, mixing conditions, and environmental conditions. Thus, variability may be introduced in the collected data and may affect study results. Third, the sample size is relatively small. Consequently, differences may not be detected in statistical analyses. Parallel studies with more experiments in controlled environment as well as field measurements with simultaneous monitoring of environmental data would be required to verify study findings. Finally, simultaneously monitoring particle mass and number distribution is suggested to further investigate the possibility of hygroscopic particle growth at higher RH conditions ($> 80\%$). Very high humidity may shift the particle mass and number distribution and subsequently impact the monitored DPM mass and number concentration levels.

CONCLUSIONS AND RECOMMENDATIONS

Comparisons between the real time monitors and the NIOSH filter sampler concentration measurements indicated good comparability among the real-time devices and the NIOSH method. The overall deviation of these monitors from the NIOSH method results was estimated to be 20% in comparisons between each monitor and the NIOSH reference. In addition, the temperature, relative humidity, and DPM levels did not significantly impact the performance of the Airtec Real-time EC Monitor. Therefore, this real-time monitor could be used to monitor EC levels in occupational settings, particularly where high EC levels and variable environmental conditions may be expected to occur (e.g., for miners). However, this monitor may not be suitable for monitoring very short-term (e.g., < 15 minutes) and low-level EC exposures (e.g., $PM_{2.5} < 50 \mu g/m^3$) because 1-minute EC measurements did not reflect slight changes in low DPM concentrations in our study. Simultaneous monitoring of temperature and relative humidity is suggested to understand and correct environmental impacts on real-time data.

Temperature and humidity had limited effects on real-time measurements, with larger effects from relative humidity than from temperature. Therefore, our recommendation is to implement these real-time monitors as supplements to the reference method to estimate in-situ occupational exposure to diesel exhaust. However, simultaneous monitoring of temperature and relative humidity would be encouraged to correct environmental impacts on real-time data. In addition, the tested AE51 micro aethalometer filter overloaded in high DPM conditions; thus, we recommend using this device for monitoring residents' exposure to DPM in urban community settings but not for occupational exposures.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIGURE 1.

The scatter plot for the EC_{realtime} and EC_{NIOSH} measurements (N=27)

*The 1:1 dotted line was added in the scatter plot for the comparison.

FIGURE 2.

Box plots for calculated relative difference (RD) between EC_{realtime} and EC_{NIOSH} measurements in different a) temperature (Temp) (H = 80 °F, L = 55 °F, M = 70 °F), b) relative humidity (RH) (H = 80%, L = 10%, M = 40%), c) diesel particulate matter (DPM) levels (H = $\sim 200 \mu\text{g}/\text{m}^3$, L = $\sim 50 \mu\text{g}/\text{m}^3$), and an interaction between Temp and RH (HH = 80 °F & 80%, HL = 80 °F & 10%, HM = 80 °F & 40%, LH = 55 °F & 80%, LL = 55 °F & 10%, LM = 55 °F & 40%, MH = 70 °F & 80%, ML = 80 °F & 10%, MM = 70 °F & 40%).

FIGURE 3.

The comparison of real-time monitors running with low DPM ($50 \mu\text{g}/\text{m}^3$), low RH (10%), and low temperature (55°F) in a session (#8) on 1/8/2014

*CO concentrations are divided by 100 for presentation purpose only.

TABLE I

Specifications for real-time monitors used in the study.

Monitor	Measure	Sensitivity/ Resolution (Accuracy)	Operation Range	Measurement Method
Airtec Diesel Particulate Monitor	Elemental carbon	< 15 µg/m ³	~50–600 µg/m ³ @ 8-hr time weighted average (TWA)	Changes in absorption of transmitted light
MicroAeth Aethalometer AE51	Black carbon	0.001 µg/m ³ (±0.1 µg/m ³)	0–1 mg/m ³	Changes in absorption of transmitted light @ 880 nm
TSI SidePak Personal Aerosol Monitor AM510	PM _{2.5} mass (0.1–10 µm)	0.001 mg/m ³	0.001–20 mg/m ³	Scattered light intensity @ 670 nm
TSI Condensation Particle Counter 3007	Particle number (0.01– 1.0 µm)	1 particle/cm ³ (±20%)	0–100,000 particles/cm ³	Counting particles grown by isopropyl alcohol
Langan T15n CO Measurer	Carbon monoxide	0.05 ppm	0–1000 ppm	Measuring electrical activities in electrochemical cells
HOBO U12 Temp/RH Data Logger	Temperature & relative humidity	0.05 °F (±0.63 °F) 0.03% (±2.5%)	0–158 °F 5–95%	Changes in resistance of a thermistor (temperature) and capacitive measurement of electric field (relative humidity)

Descriptive statistics (AVG±SD) for the real-time data monitored during the 30 sessions controlled with three temperature/RH levels and two DPM conditions (~50 and ~200 µg/m³ as of PM_{2.5}) at the EOHHSI's Controlled Exposure Facility.

TABLE II

Date	#	RH (%)	Temp (°F)	EC _{realtime} (µg/m ³)	EC _{NIOSH} (µg/m ³)	BC (µg/m ³)	PM _{2.5} (µg/m ³)	CO (mg/m ³)	PNC (particles/cm ³)
12/12/13	1	33±0.6	65±0.4	100±52	N/A	105±34	119±38	5.6±1.2	93,753±27,142
	2	38±1.7	71±0.5	116±18	N/A	N/A	128±6.7	6.8±0.3	105,474±4,605
	3	40±1.0	73±0.9	150±16	N/A	N/A	169±18	8.1±0.7	116,396±7,713
12/19/13	4	40±2.6	78±0.3	285±97	129	211±101	220±35	9.5±1.2	217,859±47,933
	5	36±8.7	71±1.0	264±19	301	N/A	204±28	8.3±0.7	232,821±18,815
12/20/13	6	25±0.8	65±0.5	62±37	42	61±27	48±11	3.4±0.4	34,569±17,560
1/7/14	7	8±0.9	61±0.7	68±27	54	84±40	55±18	4.2±0.5	71,922±30,898
	8	10±1.2	69±2.0	57±14	75	63±23	46±7.8	4.4±0.2	52,254±6,665
	9	8±0.5	76±1.6	88±11	34	85±30	69±3.3	5.1±0.1	93,427±2,788
1/8/14	10	6±0.4	62±1.1	70±23	52	89±22	51±6.4	4.2±0.2	94,986±10,054
	11	9±0.3	68±1.2	64±5	73	45±12	51±4.1	4.4±0.1	89,555±3,479
	12	8±0.6	76±2.0	71±4	41	73±26	59±4.1	4.5±0.1	96,418±3,560
1/13/14	13	35±0.7	62±0.4	64±9	24	97±30	58±8.6	4.5±0.2	83,123±8,647
	14	35±4.0	71±1.2	58±7	12	67±19	49±5.2	4.5±0.3	80,949±11,655
	15	38±4.3	78±1.0	55±5	43	69±11	53±3.0	4.3±0.1	70,783±3,014
1/14/14	16	52±1.3	67±0.3	44±8	35	65±16	42±4.3	3.7±0.1	48,063±5,476
	17	53±1.9	73±0.6	34±11	42	59±22	39±4.6	3.6±0.1	40,080±4,585
	18	54±0.6	76±0.4	23±9	23	32±4	27±2.4	3.3±0.2	18,599±2,796
2/12/14	19	33±1.3	63±0.3	500±61	428	N/A	N/A	8.1±0.4	347,141±22,220
	20	39±3.4	70±1.2	534±21	407	N/A	N/A	8.1±0.9	355,716±10,396
	21	40±2.2	76±0.2	495±54	276	N/A	124±15	18±0.5	322,935±14,482
2/14/14	22	56±2.6	65±0.6	675±169	395	N/A	285±49	12±1.2	333,644±28,472
	23	64±0.6	70±0.1	767±117	564	N/A	301±23	17±1.1	262,298±30,266
	24	70±1.7	75±1.9	819±80	617	N/A	283±30	17±2.3	219,017±10,201
2/19/14	25	21±1.6	64±0.5	389±42	317	N/A	133±9.3	17±1.3	347,420±24,283
	26	24±0.6	80±4.4	427±26	505	N/A	179±11	18±0.8	285,662±18,528
	27	22±0.3	80±0.4	339±53	338	N/A	151±12	16±0.8	273,372±20,877

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Date	#	RH (%)	Temp (°F)	EC _{realtime} (µg/m ³)	EC _{NIOSH} (µg/m ³)	BC (µg/m ³)	PM _{2.5} (µg/m ³)	CO (mg/m ³)	PNC (particles/cm ³)
2/28/14	28	56±4.7	69±0.7	312±38	271	N/A	153±26	18±2.1	330,802±46567
	29	62±1.9	71±0.5	342±70	503	N/A	186±31	18±2.0	240,176±36035
	30	72±3.0	75±1.0	369±15	429	N/A	187±10	17±0.7	211,814±9,913

TABLE III

Spearman correlation matrixes among continuous diesel exhaust measurements (EC_{realtime} , $PM_{2.5}$, PNC, and CO).

Spearman Coefficient p-value (Sample Number)	EC_{realtime}	$PM_{2.5}$	PNC	CO
EC_{realtime}	-	<u>0.88</u> <.01 (3,381)	<u>0.88</u> <.01 (3,623)	<u>0.86</u> <.01 (3,623)
$PM_{2.5}$		-	<u>0.83</u> <.01 (3,381)	<u>0.85</u> <.01 (3,381)
PNC			-	<u>0.86</u> <.01 (3,623)
CO				-

Note: Correlation coefficients in bold ($p < 0.05$) and with underline ($r_s > 0.8$).

TABLE IV

The multiple linear regression models for continuous diesel exhaust measurements with corresponding environmental variables and categorical DPM levels conducted in the study.

Parameter	Parameter Estimate	Standard Error	Pr > t	Standardized Estimate	Variance Inflation Factor	Model/Partial R ²
EC _{realtime} (µg/m ³)	-	-	<.01	-	-	0.54
Intercept	11.57	34.87	0.74	-	-	-
DPM Level (Low=0, High=1)	281.37	6.25	<.01	0.60	1.32	0.50
Relative Humidity (%)	2.72	0.15	<.01	0.23	1.29	0.04
Temperature (°F)	-0.35	0.50	0.48	-0.01	1.06	<.01
PM _{2.5} (µg/m ³)	-	-	<.01	-	-	0.71
Intercept	55.42	9.98	<.01	-	-	-
DPM Level (Low=0, High=1)	123.33	1.79	<.01	0.74	1.32	0.68
Relative Humidity (%)	0.84	0.04	<.01	0.20	1.29	0.03
Temperature (°F)	-0.39	0.14	0.01	-0.03	1.06	<.01
PNC (particles/cm ³)	-	-	<.01	-	-	0.65
Intercept	103,581	14,107	<.01	-	-	-
DPM Level (Low=0, High=1)	181,803	2,527	<.01	0.85	1.32	0.64
Relative Humidity (%)	-464	62	<.01	-0.09	1.29	0.01
Temperature (°F)	-346	201	0.09	-0.02	1.06	<.01
CO (mg/m ³)	-	-	<.01	-	-	0.67
Intercept	-3.06	0.77	<.01	-	-	-
DPM Level (Low=0, High=1)	8.87	0.14	<.01	0.74	1.32	0.65
Relative Humidity (%)	0.03	0.00	<.01	0.11	1.29	0.01
Temperature (°F)	0.09	0.01	<.01	0.09	1.06	0.01