PERSONAL EXPOSURE TO AIR POLLUTION IN THE VICINITY OF U.S.-MEXICO BORDER CROSSINGS

October 2021

CARTEEH

Center for Advancing Research in
Transportation Emissions, Energy, and Health
A USDOT University Transportation Center

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Personal Exposure to Air Pollution in the Vicinity of U.S.-Mexico Border Crossings		5. Report Date October 2021
		6. Performing Organization Code
7. Author(s) Suriya Vallamsundar, Inyang Uwak, Tara Ramani, Rohit Jaikumar, Natalie M. Johnson, Amber Trueblood, Juan Aguilera, Ivan Ramirez, Leah Whigham, and Wen-Whai Li		8. Performing Organization Report No. 01-03-TTI
9. Performing Organization Name and Address: CARTEEH UTC Texas A&M Transportation Institute The Texas A&M University System 1111 RELLIS Parkway, Bryan, TX 77807		10. Work Unit No.
		11. Contract or Grant No. 69A3551747128
12. Sponsoring Agency Name and Address Office of the Secretary of Transportation (OST) U.S. Department of Transportation (USDOT)		13. Type of Report and Period Final May 2017–December 2019
		14. Sponsoring Agency Code

15. Supplementary Notes

This project was funded by the Center for Advancing Research in Transportation Emissions, Energy, and Health University Transportation Center, a grant from the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology, University Transportation Centers Program.

16. Abstract

This study focused on evaluating pollutant exposures in border crossing regions. Specifically, the study focused on particulate matter ($PM_{2.5}$) exposure data collected from a group of schoolteachers in the El Paso region in Texas. The region is a gateway for freight movement between the United States and Mexico. A pool of teachers working at a school close to the border crossing area carried a backpack equipped with an air quality monitoring device and a portable global positioning system tracking device. A spatiotemporal exposure assessment was conducted to assess exposure in different microenvironments visited, with findings showing higher mean concentrations at school than either during commuting or at home. Personal monitoring results were also found to be higher by an average of 81 percent than readings from a regulatory monitor and a monitor placed outside the school. These findings highlight a need to expand the coverage and capabilities of current air quality monitoring networks in the region and to improve the indoor air quality in schools using targeted abatement techniques.

17. Key Words	18. Distribution Statement
Exposure assessment, geospatial analysis, hot spots, personal monitoring, traffic-related air pollution, ambient monitoring, particulate matter, polycyclic aromatic hydrocarbons, border crossings	No restrictions. This document is available to the public through the CARTEEH UTC website. http://carteeh.org

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	31	$0.00

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Executive Summary

Traffic exhaust is a major source of air pollution in urban areas. Epidemiological studies have documented adverse respiratory and cardiovascular effects for populations living within the near-roadway environment. Exposure to emissions depends on the location/time of exposure and pollutant concentrations in different microenvironments (e.g., indoor, outdoor, and during commute). Generally, epidemiological studies estimate exposure levels based on data from ambient monitors and census information. Due to the spatial movement of individuals, using ambient monitoring data leads to a possible exposure misclassification between what people are truly exposed to and what is measured at the ambient monitoring stations, which in turn affects risk estimates. This limitation can be overcome by employing personal exposure monitoring and using emerging technologies, such as smartphones and portable global positioning system (GPS) devices, to track people's activity patterns. The dynamic location information provided by these technologies can be leveraged for better estimation of exposure levels.

This study focused on the evaluation of personal and ambient monitoring of particulate matter (PM) in the El Paso area in Texas. El Paso is a gateway for freight movement between the United States and Mexico. Air quality is one of the primary health concerns for people living and working in this region. The region is negatively affected by the high number of diesel trucks, including older, poorly maintained drayage trucks; long waiting times as part of the border crossing process; meteorological conditions; and topography. As a first step, researchers conducted a geospatial analysis to identify locations in El Paso affected by emissions from traffic attributable to border crossings. Next, researchers recruited a group of schoolteachers working in a school located in an affected area close to the border to characterize their emissions exposure. A pool of participants carried backpacks equipped with air quality monitoring devices, a portable GPS tracking device, and monitors to measure temperature and humidity during a 24-hour period. In addition to personal monitoring, ambient monitors were placed at key locations around the school. A spatiotemporal exposure assessment was conducted by pairing the GPS readings with the questionnaire data obtained from the participants related to different microenvironments. The mean $PM_{2.5}$ concentration at school was 19.29 µg/m^3 ± 15.66 µg/m^3; at home it was 11.17 µg/m^3 ± 10.63 µg/m^3; and during commute it was 11.66 µg/m^3 ± 10.64 µg/m^3. Mean $PM_{2.5}$ concentrations above the National Ambient Air Quality Standards for $PM_{2.5}$ at 35 µg/m^3 (24-hour averaging period) were observed at two participants' homes located downwind within a distance of 90 m (under 300 ft) from the border highway and at the school, which was located along a major arterial. Personal monitoring results were found to be higher by an average factor of 1.8 (higher for an average of 81 percent of the sampling days) compared to the stationary ambient data measured at a regulatory monitor and a monitor placed outside the school. These findings highlight a need to expand the coverage and capabilities of current air quality monitoring networks in the region and to improve the indoor air quality in schools using targeted abatement techniques.

Acknowledgments

The research team gratefully acknowledges the assistance of the El Paso Independent School District Board for approving this study and the schoolteachers and officials who participated and supported the data collection exercise in their school. The authors would like to thank Dr. Kirsten Koehler from the Johns Hopkins Bloomberg School of Public Health for her expert input on the study design and for lending some of the equipment used in the study.

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Background and Introduction

The U.S.-Mexico border region is a dynamic region with a bustling population, large amounts of cross-border traffic, and complex terrain and meteorology. The border is nearly 2,000 mi long and has many densely populated binational urban areas located near border crossings. Air quality is a major concern in the region, especially due to congested border crossings, where large volumes of heavy-duty vehicles and long durations of idling time are a significant source of emissions. El Paso, Texas, is among the largest U.S.-Mexico ports of entry, with one of the highest volumes of truck crossings. The pollutants of particular concern in El Paso include particulate matter (PM) and ozone (a secondary pollutant formed when precursor pollutants engaged in a nitrogen dioxide photolysis cycle [volatile organic compounds and nitrogen oxides—both released from motor vehicles] react with the presence of sunlight). El Paso is currently designated as a nonattainment area for PM_{10} based on the National Ambient Air Quality Standards (NAAQS), and the region has had many episodic high PM events. The current ozone design value (i.e., the official ambient concentration statistic used for regulatory purposes such as designation of nonattainment status) for El Paso is very close to the current ozone NAAQS of 0.070 parts per million (ppm). The region's air quality issues are exacerbated by the complex terrain and frequently occurring adverse meteorological conditions, with pollutants being trapped near ground level, thereby increasing their concentrations and people's exposure. In addition, the region experiences an average of 14.5 dust storms per year that cause regional haze, reduced visibility during driving, increased PM concentration, and respiratory health effects (Novlan et al., 2007).

Epidemiological studies have found a strong association between these pollutants and an array of health effects, especially in vulnerable population subgroups such as children, pregnant women, and elderly persons who live or work in areas where high volumes of vehicular movement exist (Samet et al., 2009). These pollutants are associated with various adverse health effects, like chronic obstructive pulmonary disease, atherosclerosis, and ischemic heart disease. Mechanistic research has shown that traffic-related air pollution exposure can cause such diseases through various pathways, including oxidative stress (Kelly & Fussell, 2015). Emerging evidence suggests these pollutants can alter pathways responsible for the control of adipose tissue and affect glucose metabolism (Rao et al., 2015; Wellen & Hotamisligil, 2003). In El Paso, it is estimated that 60 percent of lifetime cancer risk is attributable to on-road sources (Collins et al., 2011). Further, a study in El Paso found Hispanics were more sensitive to $PM_{2.5}$ than other ethnic groups (Grineski et al., 2015). Schools located near areas with high air pollution have been associated with lower attendance and a higher proportion of students failing to meet state educational testing standards (Mohai et al., 2011). One study (Olvera et al., 2013) that focused on the International Bridge of the Americas in El Paso found the buffer area of 400 m around border crossings to be associated with increased levels of ultrafine PM concentration. The effects of prolonged exposure warrant a better understanding of the extent of highways' contribution to air quality on near-road neighborhoods. A report (U.S. Environmental Protection Agency [EPA], 2012) on health impacts of border crossings identified a critical need to recognize health issues related to the U.S.-Mexico border crossings. It was noted that the measurement of traffic pollution exposures for people who live or work in neighborhoods near border crossing locations is a key need. It is theorized that this population and these locations face even more adverse impacts than other areas in the region and will benefit greatly from interventions and mitigation strategies aimed at reducing exposures and improving public health.

Key factors affecting an individual's exposure to air pollution are the time and duration of exposure, location relative to the emission source, and microenvironments (MEs) (i.e., locations such as indoors at home and work, outdoors, traveling in different modes, etc.). Most of the border health impact studies (e.g., Brauer et al., 2002; Levy et al., 2010), however, have assessed exposure levels on a regional scale using ambient monitoring stations rather than border crossing MEs, except for a few studies (e.g., Galaviz et al., 2014) that focused on personal monitoring. These ambient monitors provide an overall estimate of the ambient concentrations and may be unable to capture the true exposure experienced by people. Previous studies in the Paso del Norte region (encompassing El Paso, Texas, and Juárez, Mexico) indicated that the concentration of traffic emissions may vary considerably across the region depending on the location of sources, atmospheric mixing height, meteorological conditions, and topographic characteristics of the terrain (Jeon et al., 2001; Noble et al., 2003). However, the intraurban gradient of traffic emissions has not been studied across much of metropolitan El Paso because the air quality monitoring stations operated by state and local environmental agencies are located mainly in central El Paso, with fewer stations located in more distant residential areas. Given the spatial distribution of major highways, the location of the international border crossings, and the complex river valley terrain of Paso del Norte, it is unlikely that data from existing air quality monitors are enough to characterize the gradient of exposures across the city.

Personal monitoring provides a wealth of information on the short-term exposures specific to individuals. Personal monitoring devices accurately track exposure levels in different MEs, and when combined with portable global positioning systems (GPSs), they can partition exposure according to different locations (or MEs) visited. This study focused on the evaluation of personal exposure levels to $PM_{2.5}$ (particulate matter with a diameter of less than 2.5 µm) experienced by a group of people living and working near the border crossing in the El Paso area. Data collected from the personal monitoring devices were also compared with the regional air quality levels measured by ambient monitors. This pilot study evaluated the exposure to traffic-related air pollution experienced by vulnerable population groups near the border crossing.

The study was conducted in two phases. The first was a geospatial analysis to identify neighborhoods within the border crossing region that have increased exposure to air pollution, specifically from roadways. Geographic information systems (GISs) and spatial analysis have increasingly been used to evaluate associations between health outcomes and spatially distributed environmental attributes (Musa et al., 2013). Data integration was performed with demographic, traffic, and emission data to identify the most exposed neighborhood due to border crossing activities. Statistical methods were applied to evaluate the probability of living in this neighborhood and determine the resulting demographics of the population group. Based on results from Phase One, a personal exposure assessment study was designed in the second phase to evaluate $PM_{2.5}$ exposure levels for a population group living or working within a high-exposure neighborhood. A pool of schoolteachers working at a nearby school (El Paso High School) were recruited. Participants were given a backpack equipped with air sampling devices, devices to measure the temperature and humidity, and GPS units to track their locations. Exposure data obtained from personal monitors were compared with two ambient monitoring stations, one placed outside the school and the other located close to the study region. Figure 1 shows a graphical representation of the study.

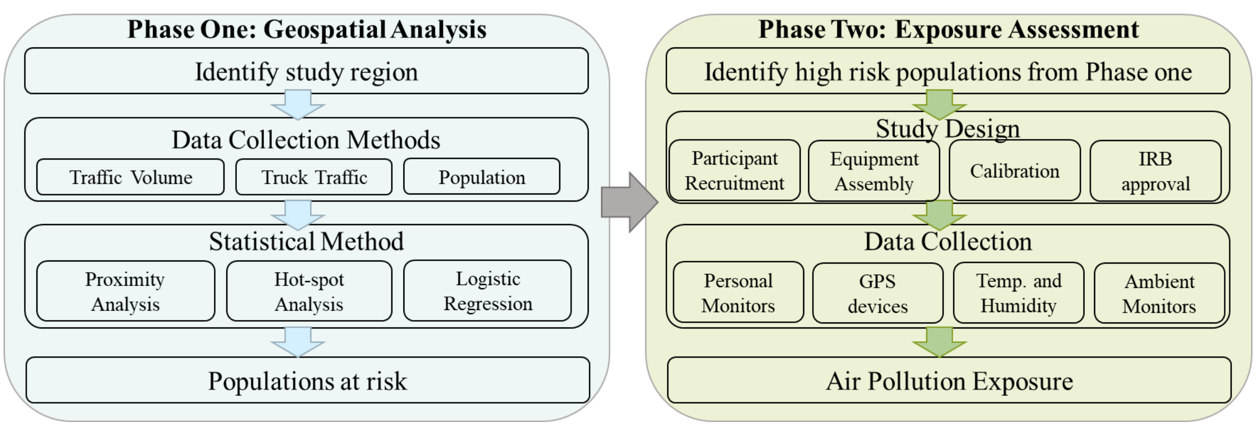


Figure 1. Study overview.

Methods

Study Location

El Paso, Texas (population 685,000), is located in the high-altitude, northern Chihuahuan desert and is separated from Ciudad Juarez, Chihuahua, Mexico (population 1.5 million), by the Rio Grande River. Table 1 lists the demographics of the El Paso region. The combination of meteorological and geographic features in the region strongly influences the mixing and dispersion of air pollutants emitted from sources in the El Paso area (MacDonald et al., 2001). The El Paso region has some of the busiest border crossings in the country. The border crossing at the Bridge of the Americas (BOTA) and the Ysleta-Zaragoza International Bridge handle both commercial and passenger vehicle traffic. Annually, more than 16 million private passenger vehicles and nearly 1 million freight carriers enter the United States via border crossing bridges in El Paso. Most of these trucks are old and poorly maintained and produce comparatively higher emissions. Trucks remain idling in queues for an average of 40 minutes as they wait for border crossing inspection (Jaikumar et al., 2019). Stable meteorological conditions during the winter, combined with the complex local terrain, significantly limit the mixing and dilution of air pollutants within the region, thereby resulting in exceedances of air quality levels on both sides of the border (Lauer et al., 2009).

Table 1. Demographic Variables for El Paso

Demographic Variable	Mean (Range)
Age	
Percent Aged 5 and Under	7.22 (0–29.17)
Percent Aged 6 to 9	6.96 (0–25.07)
Percent Aged 10 to 14	7.43 (0–19.49)
Percent Aged 15 to 17	4.58 (0–18.24)
Percent Aged 18 to 24	11.40 (0–65.49)
Percent Aged 25 to 34	13.16 (0–43.33)
Percent Aged 35 to 44	11.63 (0–32.24)
Percent Aged 45 to 54	12.65 (0–36.28)
Percent Aged 55 to 64	11.19 (0–35.76)
Percent Aged 65 or Older	13.80 (0–56.67)
Gender	
Male	48.39 (25.36–100)
Female	51.61 (7.01–74.64)
Hispanic or Latino	
Percent Hispanic or Latino (of the white population)	83.09 (15.87–100)
Race/Ethnicity	
Percent White	83.50 (0–100)
Percent Black	3.05 (0–42.81)
Percent American Indian	0.56 (0–18.61)
Percent Asian	0.93 (0–21.09)
Percent Native Hawaiian	0.12 (0–8.34)
Education	
Percent High School Diploma or GED	24.85 (0–52.63)
Percent Some College No Degree	21.99 (0–59.97)
Percent Associate Degree	6.70 (0–22.58)
Percent Bachelor's Degree	12.99 (0–44.93)
Percent Master's Degree and Higher	5.82 (0–35.29)
Employment Status	
Percent Labor Force	58.63 (0–96.46)
Percent Not in Labor Force	41.37 (3.54–100)

Study Population

Personal exposure assessment was conducted on a pool of schoolteachers who taught at and resided close to a school in a high-exposure neighborhood. The school is located about 1 km (0.62 mi) from a major freeway (I-10) and 4 km (2.48 mi) from the BOTA border crossing. The school is surrounded by a higher percentage of residential and commercial establishments than other neighborhoods in the border crossing region. Sixteen nonsmoking, healthy teachers in El Paso High School with no history of cardiopulmonary disease were initially enrolled in this study, though only 10 completed the study. Participants completed written informed consent forms before the study commenced and completed a questionnaire at the end of the study. The questionnaire included demographic information (e.g., age, sex), smoking history, and commute information. The teachers received backpacks containing air monitoring and other equipment. This study was reviewed and approved by the Texas A&M University Institutional Review Board (IRB; No. IRB2018-0209D) and the El Paso Independent School District (ISD) External Research Board. Participants' personal information was anonymized according to IRB protocols. The characteristics of the study population are listed in Table 2, and the study location is shown in Figure 2.

Table 2. Participant Demographics and Details

Parameter	Number
Age	
< 35	2 (20%)
> 35	6 (60%)
Unknown	2 (20%)
Sex	
Male	4 (40%)
Female	6 (60%)
Residential Heating Source	
Gas	1 (10%)
Central	7 (70%)
Fireplace	0
Unknown	2 (20%)
Commute Mode	
Personal vehicle	8 (80%)
Public transportation	0
Unknown	2 (20%)

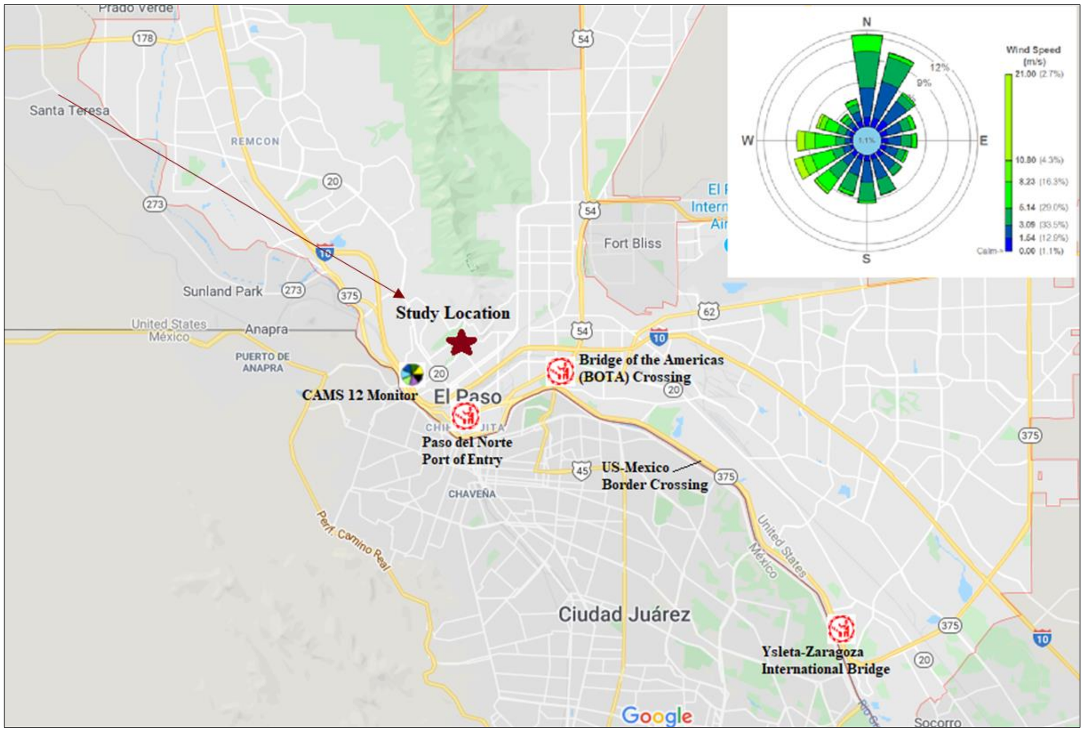


Figure 2. Study location.

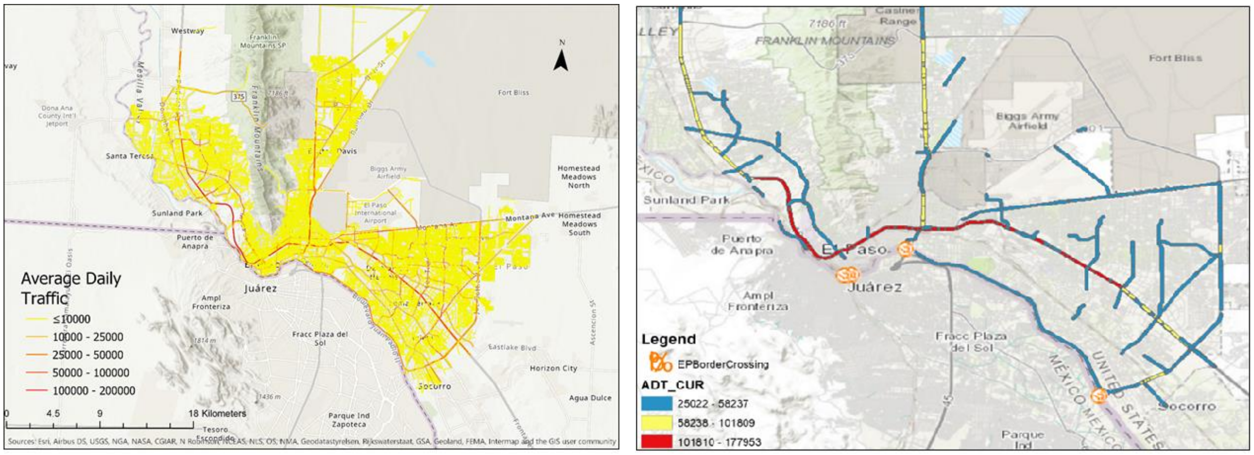
Data Collection

Geospatial Analysis

For the geospatial analysis, the following sets of data were utilized:

- Average daily traffic (ADT) was obtained from the Road-Highway Inventory Network (Rhino) database of highway performance-monitoring system road networks included in the 2010 National Transportation Atlas Database (Bureau of Transportation Statistics, n.d.). The network consists of the entire U.S. highway network and includes freeways, highways, and major and minor arterials.
- Truck traffic was obtained from the Texas Department of Transportation (TxDOT, n.d.) Statewide Traffic Analysis and Reporting System.
- Population information was obtained from 2010 U.S. Census data (U.S. Census Bureau, n.d.).

The Rhino database for El Paso is vast, with over 8,798 links covering 2,391 mi of road network, including all the local streets (Figure 3). Due to the expansive nature of the study area, roadways were classified into five categories based on ADT: (a) ≤ 10,000, (b) 10,000 to 25,000, (c) 25,000 to 50,000, (d) 50,000 to 100,000, and (e) ≥ 100,000 (see Figure 3). The high-volume roadways (≥ 100,000 ADT) were overlaid on top of truck traffic to evaluate if these roadways carried high volumes of truck traffic. The high-volume traffic routes coincided with the high-volume truck routes and corresponded mostly to limited-access divided highways and multilane urban arterials. The census block dataset was filtered to correspond to the El Paso region. The resulting dataset had a total of 513 blocks. Income information was available at the block group level. To address the mismatch, all individual blocks in each block group were assigned the block group median household income.



(a) (b)

Figure 3. Traffic routes within the El Paso region: (a) all roadways, and (b) high-volume roadways.

Personal Exposure Assessment

The participants received lightweight backpacks containing air monitoring devices and pre-cleaned silicone wristbands to be worn on their wrists for 24 hours during the sampling period to capture both air and dermal exposures. The exposure monitoring devices included a sampling pump that collected the air in the participants' breathing zone and sent it to the personal monitor DataRAM, which measured the $PM_{2.5}$, and to a GPS receiver (BT1000XT, Quartz international, Taiwan) that tracked the participants' location. The DataRAM PDR-1200 (Thermo Scientific Corp., Waltham, Massachusetts) device is a light-scattering single-beam nephelometer equipped to measure the mass concentrations of PM with an aerodynamic diameter of 2.5 µm or less in real time. The device was paired with an OMNI pump calibrated at a flow rate of 5 L/min. To measure polycyclic aromatic hydrocarbon (PAH) concentrations, a second line from the pump was used to draw air through a 2 µm pore size, 37 mm polytetrafluoroethylene (PTFE) filter (Pall Corporation, Ann Arbor, Michigan) and then through an XAD-2 sorbent tube (SKC, Inc., Eighty Four, Pennsylvania) at a flow rate of 1 L/min−1. Post-sampling, the raw black carbon data were processed using the optimized noise-reducing algorithm (ONA) developed by U.S. EPA (2017). This algorithm eliminates negative values and accounts for various environmental conditions without affecting the validity of the data. Participants were asked to place the backpack at breathing level while sleeping, driving, or sitting and instructed to wear the wristband throughout normal daily activities. The ambient level of $PM_{2.5}$ was collected continuously during the study using a GRIMM portable laser aerosol spectrometer and dust monitors.

Wristband Pre-cleaning and Post-deployment Extraction

Pre-cleaning and post-deployment extraction of wristbands were conducted based on methods described in O'Connell et al. (2014). Briefly, wristbands were pre-cleaned using 1:1 (v:v) ethyl acetate and hexane for three washes, followed by 1:1 (v:v) ethyl acetate and methanol for two washes over a total duration of 12.5 hours. Subsequently, the wristbands were dried under nitrogen and stored in airtight PTFE bags at 4°C until deployment. Post-deployment, wristbands were first rinsed with deionized water to remove surface debris and then rinsed with isopropanol to remove residual water. The wristbands were extracted with 100 mL ethyl acetate and ultrasonicated for 2 hours. Individual bands were transferred to a new vial and the process repeated. The two fractions were combined and reduced to 1 mL using a TurboVap LV evaporator with high purity nitrogen (99.99 percent) (Zymark Center, Hopkinton, Massachusetts). Samples were loaded on a multilayer chromatography column to eliminate lipids from the skin or personal care products. The cleanup column was dry-packed with glass wool and 1 percent deactivated alumina, which was preconditioned with hexane. Samples were eluted with ethyl acetate and reduced to 1 mL. Samples were spiked with 100 uL of PAH internal standard and transferred to amber GC vials for analysis.

Filter Extraction

Filters were individually placed into 60 mL vials, and 20 mL of dichloromethane was added, enough to cover the filters. A 100 uL of PAH surrogate was added to the samples. Vials were capped and sonicated for 30 minutes. The extraction process was repeated, and both extracts were combined. The filter was then removed with forceps, and the extracts were concentrated to 1 mL under nitrogen, then spiked with 100 uL of PAH internal standard.

Data Analysis

Geospatial Analysis

Using GIS and statistical methods (a combination of proximity analysis, hot-spot analysis, and logistic regression), the clusters of neighborhoods exposed to high levels of air pollution were identified. Proximity analysis is a GIS-based method to determine the relationship between two datasets based on the features in them. Proximity analysis was used in the study to compute the traffic density for each of the census blocks of El Paso. As a first step, high-volume roadways based on traffic volume and truck traffic for the study area were identified. Next, buffers of 250 m were established around these high-volume roadways because vehicular emissions have a peaking tendency close to the roadways within a distance of 0–250 m (Askariyeh et al., 2018). These buffers were intersected with the census blocks within the study domain. Based on the intersected buffers, traffic volume, and corresponding area of the census blocks, the traffic densities for all census blocks were determined. Following proximity analysis, the hot-spot analysis was conducted to evaluate the statistical significance of different census blocks. This spatial technique is used for clustering and classifies clusters into statistically significant high and low clusters based on the assessment of a feature of interest (e.g., traffic density in this case) with surrounding features. The technique based its calculations on Getis-Ord Gi*[3] statistics calculated for every feature in the dataset and was applied to the census blocks with traffic density values from the proximity analysis. The calculation produced a *z*-score and *p*-value that enabled identifying statistically significant spatial clustering. Based on this analysis, each census block was assigned a hot spot or cold spot with a measured statistical significance. While hot spots were statistically affected neighborhoods with high traffic density, cold-spot locations were not statistically significant for traffic density. The results from the hot-spot analysis were used in a logistic regression to identify the important demographic variables contributing significantly to a location (or census block) being classified as a hot spot. Logistic regression describes the relationship between exposure to multiple demographic variables using the odds ratio (OR) statistic. Univariate analyses were run for each variable. All variables with $p < 0.25$ were included in developing the final model. Variables with the highest *p*-values were removed individually from the final model until all variables were significant at $p < 0.05$ using a process of backward elimination.

Personal Exposure Assessment

For the personal exposure data, $PM_{2.5}$ and the location were tracked at a 10-second resolution, and the temperature and humidity were tracked at a 30-minute resolution. The location tracked by the GPS devices was combined with the questionnaire filled out by the participants to identify the different MEs visited. Three MEs were considered in the study: home, school, and commute. Based on the completed questionnaires, the participants did not visit any outdoor locations except for the school. Based on the speed information extracted from the GPS devices, participants were assumed to be commuting if their average speed was above 4 mph (Levy Zamora et al., 2018). All participants reported they commuted using a personal vehicle. For each ME, the average and maximum concentrations, contribution to total overall concentration, and exposure intensity were calculated in each ME. Time-weighted average exposure or exposure intensity (Levy Zamora et al., 2018) was calculated by dividing the concentration in each ME normalized by total concentration with time spent in each ME by the total time spent carrying the backpack, as shown in Equation (1).

$$Exposure\ Intensity_{ME} = \frac{\frac{Concentration_{ME}}{Total\ Concentration}}{\frac{Time\ Spent_{ME}}{Total\ time}} \qquad (1)$$

The ratio if greater than 1 implies that the ME contributed more to the participant's overall exposure in comparison to the time spent. Temporal and spatial maps were developed to evaluate the locations and periods of peak concentrations and diurnal trends in the concentration data. In addition to the personal monitoring data, ambient data from the closest monitor to the study location were utilized. Concurrent ambient data matching the sampling days were extracted. All the analyses were completed using Strava and powerBI.

Filter and Wristband Sample Analysis

Samples were analyzed for 25 PAHs using a Hewlett-Packard 6890 gas chromatograph coupled to a Hewlett-Packard 5973 mass spectrometer following methods described by Bera et al. (2019). Sample extracts were spiked with internal standards (d_{10}-fluorene and d_{12}-Benzo[a]pyrene) injected in splitless mode into a 30 m x 0.25 mm i.d. (0.5 µm) Agilent DB-5ms-fused silica capillary column. The inlet was operated at a constant temperature of 300°C. The oven temperature was initially at 60°C, ramped up to 150°C at 12°C/min post-injection, then increased to 220°C at 5°C/min, and finally set to 300°C at 10°C/min and held for 10 minutes. Helium was used as the carrier gas at a constant flow rate of 2.5 mL/min, and the transfer line and ion source temperatures were 280°C and 230°C, respectively. A solvent delay of 5 minutes was used to allow for elution of the hexane solvent peak prior to detection. The target compounds were quantified using their relative response factors to the appropriate surrogate standards (d_{10}-naphthalene, d_{10}- acenaphthene, d_{10}-phenanthrene, and d_{12}-chrysene), which were calculated using a 5-point calibration analyzed at the beginning of each sequence. Recovery was calculated as the percent difference between the concentration of surrogates injected on the GC/MS and the expected concentration based on the surrogate spike volume and concentration.

Concentrations of PAHs were reported as ng/wristband in the wristbands and ng/filter in the filters. To compare the concentration of PAHs detected from the wristbands with those from the filters, a Spearman correlation analysis was conducted. This method was used because the PAH concentrations were not normally distributed. An r_s coefficient of 0.20–0.39 was considered weak, 0.40–0.59 was moderate, 0.60–0.79 was strong, and >/= 0.81 was very strong (Mukaka, 2012). A *p*-value of < 0.05 was considered statistically significant. Statistical analyses were performed using GraphPad Prism version 8.

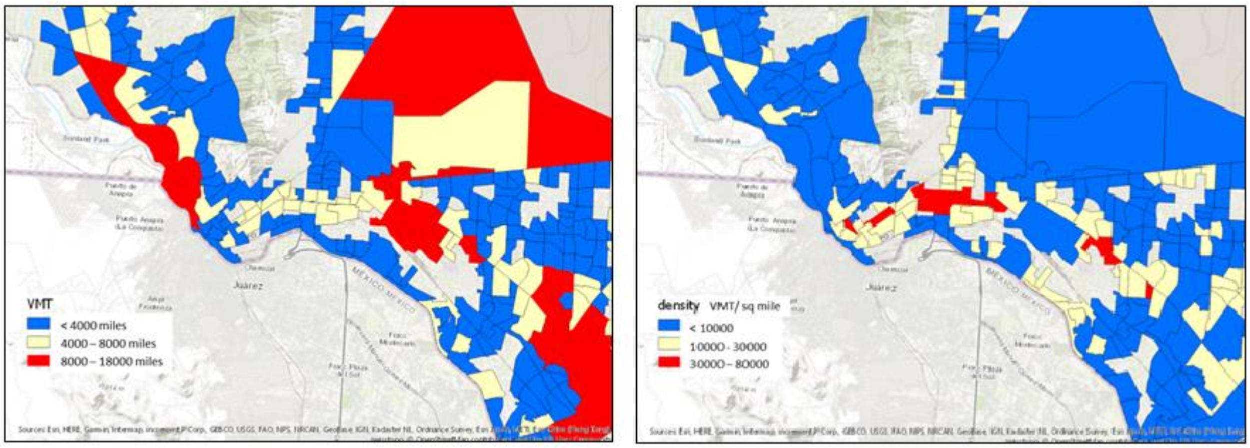
Source Identification

PAH source identification was conducted using diagnostic ratios (Zhang et al., 2008). The sum of all the low molecular weight PAHs was compared to the sum of all the high molecular weight PAHs (∑LMW/∑HMW). A ratio greater than 1 indicated that the PAHs were of a petrogenic source or from petroleum products, and a ratio less than 1 indicated that the PAHs were of a pyrogenic or combustion source. Similarly, the ratio of the concentration of fluoranthene and the sum of fluoranthene and phenanthrene (FLA/FLA+PY) was used to identify the source of the PAHs (De La Torre-Roche et al., 2009). A ratio less than 0.1 indicated a petrogenic source, and a ratio greater than 0.1 indicated a pyrogenic source. Last, to determine if the source was from traffic emissions, the ratio of benzo [a]pyrene to benzo[ghi]pyrene (BaP/BghiP) was calculated. A ratio less than 0.6 indicated a nontraffic source, while a ratio greater than 0.6 indicated the source was predominantly from traffic emissions (Katsoyiannis et al., 2007).

Results and Discussion

Geospatial Analysis

Figure 4 shows the spatial variability of vehicle miles traveled (VMT) and traffic density across different census blocks of El Paso. The blocks close to the freeways and border crossings were associated with both higher VMT and traffic density. The results from the hot-spot analysis are shown in Figure 5. The major hot spots, with a 99 percent confidence level, occurred in the region closer to the BOTA border crossing. The regions farther away from the crossings were found to not be significant hot spots of exposure to vehicular emissions. Based on the hot-spot analysis results, logistic regression was performed to evaluate the impact of demographic variables on the probability of a census block to be classified as a hot-spot location. The final model of logistic regression was developed by having the traffic density of each census block dichotomized as the dependent variable and coded as either 1 (i.e., in a hot spot) or 0 (i.e., not in a hot spot). Demographic variables from Table 1 identified as significant in the univariate analysis were used as independent variables. Table 3 summarizes the results from the logistic regression. Higher school education and median income were found to reduce the odds of a census block in a hot spot (OR < 1). On the other hand, factors increasing the odds of being in a hot-spot location were related in particular to a higher percentage of male Hispanic adults.



(a) (b)

Figure 4. Distribution of (a) vehicle miles traveled and (b) traffic density across census blocks.

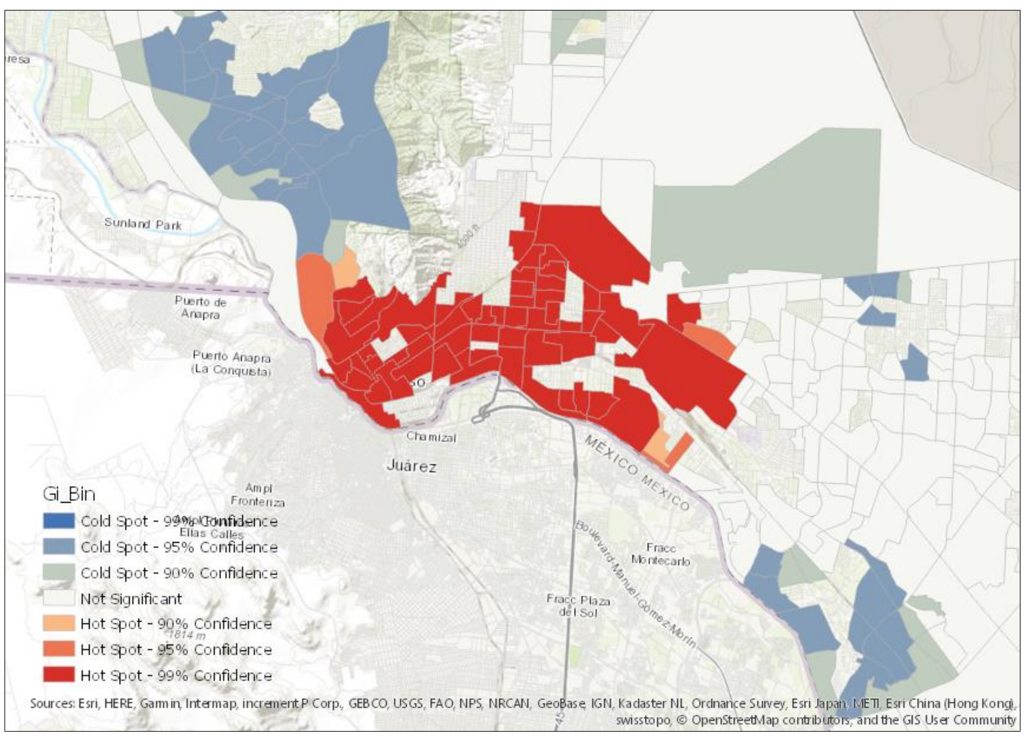


Figure 5. Hot-spot analysis results.

Table 3. Results of Logistic Regression

Demographic Variable	OR	P>|z|
Adult %	1.056	2.37
Male %	1.061	2.36
Hispanic %	1.053	2.36
Median Income	0.995	–4.17
Total Population	0.992	–2.4
Constant	0.001	–2.7

Personal Exposure Assessment

Based on the geospatial analysis, the neighborhood for the personal monitoring study was identified as being close to the BOTA border crossing in a hot-spot location. A total of 16 participants working at the school in a high-exposure neighborhood were recruited for the study. Four participants dropped out before the study, two participants did not complete the study, and data for two participants were excluded due to high values that could not be validated. This resulted in a total of ten participants, and a total of 126,566 single measurements. The quality assessment resulted in a data loss of about 12.5 percent due to technical failures or human error, and values below the detection limit (1 μg/m^3) of the equipment were not included in the analyses. The $PM_{2.5}$ estimates obtained from the personal monitors were paired with the GPS location attributes and the questionnaires filled out by the participants. The location traces for all participants are shown in Figure 6. On average, the distance between participant homes and the school was 7.5 mi.

The spatial distribution of $PM_{2.5}$ mass concentration for all participants as a function of the GPS coordinates is shown in Figure 7. The gradient of pollutant concentrations is shown using gradients from green to red, with green corresponding to lower values and red corresponding to higher values. Clustering of peak concentrations were observed at the school location and some of the participant home locations. The average mass $PM_{2.5}$ concentration for all eight participants ranged between 1.5 μg/m^3 and 34.4 μg/m^3, with an average personal exposure of 13.1 μg/m^3 and a standard deviation of 12.5 μg/m^3. Mean $PM_{2.5}$ concentrations above the NAAQS for $PM_{2.5}$ at 35 μg/m^3 (24-hour averaging period) are also shown in Figure 7. Mean $PM_{2.5}$ concentrations above the NAAQS were observed at two participants' home locations, at the school, and along Mesa Street leading to the school.

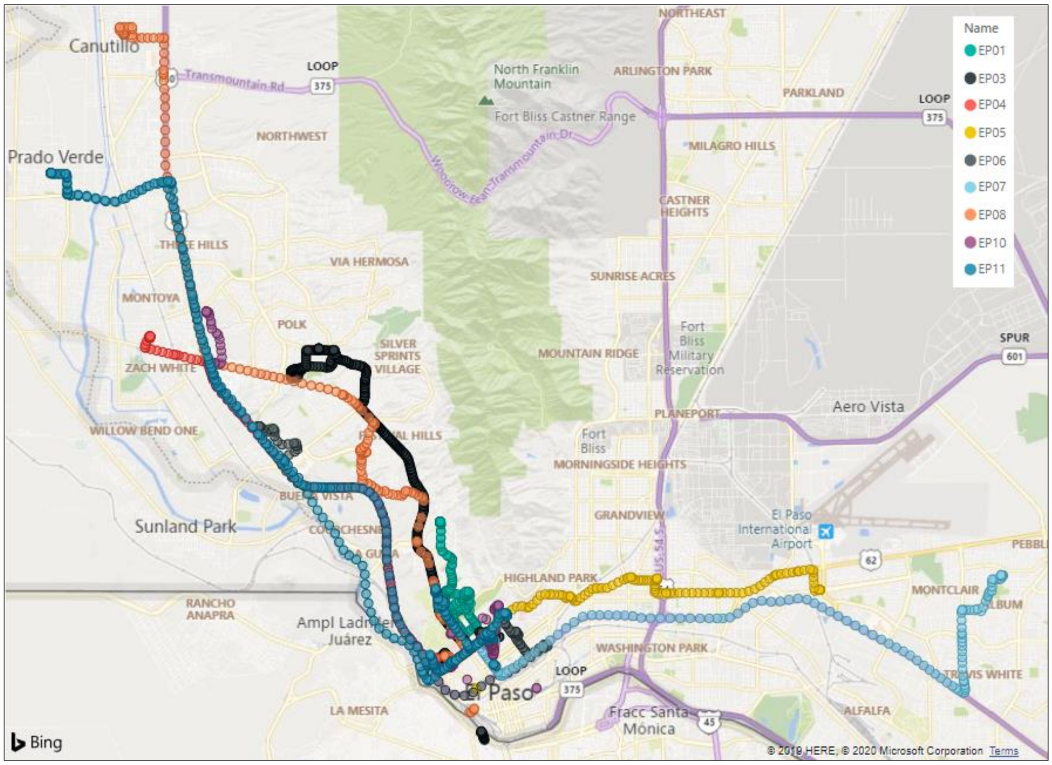
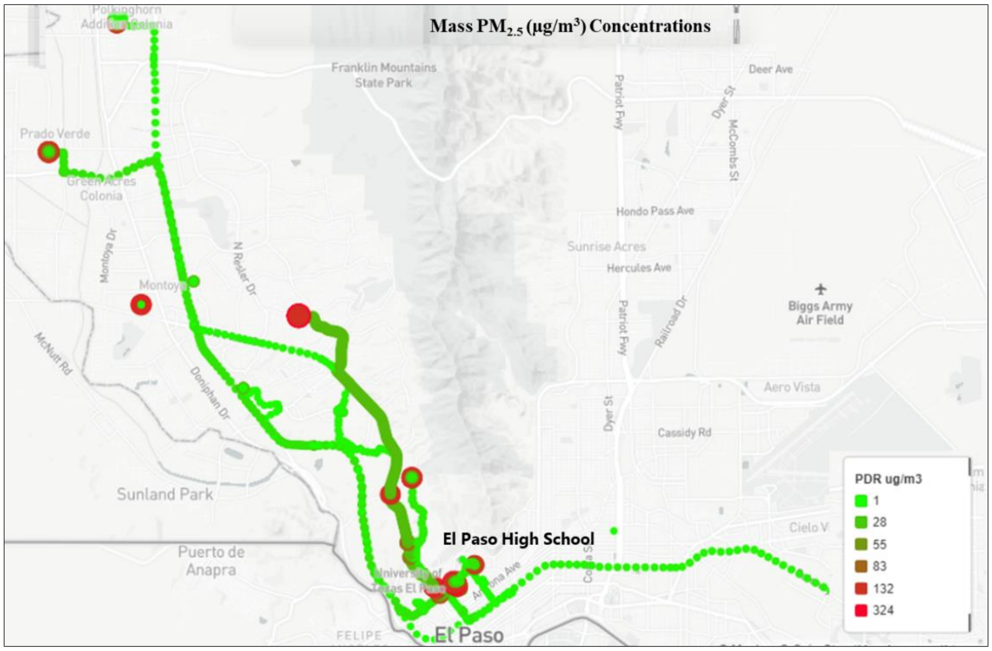


Figure 6. Participant location traces.

These concentrations were further analyzed for the proximity of each participant's home location to a major roadway and wind directions (being upwind or downwind relative to the roadway). The distance from the participant's home to a major roadway ranged between 90 m and 3 km. Downwind conditions (shown in Figure 2) are defined by wind directions in the 90- to 270-degree sector and upwind directions in the 0- to 90-degree and 270- to 360-degree sectors. This investigation found the peak concentration (> 35 µg/m^3) at two participants' home locations located downwind at 90 m from I-10 and 152 m from US 54. I-10 and US 54 serve as the major east-west and north-south freeway corridors in the vicinity of the border crossing, carrying an annual average daily traffic (AADT) of 176,789 and 37,744 in 2018, respectively. Mesa Street is a major arterial leading to the school location and carries an AADT of 38,000 (TxDOT, n.d.). The temporal variation of $PM_{2.5}$ mass concentration for all participants as a function of time is shown in Figure 8. Variation of participants' exposure as a function of hourly traffic volume is shown in Figure 9. The peak concentrations were observed from 6:00 a.m. to 8:00 a.m. and from 11:30 a.m. to 12:30 p.m. The highest peak exposure, from 7:00 a.m. to 8:00 a.m., was found to coincide with the highest peak traffic in the morning period. These periods corresponded with the morning traffic period when the participants commuted to work and the lunchtime period. A spike in the exposure levels during evening traffic peak time was not observed because unlike regular working hours, the school closes at 3 p.m. The distribution for all participants was lognormally distributed, meaning that the participants were exposed to short periods of high exposure and had many observations of low-exposure levels.



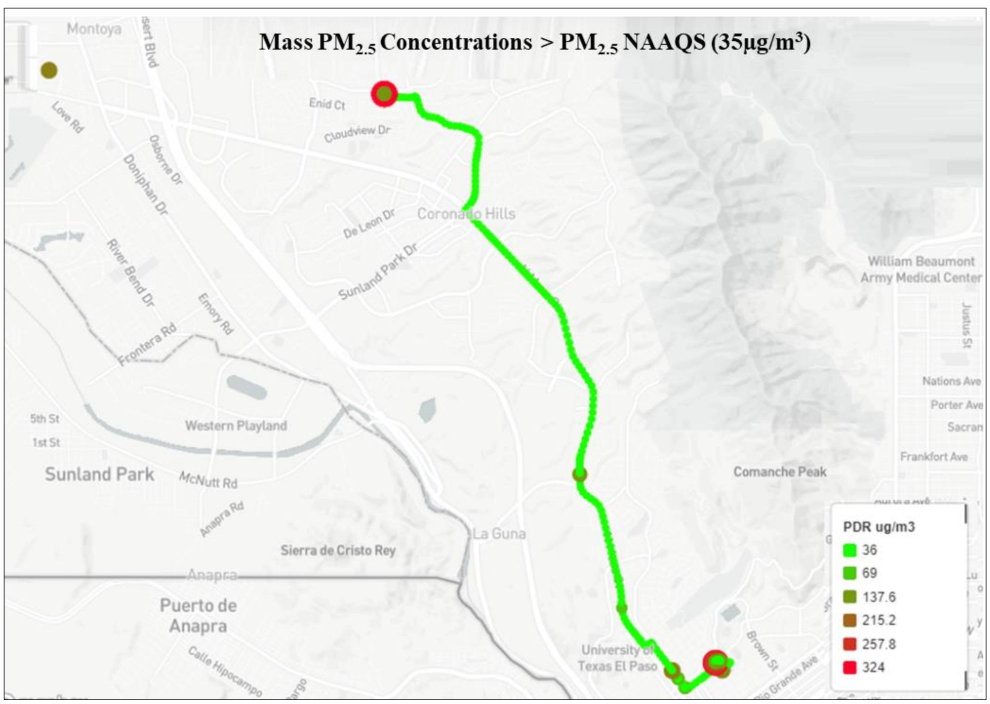


Figure 7. Variation of $PM_{2.5}$ concentrations as a function of the GPS coordinates.

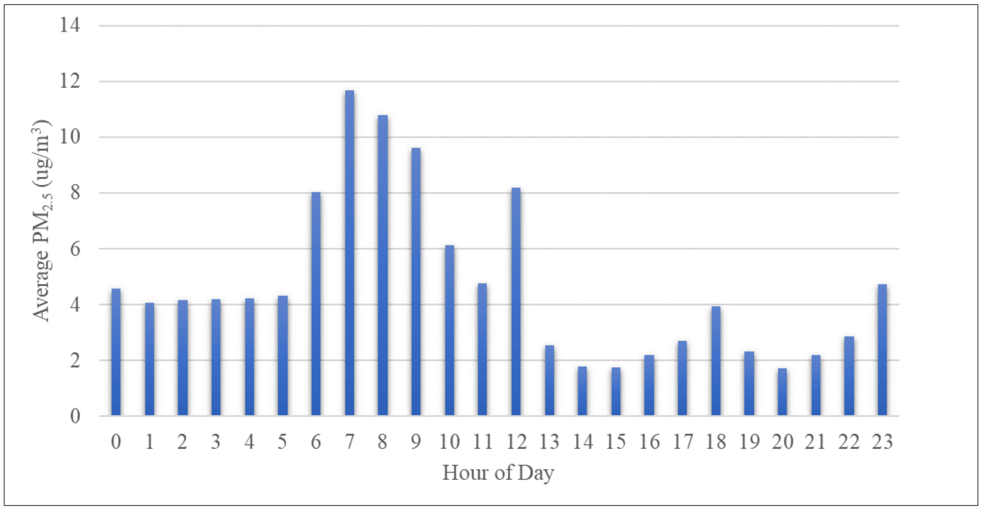


Figure 8. Temporal variation of $PM_{2.5}$ concentrations.

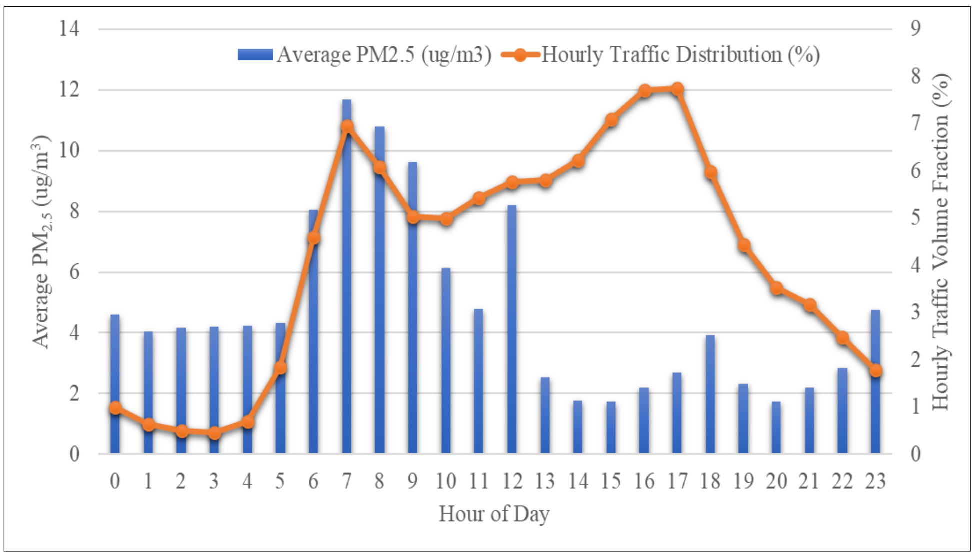


Figure 9. Hourly variation of traffic volume fraction (%) and $PM_{2.5}$ concentrations.

Based on the questionnaires and speed information extracted from the GPS coordinates, the participants spent an average of 70.4 percent of their time at home, 23.7 percent at the school, and 5.9 percent commuting. The participants reported using their vehicle for the commute; none of them used public transit, walking/biking, or other ride-sharing modes. The participants did not report visiting locations other than their homes, which was also verified from the GPS coordinates. Box plots comparing the exposure concentrations in the different MEs are shown in Figure 10. The ME mean $PM_{2.5}$ concentration at school was 19.29 μg/m^3 ± 15.66 μg/m^3, at home was 11.17 μg/m^3 ± 10.63 μg/m^3, and during commute was 11.66 μg/m^3 ± 10.64 μg/m^3. The highest average concentration was encountered at home (129.25 μg/m^3) for the participant whose home was located 90 m from I-10. In terms of participants' contribution to overall mass concentration, the home ME accounted for 59.9 percent, followed by the school at 34.9 percent and the commute at 5.2 percent. The relationship between the time spent and the mass concentration experienced by participants is shown in Figure 11. The participants carried the backpack for an average period of only 10 hours within the assigned 24-hour period, thereby leading to a discrepancy in the amount of time spent at school among the participants. This drawback was overcome by using the exposure intensity (Eq. 1), which weighs the average concentration in each ME by the time spent in the ME. The highest exposure intensity was observed in the school ME (1.47), followed by in the home (1.18) and during the commute (0.89). This finding implies that both the workplace and home contributed more to the participants' exposure relative to the time spent there (i.e., exposure intensity > 1). Time spent commuting contributed slightly less (i.e., exposure intensity < 1), which could be due to the relatively short distance between homes and the school for all participants.

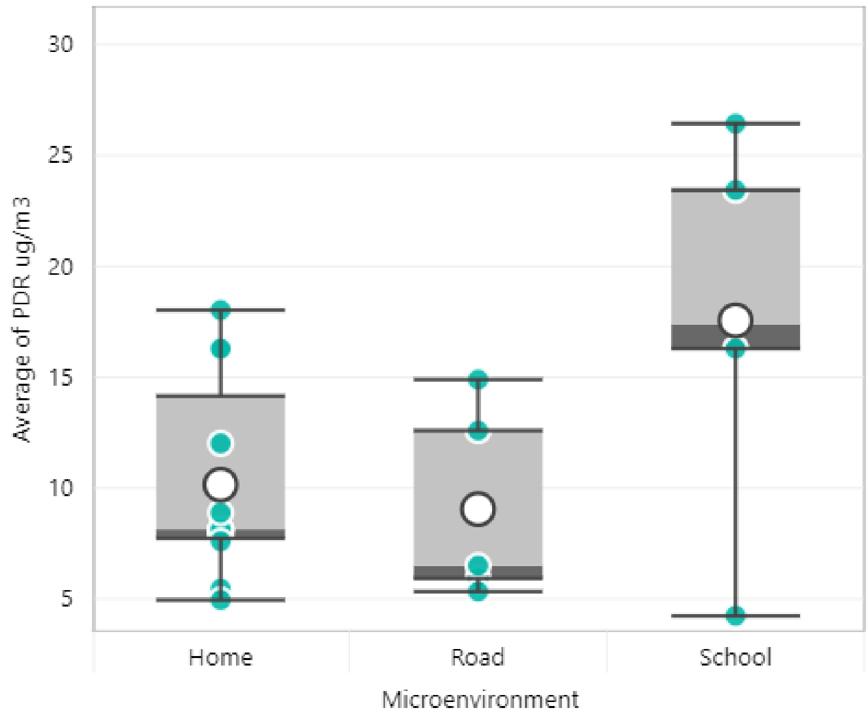
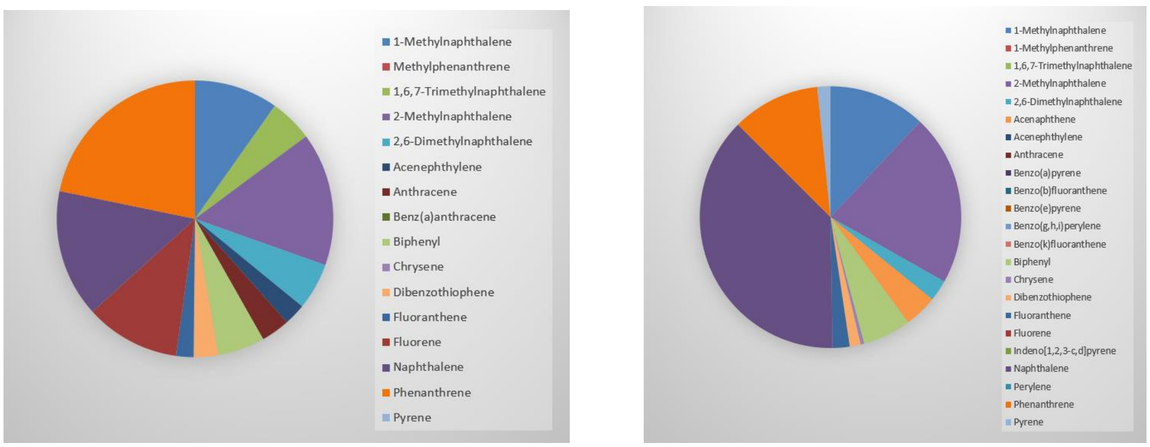


Figure 10. Exposure concentrations in different MEs.

Figure 11. Comparison of contribution of time spent and mass concentrations in different MEs.

Out of the 25 PAHs measured, eight compounds were present in 50 percent or more of the samples, and a total of 15 were found in at least one wristband and filter sample. Naphthalene, 2-methylnaphthalene, 1-methylnapthalene, 2,6-dimethylnapthalene, biphenyl, and phenanthrene were detected in all 10 samples (both wristbands and filters). In the wristbands, a total of 16 out of the 25 PAHs analyzed were detected. Nine of the PAHs detected in the wristbands were priority PAHs as defined by U.S. EPA due to their potential toxicity to humans. Similarly, 23 PAHs were present in the filters, out of which 14 were priority PAHs.

Phenanthrene was the most abundant PAH measured in the wristbands, followed by 2-methylnaphthalene and naphthalene (Figure 12a). The median concentrations were 20.34 ng wristband^{-1} (phenanthrene), 14.03 ng wristband^{-1} (2-methylnaphthalene), and 13.67 ng wristband^{-1} (naphthalene), as illustrated in Figure 12a. For the filter samples, naphthalene, 2-methylnaphthalene, and 1-methylnapthalene were the most abundant compounds (Figure 12b), with median concentrations of 35.68, 20.05, and 11.33 ng wristband^{-1}, respectively.



(a) (b)

Figure 12. Distribution of PAH compounds in (a) wristbands and (b) filters for each participant. The PAH compounds with the highest concentrations in the wristband were phenanthrene, 2-methylnaphthalene, and naphthalene. For the filter, the highest PAH concentrations measured were for naphthalene, 2-methylnaphthalene, and 1-methylnapthalene.

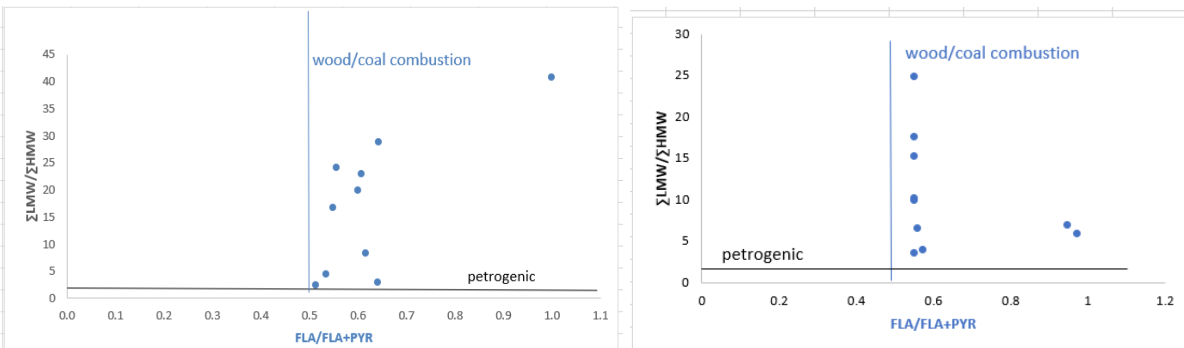
The Spearman correlation analysis was restricted to eight PAHs that were detected in 50 percent or more of the filters and wristbands (Table 4). A strong and significant positive correlation existed between 1-methylnaphthalene ($r_s = 0.73$, *p*-value = 0.03) in the wristband and filter PAHs. Moreover, a strong significant negative correlation existed for fluoranthene ($r_s = -0.70$, *p*-value = 0.04), while 2-methylnaphthalene had a moderate correlation. The rest of the PAH compounds had mostly weak correlations.

Table 4. Correlation Table for Eight PAHs with >/= 50% Detections in Both Filters and Wristbands

PAHs	Wristband PAH and Filter PAH	
	r_s	*p*-value
Naphthalene	−0.08	0.8432
1-Methylnaphthalene	0.73	0.0313*
2-Methylnaphthalene	0.40	0.2912
2,6-Dimethylnaphthalene	0.24	0.5250
Biphenyl	0.20	0.6144
Phenanthrene	0.28	0.4663
Dibenzothiophene	−0.33	0.3845
Fluoranthene	−0.70	0.0423*

*Significant *p*-value (α < 0.05).

The diagnostic ratios calculated for filter samples using FLA/FLA+PYR were > 0.5 (Figure 13A), indicating the source is from grass, wood, or coal combustion (De La Torre-Roche et al., 2009). Furthermore, the diagnostic ratios calculated for the filters using ∑LMW/∑HMW were all greater than 1, indicating a petrogenic source (Zhang et al., 2008). Similar results were found when the diagnostic ratios were calculated from the wristband samples (Figure 13B). All the FLA/FLA+PYR ratios calculated from the wristband samples were also higher than 0.5. These diagnostic ratios confirm that the dominant source of the PAHs encountered by the participants was petrogenic. To confirm that the petrogenic PAHs were from traffic emissions, the ratio of benzo[a]pyrene to benzo[ghi]perylene (BaP/BghiP) was calculated for the filter samples only since the wristbands did not capture those compounds. The results were greater than 0.6, indicating that the source of the PAH was predominantly from traffic emissions (Katsoyiannis et al., 2007).



(a) (b)

Figure 13. Diagnostic ratio for the PAHs in (a) filter samples and (b) wristband samples.

Studies have found that a wide range of variability exists between different MEs and is affected predominantly by within-person variability (i.e., activity patterns). A recent study (Levy Zamora et al., 2018) found personal exposure to $PM_{2.5}$ in a population of pregnant women to be higher in residential locations, especially during cooking activities. Another study (Dons et al., 2011) evaluated the impact of activity patterns for eight couples living in the same household, with one individual from each couple being a full-time worker and the other staying at home. The authors found the exposure levels to vary by up to 30 percent depending on their activity patterns. Another study (Fsadni, 2015) evaluating the impact of indoor school air quality on children's respiratory health found both the average indoor $PM_{2.5}$ of 17.78 µg/m^3 and carbon monoxide of 9.11 ppm exceeded European standards and World Health Organization thresholds. The study found an association between heavy traffic near the school and increased wheezing in children. The values obtained from that study were found to be consistent with similar studies conducted in the El Paso region. A binational study (Raysoni et al., 2011) collected pollutant measurements from monitors placed at two schools in El Paso and two other schools in Ciudad Juarez and found the mean $PM_{2.5}$ value ranged between 7.6 µg/m^3 and 26.7 µg/m^3, with higher concentrations from schools in the Ciudad Juarez region. A similar study (Raysoni et al., 2013) characterized exposure metrics at a mix of low- and high-exposure schools based on proximity to a major roadway in the El Paso region. The study found the average $PM_{2.5}$ concentration of 13 µg/m^3 for the three high-exposure schools to be 50 percent higher than that observed at an ambient monitoring station.

Studies (McCarthy et al., 2013; Morawska et al., 2017) have also found indoor air quality levels to be influenced by outdoor conditions and indoor sources. Outdoor conditions are related to proximity to major roadways, high traffic activities (including increased idling), prevailing wind conditions, and other emission sources. Indoor sources are related to poor ventilation, ineffective ventilation, open windows and doors letting outdoor air inside, and high student occupancy. The school in this study is in the downwind direction, approximately 1 km from a major highway (I-10) and 2.5 km from a major port of entry (BOTA) characterized by high levels of idling activities, especially from heavy-duty truck traffic. Built in 1916, the school is one of the oldest operating schools in the region (El Paso ISD, n.d.), and the maintenance and upkeep of the school has been lacking, especially in terms of the heating, ventilation, and air-conditioning (HVAC) system; electrical upgrades; and building repairs (Mares, 2018). An effective HVAC system is essential to filter out the outside air pollutants, and poor maintenance of the system could lead to increased pollution both from outside air and from the HVAC system through self-pollution (National Research Council, 2007). Studies (e.g., Shendell et al., 2004) have found an association between poorly maintained and ventilated schools and increased student absenteeism and lower performance. These findings highlight a critical need to improve the indoor air quality in the school using targeted abatement techniques, such as upgrading the filtration systems, using mechanical ventilation units, timing the opening and closing of windows and doors to avoid inflow of outdoor pollutants during peak traffic activities, and conducting anti-idle campaigns to reduce idling of vehicles during student pick-up and drop-off periods (U.S. EPA, 2015).

In addition to the personal monitoring data, concurrent ambient data matching the sampling days were extracted from a permanent monitoring site, CAMS 12 UTEP (site number: 481410037, latitude 31.7682914º, longitude −106.5012595º). Average $PM_{2.5}$ mass concentration measured at CAMS 12 during the sampling period was 7.18 $\mu g/m^3$. Compared to the ambient data, personal monitoring data were higher for 88 percent of the sampling days. The personal monitoring data were also compared to the ambient data measured at a monitor placed outside the school for the same sampling period. Although the match between the personal and ambient monitoring improved—with the outside school monitor measuring an average of 7.57 $\mu g/m^3$—the personal monitoring data still measured higher for 75 percent of the sampling days. No statistically significant relationship between personal and stationary monitoring data was observed, which is consistent with other studies (Askariyeh et al., 2019; Levy Zamora et al., 2018) that have found personal monitoring to reduce the exposure misclassification inherent with ambient monitoring.

Conclusion

The U.S.-Mexico border region has undergone rapid growth in the economy and population in recent years. This development has put a large population at risk of air pollution exposure due to the high levels of traffic movement, idling at the border checkpoints, complex terrain and meteorology, regional transport, and other emission sources. This study was conducted in two phases. The first involved the identification of high-exposure neighborhoods, while the second part was a personal exposure assessment conducted on schoolteachers living and working in those neighborhoods. As part of Phase One, a geospatial analysis was conducted to evaluate the neighborhood with a high probability of exposure to traffic-related air pollution. A systematic approach based on a combination of proximity, hot-spot, and regression analysis was performed to evaluate the different neighborhoods and the influence of demographic variables. The results found the neighborhoods surrounding the border crossing locations to be major hot-spot locations for exposure. Socioeconomic indicators like lower median income, lower education, and higher number of Hispanic or Asian populations increased the odds of a neighborhood being in a hot spot for potential high exposure.

Based on the high-exposure neighborhoods identified, a personal exposure assessment was conducted for a pool of schoolteachers. The school proved to be a good location because of its proximity to a major border highway (I-10) and the BOTA port of entry. The personal exposure levels combined with the location information tracked by the GPS devices and filled-out questionnaires helped to apportion the exposure levels in different MEs. Daily average $PM_{2.5}$ ranged between 1.5 $\mu g/m^3$ and 34.4 $\mu g/m^3$, with an average mass concentration of 13.12 $\mu g/m^3$. In terms of the time spent in different MEs, participants spent the maximum at home (70.4 percent), followed by the school (23.7 percent) and then the commute using a personal vehicle (5.9 percent). Time-weighted average $PM_{2.5}$ concentration (exposure intensity) was found to be the highest for school (1.47), followed by home (1.18) and then commute (0.89). Peak concentrations greater than $PM_{2.5}$ NAAQS were found at the school location, two participants' homes located downwind at 90 m from I-10 and 152 m from US 54, and along a major arterial connecting to the school. The personal monitoring data were compared to a nearby Texas Commission on

Environmental Quality ambient monitor and a monitor placed outside the school. The ambient monitors measured an average of 7.18 $\mu g/m^3$ and 7.57 $\mu g/m^3$, respectively. Key factors influencing the exposure levels were related to the proximity of the school and the participants' homes to major roadway and wind conditions. Readings from the stationary ambient monitoring stations were found to be lower than personal monitoring data and consistent with other studies in the literature. These findings demonstrated that the ambient monitors vastly underrepresent true exposure experienced by people and that a critical need exists to expand the coverage and capabilities of air quality monitoring networks.

Wristbands and filters worn by teachers in El Paso were able to recover both dermal and inhalational PAH exposures in a 24-hour period. A total of 23 PAHs were detected by the filters, and 16 PAHs were captured by silicone wristbands. Naphthalene and its related compounds appeared to be the most prevalent PAH of concern. Based on the diagnostic ratios, the PAHs were mostly from petrogenic and traffic sources. Currently, no regulations for traffic emissions exist around school environments. Similar studies should be conducted in a larger, more diverse population to increase generalizability and strengthen the evidence for driving regulations and policy change.

Limitations of this study included the small sample size, which reduced the ability to track exposure levels across a wider population group. The sampling was performed in December to coincide with the region's $PM_{2.5}$ nonattainment status for the winter season. However, the research would benefit from examining the impact of seasonal factors (wind conditions, temperature, etc.) on the exposure levels. The traffic counts are based on ADT collected from statewide installed traffic counters. Accurate measurement of vehicle data during the sampling period could improve the interpretation of the results. This study was performed in one school located in a high-traffic-density area. Additional data from schools located in a low-traffic-density area (i.e., as control schools) could improve the assessment of the traffic impacts on school exposure.

The findings from this study contribute to the body of literature on air quality and microenvironmental exposure. The methods developed in the study can be used by city planning and air quality organizations to screen highly impacted neighborhoods and develop targeted strategies to improve air quality. The study addresses the gap in limited studies focused on vulnerable population groups living and working near major roadways and border crossings. The findings highlight the differences in air pollution exposure at different MEs, including at school, at residences, and during commutes. These findings provide insights into the environmental justice concerns that have become central concerns for people who live close to major roadways. Findings not only show the harmful health effects of these highways on the surrounding neighborhoods but also how they disproportionally affect low-income and minority population groups. These findings are in line with similar studies in the literature. A U.S.-wide study linked survey data to the highway network and found minority populations and people living below the poverty line had higher near-road exposure levels (Parker et al., 2012). Another study analyzed national data at an aggregate level and found minority and low-income people associated with high traffic volume and density (Rowangould, 2013). The results reveal a critical need to focus on mitigation strategies targeted at addressing indoor sources of air pollution, including improving ventilation and filtration systems, the timing of recess, opening and closing of windows and doors, and anti-idling campaigns. The evidence from these studies highlights the fact that more research is needed on developing measures to protect people from the impacts of near-roadway exposure, which will also reduce the infiltration of pollutants inside homes and schools. These measures have to take into consideration the impact of atmospheric processes on near-road pollutant dispersion.

Outputs, Outcomes, and Impacts

Research Outcomes

This project was presented at international conferences and symposiums, and two journal papers are in preparation for submission. Presentations included the 2018 International Conference on Transport and Health;

the 2018 American Public Health Association Annual Meeting and Expo; the 2019 CARTEEH Transportation, Air Quality and Health Symposium; and the Lone Star Regional Chapter of the Society of Toxicology Annual Meeting.

Technology Transfer Outputs

Relevant project datasets (appropriately anonymized) will be made available on the CARTEEH Data Hub. The research team also capitalized on opportunities for information sharing and technology transfer with stakeholders in El Paso and presented key information about the project and traffic-related air pollution issues to school officials and teachers.

Education and Workforce Development Impacts

Graduate students were involved throughout the course of the project in data collection, literature review synthesis, data analysis, manuscript writing, and documentation. Graduate students also presented the work at conferences.

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