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Comparing Gravimetric and Real-Time Sampling of $PM_{2.5}$ Concentrations Inside Truck Cabins

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Abstract

As part of a study on truck drivers' exposure and health risk, pickup and delivery (P&D) truck drivers' on-road exposure patterns to $PM_{2.5}$ were assessed in five weeklong sampling trips in metropolitan areas of five U.S. cities from April to August of 2006. Drivers were sampled with real-time (DustTrak) and gravimetric samplers to measure average in-cabin $PM_{2.5}$ concentrations and to compare their correspondence in moving trucks. In addition, GPS measurements of truck locations, meteorological data, and driver behavioral data were collected throughout the day to determine which factors influence the relationship between real-time and gravimetric samplers. Results indicate that the association between average real-time and gravimetric $PM_{2.5}$ measurements on moving trucks was fairly consistent (Spearman rank correlation of 0.63), with DustTrak measurements exceeding gravimetric measurements by approximately a factor of 2. This ratio differed significantly only between the industrial Midwest cities and the other three sampled cities scattered in the South and West. There was also limited evidence of an effect of truck age. Filter samples collected concurrently with DustTrak measurements can be used to calibrate average mass concentration responses for the DustTrak, allowing for real-time measurements to be integrated into longer-term studies of inter-city and intra-urban exposure patterns for truck drivers.

Keywords

gravimetric; $PM_{2.5}$; real-time; spatial variability; truck driver; traffic; temporal

INTRODUCTION

$PM_{2.5}$ is one of the most widely monitored and studied components[1–5] in traffic-related air pollution. It is linked to numerous cardiovascular and pulmonary diseases[6–12] because of its ability to penetrate to the deepest portions of lungs and its large surface area that may favor adsorption of toxic substances (e.g., polycyclic aromatic hydrocarbons and soluble metals).[13, 14]

Gravimetric samplers are routinely used to estimate time-weighted average (TWA) levels of $PM_{2.5}$ in various settings when coupled with a designed inlet, such as ambient[15,16] and occupational microenvironments with heavy diesel exposure.[17,18] However, because of

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their generally long averaging times (> 8 hr) to collect enough mass, they cannot show short-term temporal patterns. On the other hand, portable real-time $PM_{2.5}$ samplers such as the DustTrak (TSI Model 8520, Shoreview, Minn.), which uses light scattering to measure 10-sec average concentrations, can readily show short-term temporal variations in $PM_{2.5}$. The DustTrak's key limitations are that light scattering is sensitive to particle size distribution, shape, and composition (refractive index and absorption),[(19)] which potentially implies that the relationship between gravimetric samples and DustTrak measurements would not be consistent across settings. Though the DustTrak likely has greater measurement error than the federal reference method (FRM) gravimetric $PM_{2.5}$ samplers,[(20)] it can provide useful real-time information (which is interpretable if any biases are consistent) and can have improved accuracy through statistical adjustment.[(21)]

Past investigators have compared averages of DustTrak measurements with concurrent gravimetric sampler readings. Kim and co-workers[(18)] compared both types of samplers to assess exposures of a group of boilermakers who were exposed to residual fuel ash and welding fumes. Average $PM_{2.5}$ concentrations measured by DustTrak monitors were correlated with data from the gravimetric sampling (correlation coefficient r = 0.68), though their difference varied by season (significantly higher in the summer [geometric mean 0.59, GSD 3.38] than in the fall/winter [geometric mean 0.29, GSD 2.40]). The composition and types of aerosols measured also affected the response; one unit of increase in $\log_e PM_{2.5}$ using the DustTrak was associated with a lower unit of increase in gravimetric $PM_{2.5}$ for welding at the power plant (0.55 unit, 95% confidence interval: [CI] 0.37, 0.72) than welding at the apprentice school (0.89 unit, 95% CI: 0.68, 1.10) due to differences in primary particle exposures at the two locations (power plant overhaul site: residual oil fly ash that has a larger particle size and contains a significant component of water-soluble metal sulfate; apprentice school: submicron welding metal fumes of iron oxide). In an ambient setting, Chang and co-workers[(22)] found that the DustTrak overestimated the daily mean ambient $PM_{2.5}$ by a factor of about 2 compared to 12-hr gravimetric $PM_{2.5}$. The correlation between the two was fairly consistent across seasons (R^2 is 0.87 in the summer and 0.81 in the winter), after the DustTrak response was corrected.

However, to our knowledge, no study has considered this relationship during in-vehicle exposures, which can have a strong influence on personal exposures of driver/passengers in diesel-powered school buses[(23,24)] and trucks[(25)] in metropolitan areas. In this study, we focus on pickup and delivery (P&D) drivers who are participants in the Trucking Industry Particle Study (TrIPS),[(2,25–28)] which researches the association between occupational exposure to traffic-related particulate matter in the U.S. trucking industry and its health effects. The truck drivers' close proximity to traffic for 8 to 12 hr on a daily basis, making deliveries in the metropolitan area of large cities with no air-conditioning system setup in their truck cabins, leads to a significant percentage of their $PM_{2.5}$ exposures occurring in this occupational setting.

The objectives here were to investigate the association between real-time and gravimetric measurements taken side by side on moving trucks in five cities, which allow us to assess the accuracy of the DustTrak in measuring driver on-road personal exposure in intra-urban settings and across cities, and if the DustTrak proves sufficiently interpretable in this context, to find factors influencing the ratios between them and to assess how the DustTrak can help assess exposure patterns.

METHODS

This evaluation of truck driver exposures was conducted during weeklong visits in a city each month from April to August of 2006 in five cities across the United States. The sequence of the weekly visits was: Columbus, Ohio; Milwaukee, Wisc.; Phoenix, Ariz.; Portland, Ore., and Denver, Colo. The five cities observed for this study represent the second sampling trip to cities with real-time sampling equipment within the larger set of 36 original TrIPS locations and were selected randomly with the restriction that they occur during the same season as the original site visit.[26]

On each day of our visit, measurements were attempted on two P&D trucks. Recruited truck drivers were volunteers, with a small percentage (9.5%) of smokers. Informed consent to be monitored was obtained with a human subjects protocol approved by the Harvard School of Public Health IRB, which informed the potential subjects of any risks associated with collecting samples and their being identified. No subject identifiers were retained by the investigators. Truck drivers usually drove in a 50–100 km radius around their home terminal during the daytime for 8 to 12 hr depending on their tasks.

Sampling and Data Collection

In-Cabin Particulate Matter Monitoring—A real-time monitor for $PM_{2.5}$ and a field sampling (FS) box were fixed on the dashboard, passenger seat, or raised above the passenger floorboard inside each truck cab depending on the configuration of the sampled truck. Real-time $PM_{2.5}$ levels were measured using the DustTrak, which measures particles with a laser photometer based on light scattering technology. It has an impactor on the inlet to exclude particles larger than 2.5 μm and is operated with a flow rate of 3.5 L/min. The DustTrak monitor was calibrated with Arizona Test Dust (ISO 12103-1, A1 test dust) annually at the factory and zero checked daily before sampling.

Gravimetric $PM_{2.5}$ was measured by a method that has results consistent with the Environmental Protection Agency (EPA) PQ200 federal reference method.[29] On the exterior of the FS box were mounted precision stainless steel cyclone particle separators (GK2.05 SH (KTL); BGI, Inc., Waltham, Mass.) to remove large particles from PM_1 and $PM_{2.5}$. PM_1 was measured in parallel with $PM_{2.5}$ to provide elemental carbon (EC) and organic carbon (OC) data on combustion particles in vehicle exhaust that are predominantly < 1.0 μm diameter. Particles were then collected on a 37-mm Teflon filter with 0.2 μm diameter pore size. Gravimetric analysis was used to determine the particle mass on the filter. The filters were weighted before and after sampling after they were equilibrated in a room with controlled temperature within 20–23°C and relative humidity 40±5% for at least 48 hr. A precision machined cyclone separator (SCC1.062 Triplex; BGI) removed particles greater than 1.0 μm before collecting PM_1 on a 22-mm quartz tissue filter. Elemental carbon (EC) and organic carbon (OC) in PM_1 were measured by NIOSH method 5040. Inside the FS box were pumps that operated at a flow rate of 3.5 L/min and a real-time monitor for temperature and humidity (HOBO; Onset Computer Corp, Bourne, Mass.).

Spatial and EPA Monitoring Data—Truck location (in latitude and longitude) was recorded every 29 sec during each driver's truck route by GPS (Protrak scout by Tracking Products, Inc., Boulder, Colo.), which also recorded time, truck speed, and truck direction. The street map of each of the five states where the terminals were located was obtained from ESRI (Environmental Systems Research Institute, Redlands, Calif.) Census 2000 TIGER/Line Transportation Data.

Land use data were obtained from the National Land Cover Dataset (NLCD) 1992 of the United States Geological Survey (USGS) to be consistent with our previous research.[30] The Anderson land-use and land-cover classification system was derived from and modified by data from aerial photography and used for the NLCD classification system.[31] Commercial, industrial, transportation, and communications/utilities land uses were grouped and treated as one NLCD class (#23, commercial/industrial/transportation) in the form of raster data. These raster data were projected to points, which were used to create a variable representing the percentage of industrial land-uses within a 500 m radius for every point on the map.

Daily ambient $PM_{2.5}$ concentrations in the area of the terminal on sampling days were estimated with data downloaded from the Air Quality System (AQS) maintained by the U.S. EPA. Since there are very limited numbers of EPA samplers available in each state (e.g., 18 samplers in Colorado), a spatial estimation method, kriging,[32] was used to estimate location-specific daily ambient $PM_{2.5}$ concentrations for our truck routes. We interpolated the value of ambient $PM_{2.5}$ for an unobserved location from observations of its value at nearby locations, assuming a smooth change in $PM_{2.5}$ with distance. ArcView 9.0 (ESRI, Redlands, Calif.) was employed to integrate all spatial and temporal information above into a Geographic Information System (GIS) database.

Meteorological Data—Meteorological data were collected from two sources. One was in-cabin conditions obtained from HOBO sensors inside of the sampling box, which measured in-cabin temperature and relative humidity every minute. The other source was hourly local weather data obtained from an online source (Weather Underground, Inc., Ann Arbor, Mich.), including outdoor temperature, relative humidity, precipitation, and wind speed and direction.

Questionnaire Data—A brief questionnaire from each sampled driver obtained information about truck cabin window position status (closed, partially open, and fully open), cigarette smoking activity (smoked or not smoked; if smoked, how many cigarettes were smoked) and traffic intensity levels (heavy, medium, or light) for each truck route three times (morning, afternoon, and evening) on the sampling day.

Data Processing and Analysis

Construction of a GIS Database for Each Truck's Trip Route—The temporal resolution of the GPS monitor, 29 sec, was chosen to be the resolution of the entire dataset to combine all collected information into one matched dataset. This was chosen because the GPS records were two-dimensional geographic information at each time point and it is difficult to interpolate locations for the sometimes curved road trajectories and estimate time points that match the other one-dimensional temporal data streams. Assuming all other real-time measurements changed linearly between measurement reading points, the DustTrak and HOBO data were interpolated to match the GPS time points. After all the data above were merged into one dataset, they were imported into our GIS database and superimposed onto the U.S. Census Bureau TIGER 2000 transportation layer to create a multidimensional map with time, meteorological, geographic, and $PM_{2.5}$ concentration information at each truck route data point.

Data Cleaning and Quality Control—Misassignment of a truck's location to the wrong road happened in ArcGIS, because the national database used in this study omitted the width of roads, so that a moving truck's geographic position recorded by GPS did not always align perfectly with the lines that represent roads on maps. The wider roads, such as multilane highways, were more likely to have this misassignment. Road misassignments could cause road type misclassification, which then leads to errors in regression analyses. The misclassification was rectified by manually verifying the location assignment in the GIS database.

Comparison Between Gravimetric and Real-Time $PM_{2.5}$ Measurements—We initially compared gravimetric and TWA DustTrak samples to determine the strength of association and potential degree of bias. Potential variables were examined to explain variability in the ratio between the time-averaged DustTrak concentrations and the gravimetric samples, including the percentage of time spent driving on the road, seasonal and meteorological factors, city characteristics (including mean concentrations of driver exposure to EC and OC, and industrial land use), truck characteristics (truck production year and model), and driver behaviors (cigarette smoking, traffic intensity, and truck window position status). Statistical analyses were performed using STATA version 10.0 (StataCorp, College Station, Texas). Due to sampling across cities and small sample sizes overall, a significance criterion of p-value < 0.1 is used in this study.

RESULTS

Real-Time $PM_{2.5}$ Concentration Patterns

Examination of real-time $PM_{2.5}$ concentrations across the 34 truck routes in five cities demonstrates some of the factors that may influence the gravimetric-DustTrak relationship. Figure 1A illustrates one of the truck delivery routes (dots in map) in Phoenix, with Figure 1B showing that the time when the truck was driving on-road (areas in white) is much shorter than the total time spent parked at terminal and delivery sites (gray areas). In fact, across all truck routes, more time was spent at terminal and delivery sites than on-road (Table I).

Real-time in-cabin $PM_{2.5}$ concentrations for the 34 truck routes from the five cities are shown in Figure 2. Concentrations in most cases are quite variable, and those routes with smoking drivers all demonstrated a pattern of multiple high $PM_{2.5}$ peaks (5^{th} route in Columbus, 4th route in Milwaukee, 6th route in Phoenix, and 6th route in Portland in Figure 2). Compared with the other three routes with smoking drivers, $PM_{2.5}$ levels were lower in the 4th route in Milwaukee due to lower traffic intensity. However, as illustrated in Table I, those routes with multiple $PM_{2.5}$ exposure peaks do not necessarily have high on-road mean exposure to $PM_{2.5}$ because peaks have short durations. Both gravimetric data and real-time averages sampled have log-normal distributions.

Comparison Between Gravimetric and Real-Time $Pm_{2.5}$ Measurements

Out of the 34 collected routes, 30 pairs of $PM_{2.5}$ concentrations measured simultaneously by DustTrak and gravimetric samplers were compiled and summarized in Table II. The four excluded routes had incomplete (less than 6 hr) DustTrak measurements due to battery failure.

When all 30 truck routes were combined, the DustTrak measurements had an overall arithmetic mean of 42.4 $\mu g/m^3$, while the arithmetic mean from their matching gravimetric samples is 20.9 $\mu g/m^3$. As indicated in Table II, the ratio between DustTrak and gravimetric concentrations did vary across observations (range of 0.92–3.74), with a median and arithmetic mean near 2. The Spearman rank correlation coefficient for the DustTrak and gravimetric $PM_{2.5}$ concentrations was 0.63 (95% CI: 0.35, 0.81).

To examine this relationship more formally, we first regressed gravimetric concentrations against DustTrak means in linear regressions forcing the line through the origin because there are strong a priori arguments to omit the intercept.[15,21,22] The slope of this regression line was 2.11, similar to the mean and median ratios in Table II and indicating a similar degree of overestimation for the DustTrak relative to gravimetric samples as reported by other studies.[15,21,22] Given skewed distributions, we also tested regressing $\log_e$DustTrak and $\log_e$gravimetric (Figure 3B). This yielded an R^2 of 0.51 and a slope that similarly indicated an overestimation by a factor of 2.09.

However, these relationships are potentially driven by outliers and influential points. If we exclude two high-concentration points associated with smoking drivers (the circle in Figure 3A), the linear regression slope remains close to 2 but loses statistical significance, in part because of four low-ratio influential points (Figure 3C). Without these four points (Figure 3D), the slope is still close to 2 but the relationship regains statistical significance (p-value < 0.05, $R^2 = 0.27$).

Predictors of Variation in Ratios Between Dusttrak Averages and Gravimetric Sampling

Although the ratios between DustTrak means and gravimetric samples were consistent, there remains residual variability that is worth exploring in more detail. We first consider whether there is a significant city effect on the ratios between DustTrak averages and gravimetric sampling. The distribution of those ratios is close to a normal distribution. Regression on those ratios using indicator variables for cities indicated a statistically significant city effect (p-value = 0.093) between the industrial Midwest cities (Columbus and Milwaukee) and the non-Midwest cities (Phoenix, Portland, and Denver). Although the small sample size (n = 4) may have failed to show a strong significant difference (p-value = 0.178) from Columbus, Milwaukee stood out as a potential outlier with the lowest ratio (all ratio values smaller than 1.7) among the five cities (Figure 4). The unique exposure conditions while sampling in Milwaukee were that it was sampled in the spring, had lower values of industrial land use, higher in-cabin humidity (in a range below 60%), and faster wind and truck speeds than the other four cities (Figure 5).

We tested all of the descriptive variables other than city dummy variables described earlier using a stepwise regression procedure in an attempt to explain the variability in ratios, using p-value < 0.10 as our significance level cutoff. We also tested the fraction of time spent in on-road driving as a potential explanatory variable, although all DustTrak readings (both on-road and stopping at terminal/delivery site) were used in the comparison between DustTrak and gravimetric readings because the two portions cannot be separated in gravimetric readings. Additional potential explanatory variables were percentage of time on the road, truck production year and model, outdoor and in-cabin temperature and relative humidity, in-cabin EC and OC concentrations, and questionnaire responses on traffic intensity, window position status and driver smoking.

When stepwise regression was applied, only truck production year was weakly significant and negatively associated with the ratio between DustTrak averages and gravimetric sampling (p-value = 0.089), which means that older trucks tended to generate higher readings in the DustTrak than in the gravimetric sampler. Although other covariates were not significant, they provided some limited insight about how they affected the ratios between the two types of sampling given a small sample size, which will be discussed in detail in the next section.

DISCUSSION

From previous studies in the general ambient environment, the DustTrak mean tends to overestimate a gravimetric sample collected during the same period by a factor of two to three when using Arizona Test Dust for calibration,[15,21,22] while maintaining a correlation with gravimetric readings. DustTrak measurements in high-concentration occupational settings (>10 times the ambient environment) were also well correlated with gravimetric samples but gave results that were more comparable in magnitude.[18] The range of $PM_{2.5}$ concentrations tested in the present study (means of 13.4 to 192.6 μg/m^3 by DustTrak) lies between the ambient $PM_{2.5}$ levels (about 5.0 to 20.4 μg/m^3)[21] and high-concentration occupational levels (geometric mean concentration of 300 μg/m^3).[18] While the literature would imply that a simple multiplying factor may not be enough to capture the complexities of in-cabin concentrations, which are a combination of these two types of measurements, our regression modeling showed a reasonably consistent ratio with limited fixed factors that explained variability. That said, both mobile (on-road driving) and stationary (stopped at terminal/delivery sites) sampling portions were included in the present study, and changing sources with varying intensities may have led to changes in light scattering and hence response changes in the DustTrak between the two portions of the drivers' work routines.[18]

While our hypothesized predictors did not readily explain the differences in the ratios between DustTrak and gravimetric measurements, there were some indications of trends within our data that may merit further exploration in the future. Removal of two high-concentration points associated with smoking drivers reduced the significance of our association, which may indicate that at lower exposure levels, the association between the two types of measurements may be subject to higher influence from other factors, such as particle sources and their intensities, seasonal change, and city characteristics. Another possible explanation of this influence of tobacco smoking could be that the association is confounded by possible differences in particle size distribution and composition between tobacco smoke and other components of $PM_{2,5}$.

A statistically significant city effect was found between the industrial Midwest cities and the rest of the sampled cities. Four possible factors may have contributed to the exposure differences across cities: (1) differences in $PM_{2.5}$ sources, concentrations, and size distribution; (2) factors associated with seasonal weather; (3) truck routes and associated exposures; (4) other possible contributors, such as small sample size, DustTrak calibration, and challenges in synchronizing multiple samplers and matching data from various sources, especially those from questionnaires. The first three factors are discussed in more detail below.

(1) $PM_{2.5}$ composition (particle types and sources), concentration and size distribution

While we have limited information available about particle size distributions across the cities, there are some likely differences in composition. Columbus and Milwaukee both are located in the industrial Midwest region of the United States, and ambient $PM_{2.5}$ is higher in sulfate and nitrate but lower in OC compared with the other three cities located in other parts of the country.[33] However, our in-cabin sampling indicates extremely high OC contributions across all cities (Figure 6), which may come from driving in traffic.[34] All drivers tested across cities had OC levels higher than 70% of $PM_{2.5}$ concentrations. Columbus and Milwaukee had ratios between 70% and 76.9%, lower than the other three cities with OC levels higher than 80% of $PM_{2.5}$. Our results showing lower OC in the industrial Midwest compared with those in the West in spring and summer is consistent with the findings by Bell el al.[33] That said, drivers in Milwaukee had lower $PM_{2.5}$, EC and OC concentrations, which may have led to different responses of the DustTrak. One prior study suggested that, compared with gravimetric sampling, the DustTrak tends to overestimate particulate levels during higher relative humidity for sulfate and nitrate dominated aerosols but underestimates readings for vehicle exhaust and fuel burning.[35] This is because DustTrak does not heat airflows and measures light scattering particles that may be skewed by high humidity enlarged sulfate and nitrate particles. However, this does not help explain the lower DustTrak responses in Milwaukee with higher relative humidity (in a range less than 60%, Figure 5) and higher regional levels of nitrate and sulfates.

(2) Seasonal change (spring vs. summer)

Phoenix, Portland, and Denver were sampled in the summer with higher ambient temperature than in the other two cities. Though gravimetric sampling is considered the "gold standard," in the summer, semivolatile compounds collected on filters may evaporate

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before weighting in lab even though they were measured by the DustTrak.[36] This may have led to underestimation in gravimetric measurements and, hence, higher ratios between DustTrak vs. gravimetric sampling in the three cities sampled in summer. Higher RH will shift sulfate and nitrate particles into the higher response sizes for the DustTrak.

(3) Truck routes and associated exposures

A lower percentage of roads driven in Milwaukee were local roads, which explains the higher truck speeds observed in this city (Figure 5). Truck speeds were generally close to the speed limit, suggesting low levels of traffic congestion. With higher truck speeds and mostly open cabin windows, plus higher wind speeds compared with other cities (Figures 5C and 5D), higher in-cabin air exchange rates were likely in Milwaukee. Higher concentrations of $PM_{2.5}$, EC and OC, lower wind and truck speeds, and higher industrial land use in Columbus may have led to the different response of the DustTrak between Columbus and Milwaukee, even though they were both sampled in the spring and in the same general geographic region.

Additional deviations between DustTrak and gravimetric samples are potentially attributable to short-term excursions that are not readily explained by available covariates. Based on driver GPS, questionnaire data and other matching information, most high peaks occurred under at least one of the following scenarios: (a) when the driver smoked in the truck cabin; (b) when the truck was parked in the parking lot of terminals or delivery sites; (c) when the truck was driving past or waiting at a major road intersection; and (d) when the truck was in heavy traffic, usually in early mornings on major highways.

Regarding smoking, which appears as multiple short-duration events in an 8–12 hr P&D route, route-average TWA may be minimally affected, but the degree of the effect could differ across the real-time and gravimetric samplers. We did not have a sufficient number of smokers to test this hypothesis, but the two high-concentration points in Figure 3 (associated with smokers) did have ratios exceeding 2, so this question is worth exploring further. Very high concentrations of ultrafine particles in cigarette smoking may lead to coincidence errors where random clumps of particles look like larger particles because they are not resolved as separate particles. High exposures were also observed when trucks stopped at delivery sites in some cases (Figure 1B). When trucks stopped to deliver or pick up a shipment, they usually backed into a dock and may have kept their engine running, which can create high $PM_{2.5}$ levels when emissions accumulate in this semi-enclosed environment. Higher in-cabin concentrations also can happen when several vehicles are present in a parking lot where trucks are coming and going, or idling, while the in-cabin ventilation rate is lower than when driving on road. Since this microenvironment contributes a majority of the sampling time and some concentration peaks, it may contribute appreciably to the TWA concentrations, but we lacked the available covariates to capture these settings in detail. We finally observed morning rush-hour $PM_{2.5}$ peaks on trucks that travelled on major interstate highways before 9 a.m. (Figure 2) but could not determine if this contributed to biases in the relationship between DustTrak and gravimetric samples.

Limitations

This comparative analysis is limited by a small sample size, which did not allow us to explore in detail the effects of various factors on the ratio between DustTrak and gravimetric samples, especially those (such as smoking) that were only found in a small number of cases. We also lacked sufficient time-resolved data on factors like window opening activity that could facilitate interpretation of real-time concentrations. Mobile and stationary sampling periods for trucks had different $PM_{2.5}$ sources with varying intensities, though the two periods could not be separated; hence, their potentially different contributions to sampler responses could not be identified. That being said, our study provides the first concurrent observations with these sampling instruments in a high-concentration microenvironment, demonstrating a similar bias as shown elsewhere but providing reassurance that the bias is sufficiently consistent for the DustTrak to yield interpretable and meaningful findings showing when peak exposures occur and how high they may be.

CONCLUSIONS

This study utilized both gravimetric and real-time instruments side-by-side to measure average $PM_{2.5}$ concentrations in truck cabins during pickup and delivery truck drivers' work routines. Statistical analyses indicated that gravimetric and real-time measurements were reasonably well correlated in this microenvironment, with the DustTrak generally overestimating the mass concentrations by a factor of two or more compared with gravimetric sampling. Ratios did vary between and within cities and could be potentially influenced by numerous factors. Although regression analyses were underpowered to capture these factors, a significant city effect was found between the industrial Midwest cities and the rest of the sampled cities. Also, there is a clear theoretical rationale for effects of truck age, traffic patterns, smoking, and season, among other factors. Gravimetric analysis of filter samples collected concurrently with DustTrak measurements may be used to calibrate the average mass concentration responses for the DustTrak, to allow the real-time measurements to be utilized in models of long-term $PM_{2.5}$ exposures for truck drivers.

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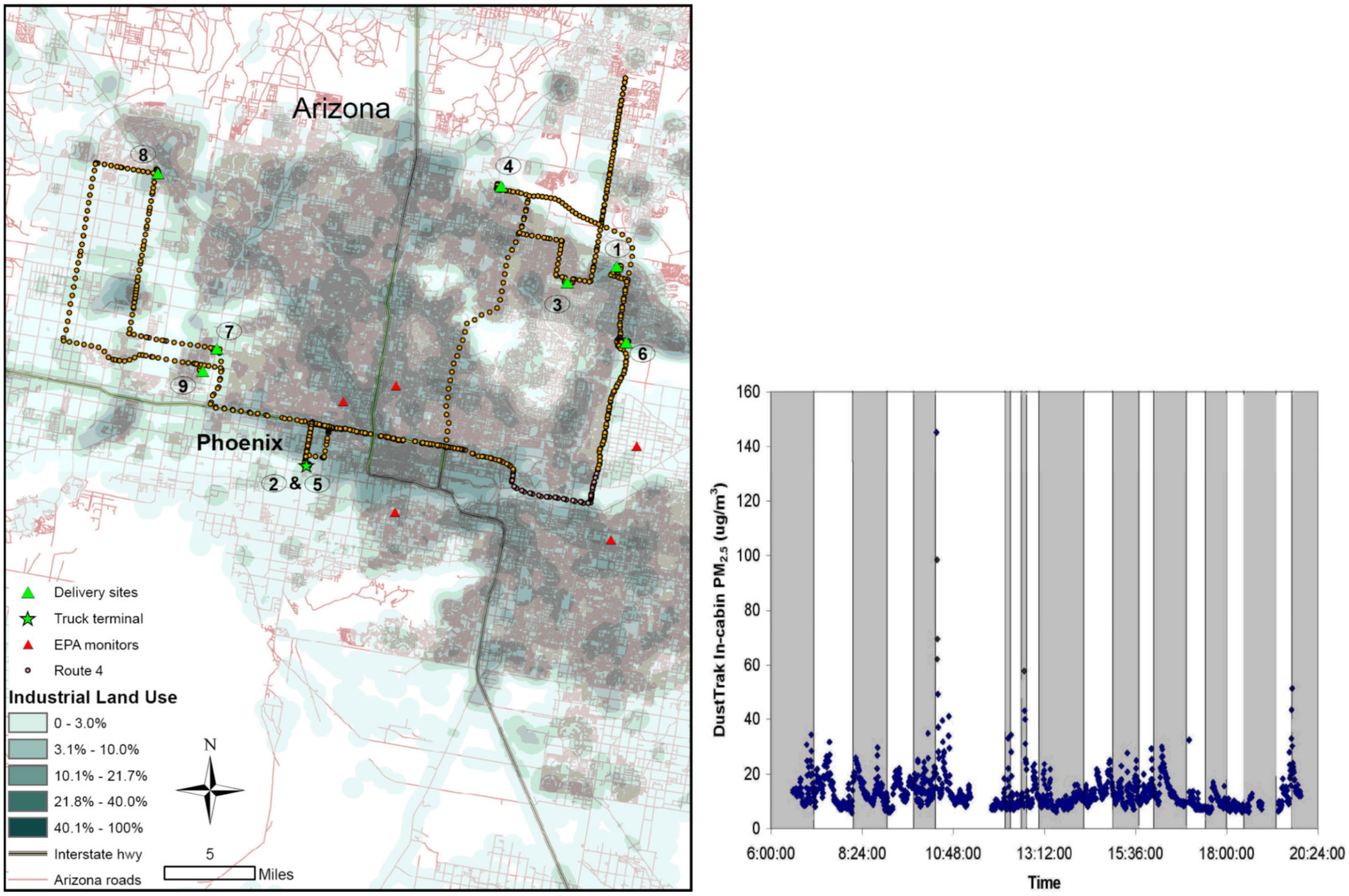

FIGURE 1.

GIS map of matched DustTrak $PM_{2.5}$ concentrations with GPS of a truck route in Phoenix, Ariz. (A); the terminal site and seven terminal or delivery sites in the order of visit are listed as gray areas in (B); the white columns represent the time periods when the driver was on the road.

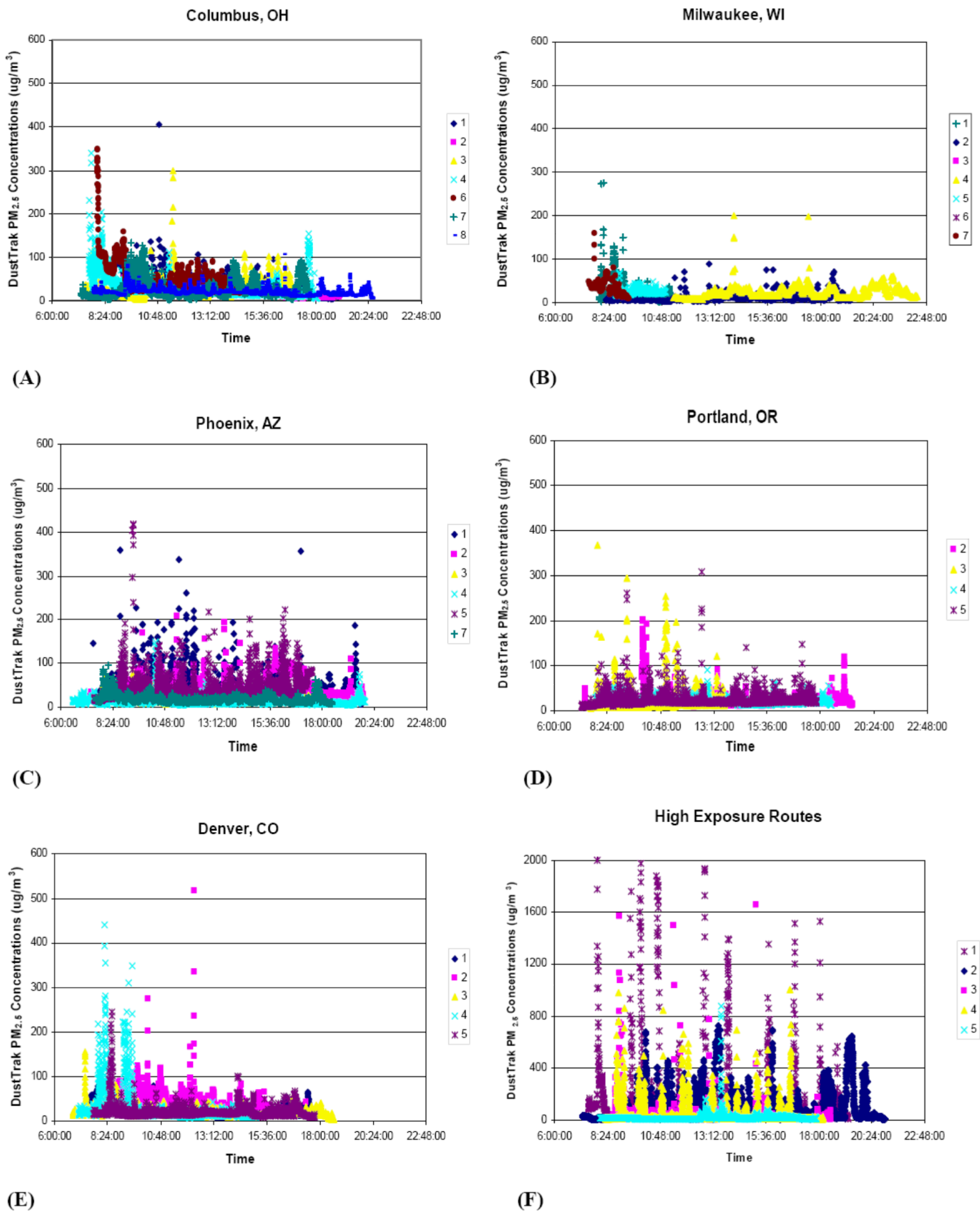

FIGURE 2.

Plots of real-time in-cabin $PM_{2.5}$ concentrations for low-exposure routes (maximum < 600 μg/m^3) in cities of (A) Columbus, Ohio, (B) Milwaukee, Wisc., (C) Phoenix, Ariz., (D) Portland, Ore., and (E) Denver, Colo. In (F), high-exposure routes – 1: 5th route in Columbus; 2: 6th route in Phoenix; 3: 1st route in Portland; 4: 6th route in Portland; 5: 6th route in Denver

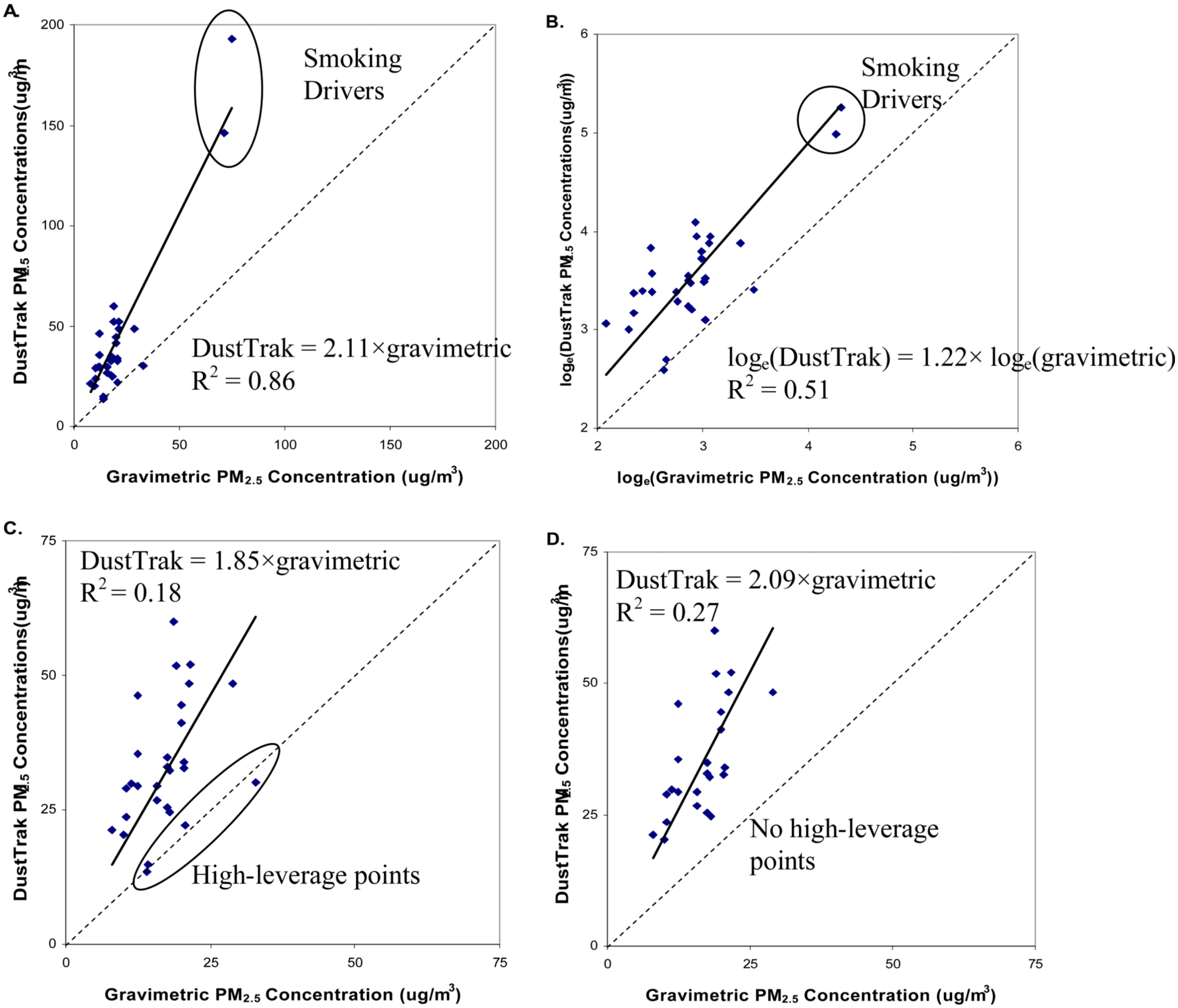

FIGURE 3.

Relationship between the mean of DustTrak and gravimetric $PM_{2.5}$ kconcentrations (A) all 30 pairs from five cities; (B) all 30 pairs that are log-transformed; (C) without the two high-concentration points from smoking drivers; and (D) without the four high-leverage points circled in (B). *Note:* The dotted line in all figures represents a 1:1 line, and equations are based on linear regressions with intercepts forced to zero, so R^2 values should be interpreted with caution.

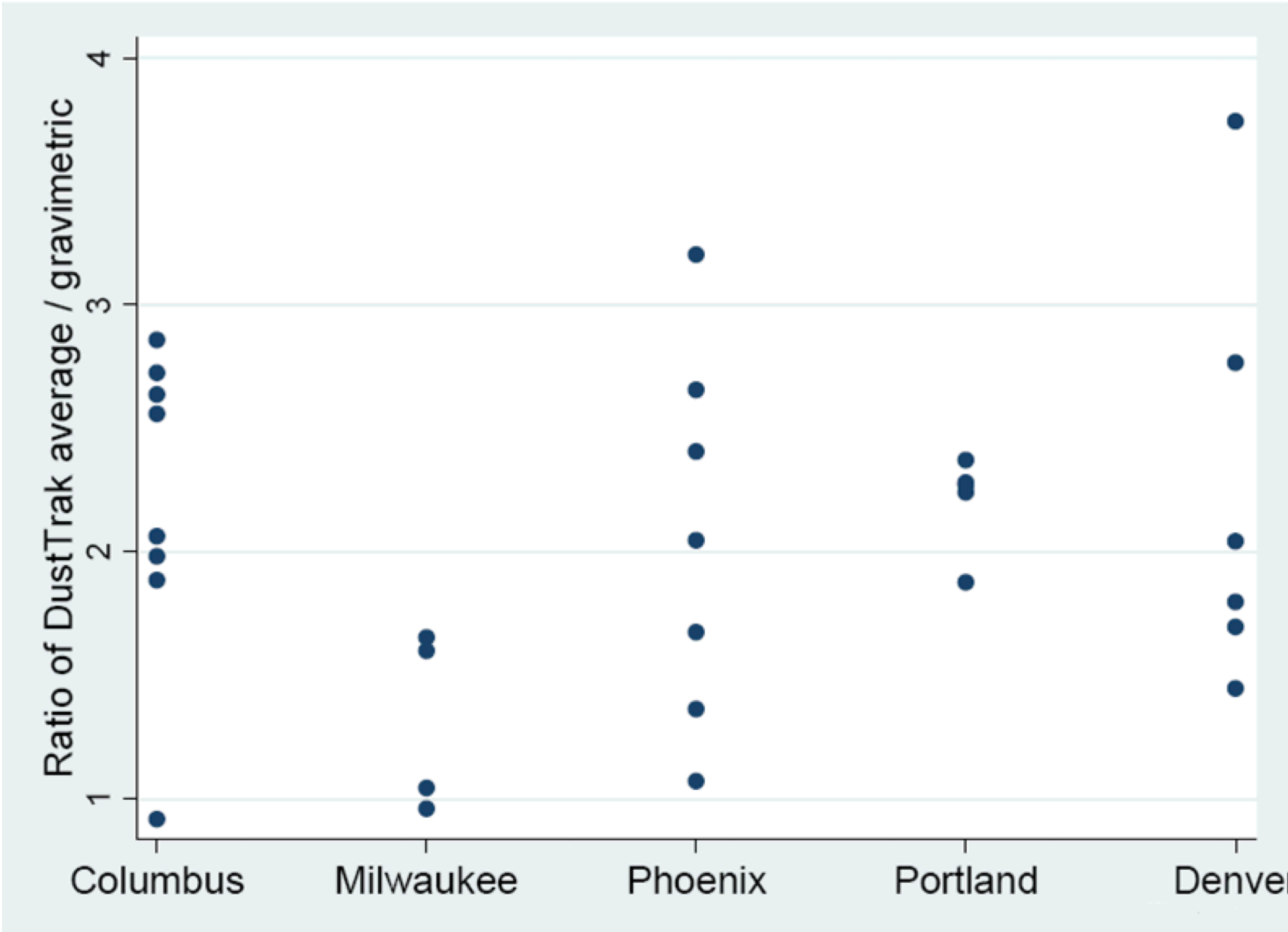

FIGURE 4.

Plot of ratio distribution between the averages of DustTrak readings and their corresponding gravimetric reading in each truck route (Columbus, Ohio (n=8), Milwaukee, Wisc. (n=4), Phoenix, Ariz. (n=7), Portland, Ore. (n=5), and Denver, Colo. (n=6))

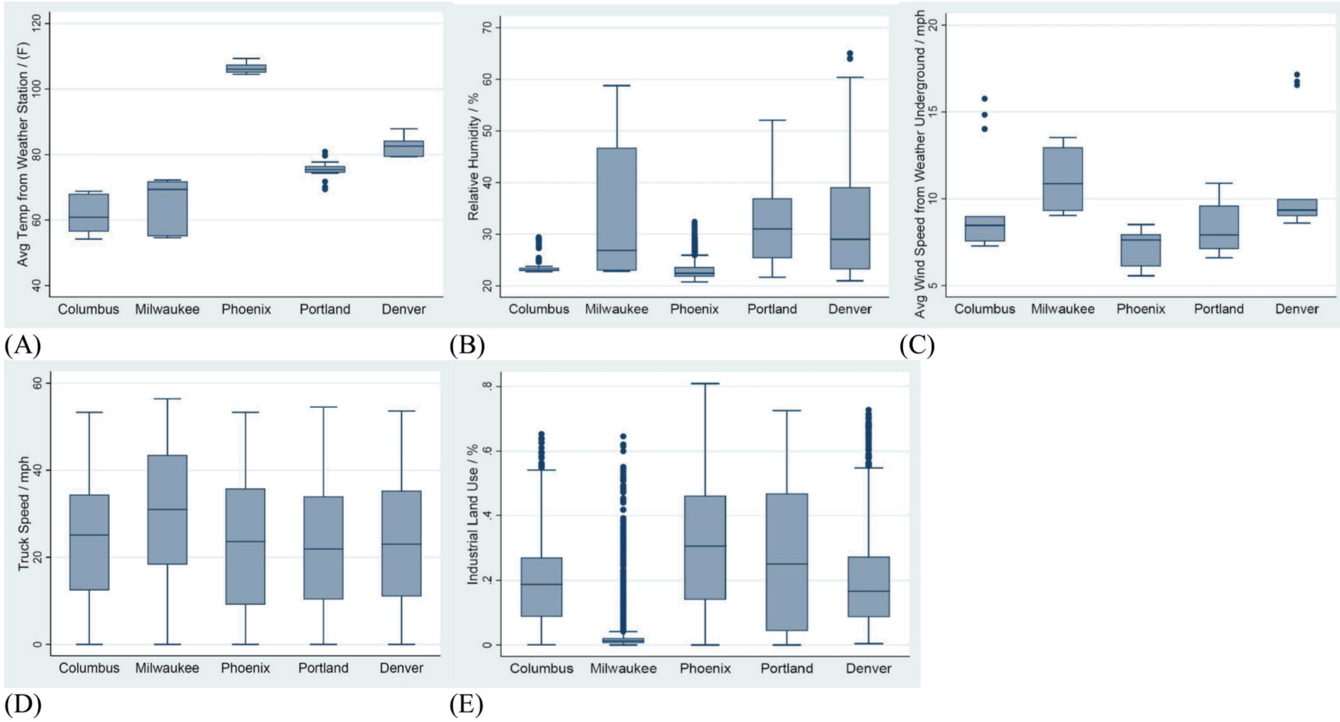

FIGURE 5.

Box plots of data distributions of (A) average outdoor temperature, (B) in-cabin relative humidity, (C) average wind speed, (D) truck speed, and (E) industrial land use percentage. Upper and lower quartiles (box); median, black line in box; 1.5 interquartile ranges (bar); and outliers (•)

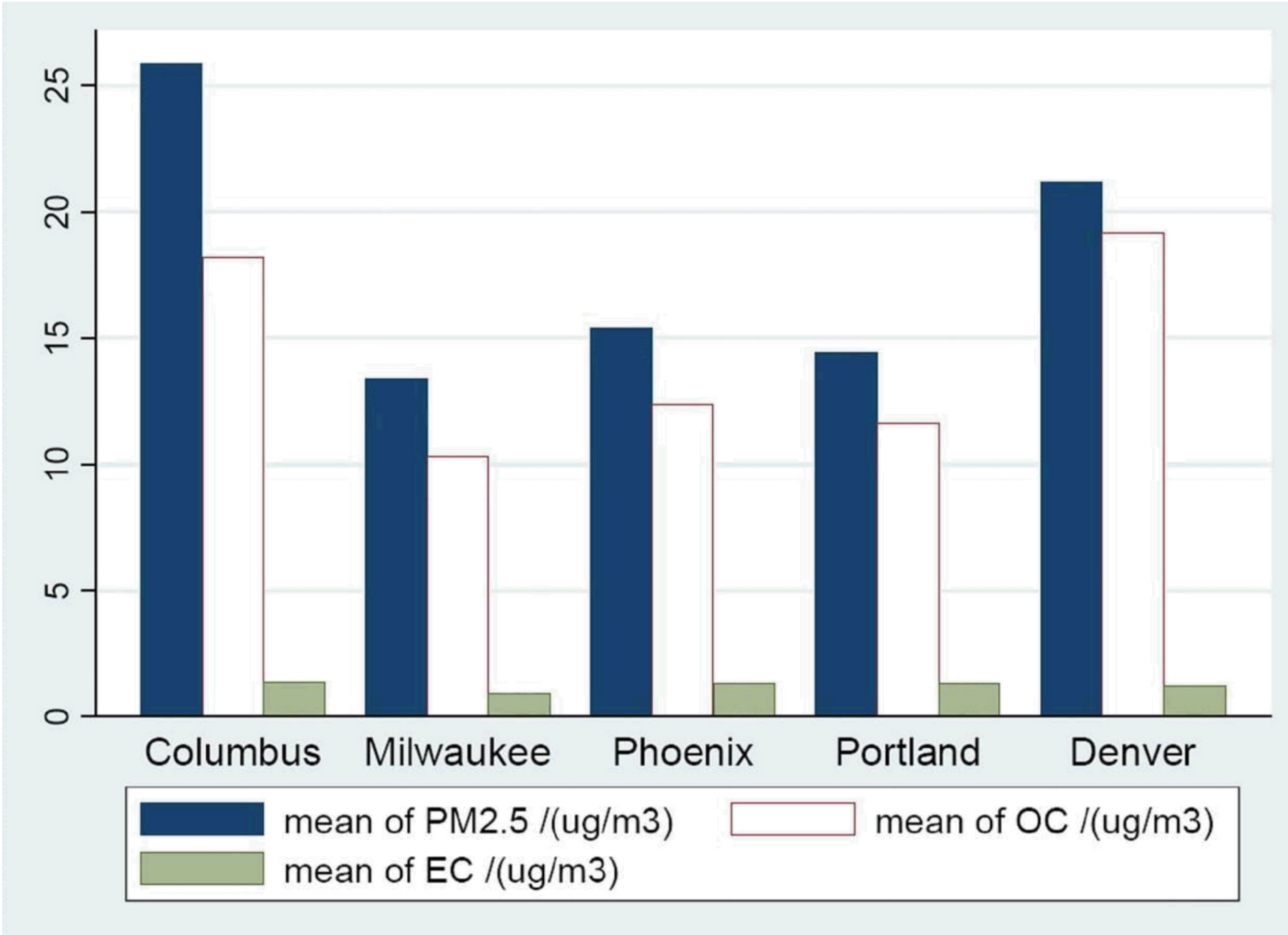

FIGURE 6.
Bar graph of mean concentrations of in-cabin $PM_{2.5}$, EC, and OC

TABLE I

Summary of Real-Time $PM_{2.5}$ Concentrations Measured by DustTrak for the Subset of Truck Routes with Matching GPS (n=21)

Cities	Truck Routes[A]	Number of measurements: On-Road	Number of measurements: Total	% On-Road	On-Road Mean Conc. of $PM_{2.5}$ (μg/m³)	Cities	Truck Routes	Number of Measurements: On-Road	Number of Measurements: Total	% On-Road	On-Road Mean Conc. of $PM_{2.5}$ (μg/m³)
Columbus, Ohio	3	184	798	23.1	31.6	Portland, Ore.	1[B]	383	980	39.1	23.3
	6	181	841	21.5	43.6		2	472	1455	32.4	17.0
Milwaukee, Wisc.	2	412	1344	30.7	10.3		4	288	1102	26.1	25.4
	3	155	861	18.0	18.3		5	304	1251	24.3	25.2
	6	464	1534	30.2	27.5		6[B,C]	320	1182	27.1	62.3
Phoenix, Ariz.	1	344	1396	24.6	27.9	Denver, Colo.	1	326	1501	21.7	50.8
	2	280	1290	21.7	59.9		2	251	1139	22.0	51.3
	3	408	1021	40.0	17.3		3	197	1415	13.9	17.9
	4	637	1471	43.3	11.6		4	246	993	24.8	26.1
	5	304	1170	26.0	57.3		6[B]	203	591	34.4	24.8
	6[B,C]	382	1240	30.8	19.6						

[A] Truck route numbers correspond to those in Figure 3.

[B] Routes with high particulate exposure peaks.

[C] Truck driver smoked.

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TABLE II

Summary of DustTrak and Gravimetric $PM_{2.5}$ Concentrations and Their Ratios for Each Pair (n=30)

	DustTrak (μg/m^3)	**Gravimetric Sampler (μg/m^3)**	$\frac{\textit{DustTrak}}{\textit{Gravimetric}}$ **Ratios**
Arithmetic mean[A]	42.4 (36.8)	20.9 (15.2)	2.03 (0.67)
Geometric mean[B]	35.1 (1.74)	18.0 (1.64)	1.95 (1.42)
Median	32.5	17.8	2.04
Range	13.4–192.6	8.0–75.3	0.92–3.74

[A]Standard deviation shown in parentheses.

[B]Geometric standard deviation shown in parentheses.