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Los Angeles

Identifying Traffic-Related Air Pollution Hotspots in the Built Environment

A thesis submitted in partial satisfaction
of the requirements for the degree Master of
Urban and Regional Planning

by

Lisa Wu

2014

ABSTRACT OF THE THESIS

Identifying Traffic-Related Air Pollution Hotspots in the Built Environment

by

Lisa Wu

Master of Urban and Regional Planning
University of California, Los Angeles, 2014
Professor George DeShazo, Chair

This study characterizes the spatial and temporal distribution of air pollution in an urban street environment given traffic and meteorological conditions. A mobile air monitoring platform was used to measure ultrafine particle (UFP) counts on a 1-second basis along a 3 mile-long transect in Downtown Los Angeles in April-July 2008 for a total of 12 runs and roughly 7,500 observations. Significantly higher UFP concentrations were found in morning compared to afternoon measurements. Spatially speaking, mean UFP concentrations were higher at intersections. High emitting vehicles (HEV), typically old light duty vehicles or medium and heavy duty diesel trucks, were associated with higher spikes of pollution. Advanced statistical modeling is needed to understand how UFP plumes from accelerating vehicle queues disperse in the built environment while controlling for wind conditions. These findings inform smart growth and traffic management strategies, and ultimately, support the creation of a toolkit for transportation planners and policy decision makers to mitigate air pollution exposures in urban street environments and near transit-oriented development (TOD).

The thesis of Lisa Wu is approved.

Douglas Houston

Paul Ong

George DeShazo, Committee Chair

University of California, Los Angeles

2014

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INTRODUCTION

Policy. While many states in the US have made tremendous progress in reducing vehicular emissions, evidence of the dangers of roadway pollutant exposure is growing. In order to address this issue in California, the Sustainable Communities and Climate Protection Act of 2008 (SB 375) was enacted to direct the Air Resources Board (ARB) to set regional targets for reducing greenhouse gas (GHG) emissions. More specifically, SB 375 requires Regional Metropolitan Planning Organizations to develop Sustainable Community Strategies as part of their Regional Transportation Plan (RTP) to demonstrate how they will achieve regional GHG reduction targets through land use, transportation, and housing planning (California Air Resources Board [CARB], 2013). One prevailing approach to involve cities and counties in developing RTPs is to reduce vehicle miles traveled by shifting development and population growth along transit corridors. However, this dominant strategy adopted by states across the country to encourage greater residential density around transit corridors may lead to the unintended effect of greater pedestrian exposure to roadway air pollutants (Ewing and Cervero, 2001). This problem may be especially acute at public transit stops deliberately located on high-volume arterial roadways to increase the passenger connectivity, accessibility, and multi-modal travel (Houston et al., 2013). From a policy standpoint, the National Ambient Air Quality Standards (NAAQS) only regulates criterion pollutants carbon monoxide (CO), lead, nitrogen dioxide (NO2), ozone, sulfur dioxide and lastly amended to include particulate matter (PM2.5 and PM10); ultrafine particulate matter has yet to be regulated (U.S. Environmental Protection Agency [EPA], 2013). Furthermore, monitoring stations used to measure NAAQS tend to be dispersed within regions and are largely insufficient to measure and characterize potentially harmful air pollution concentrations in urban street environments (Boarnet et al., 2011).

Los Angeles. Despite tremendous air quality improvements since the implementation of NAAQS, Los Angeles has still been designated as a nonattainment area for criteria pollutants

(EPA, 2013). This may be partially due to the climate conditions of Los Angeles which includes large amounts of sunlight, mild prevailing winds enclosed by mountains, and frequent heat inversion layers that tend to trap air pollution concentrations on the ground level (CARB, 2012). As part of new EPA federal regulations, four new air monitoring stations are being installed in the South Coast Air Basin near freeways starting this year. However, these sites are only federally required to monitor NO2, CO, and PM2.5 even though the studies used for site selection included instruments monitoring ultrafine particles (Air Quality Management District [AQMD], 2014).

Hudda and Fruin (2013) found that Los Angeles air pollution concentration is five to ten times higher near freeways. In an attempt to discourage the use of single occupancy vehicles, Los Angeles has continued to expand their public transportation infrastructure. The county's public transit has experienced very rapid growth over the last ten years, and this is expected to double over the next 30 years. In 1990, there was no rail transit or bus rapid transit in Los Angeles County and only limited service in the City. By 2010, there were 79 miles of heavy and light rail and 30 bus rapid transit routes (Rapid and Express Metro) with over two hundred stops and stations. The passing of the sales tax, Measure R, accelerates financing transportation projects such as light rail extensions which spur even more opportunities for transit-oriented development (Los Angeles County Metropolitan Transportation Authority [LACMTA], 2013). However as eluded to earlier, traffic-related pollution may be concentrated along these densely developed, major arterials that carry both heavy duty diesel truck and pedestrian vehicle traffic.

STATEMENT OF THE PROBLEM

Traffic pollution. Roadway emissions tend to be highly localized within a few hundreds of meters from major roadways (Houston et al., 2004; Zhu et al., 2002). The Health Effects Institute (HEI, 2010) report on traffic-related air pollution stated over 30-45% of American people in large cities live in these exposure zones that include up to 300-500 meters away from major roads. However, other studies have shown elevated concentrations could extend to over 1000 meters away before returning to ambient levels depending on time of day, season, and meteorological conditions (Boarnet et al., 2011; Hu et al., 2009). A Van Nuys study conducted remote sensing on vehicles along Sherman Way claiming half of roadway emissions are from older, poorly maintained vehicles (Bishop et al., 2012). Roadways involve a large number of pollutants, including carbon monoxide, nitric oxide, various toxic organics, and particulate matter. Particulate matter consists of very small particles including PM10, PM2.5 and also ultrafine particles, generally smaller than 0.1 microns in diameter (HEI, 2010).

Ultrafine particulate matter (UFP) is typically used as a tracer for vehicle exhaust especially in diesel (Kumar et al., 2010; HEI, 2010). Since these particles quickly (within ~30 minutes) coagulate with one another and with larger particles, their background concentrations can fluctuate drastically in short time periods (Kozawa et al., 2012; Kumar et al., 2011). Most of the coagulation of UFP occurs within 20 meters after being emitted from a vehicle’s tailpipe with the help of traffic-induced turbulence. Beyond this distance, most mixing of these concentrations occurs due to atmospheric conditions (Kumar et al., 2011). However, ultrafine particulate matter also tends to have higher suspension rates in the atmosphere and therefore linger longer and consist of about 80% of the total particle number (not mass) concentration of ambient nanoparticles (Kumar et al., 2010). For other pollutants, the roadway signal may be only 30-100% larger than the background, while for UFP, the roadway levels are typically 100-1000% or more above the background (Hu et al., 2009).

Equity concerns. A history of racial discrimination, disjointed land use development, and highway construction in Southern California has concentrated poor minority communities in the urban cores where traffic densities are higher. In contrast, the wealthy non-minorities who contribute to the traffic congestion on major roadways commute from the suburban outskirts. A study by Houston et al. (2004) focused on the traffic densities and racial, socioeconomic composition of neighborhoods in five Southern California counties using census and traffic data from 2000. Impoverished and minority neighborhoods are twice as likely to be exposed to high levels of traffic, which suggests these communities had higher level of exposure to associated vehicle pollution and may experience higher indoor pollution due to higher exchange rates of outdoor air that carry vehicle pollutants into older multi-family buildings. Houston et al. (2013) examines the travel activity patterns of residents of Boyle Heights, a largely low-income, Hispanic and immigrant community near downtown Los Angeles, California, who during the 5% of their day spent traveling are disproportionately exposed (27%) to polycyclic aromatic hydrocarbons (PAH), which are typically bounded to ultrafine particles. This could represent an environmental injustice since low income neighborhoods tend to have lower rates of car ownership in comparison to wealthy commuters yet are often disproportionately exposed to vehicle pollution. Most recently, the Environmental Protection Agency created an environmental health screening tool called CalEnviroScreen which scores disadvantaged communities by zip code based on their exposure to different pollution sources including particulate air pollution (Faust et al., 2013).

Health effects. While most epidemiological studies have focused on PM10 and PM2.5, the case has been building that the adverse health effects could be associated with short term exposure to high ultrafine particle concentrations (Kumar et al., 2011; Andersen et al., 2010; Brugge et al., 2007; Pope III & Dockery, 2006; HEI, 2010; Westerdahl et al., 2005). Ultrafine particles are in the same size range as viruses (< 0.1 µm in diameter), and thus appear to have a special ability (which larger particles do not have) to transfer from the respiratory system into other human tissues, including the cardiovascular system and brain, exacerbating likelihood in developing asthma, cardiovascular disease and cancer (Li et al. 2003; Veronesi et al. 2005; Araujo and Nel 2009; Oszlanczi et al. 2010; HEI, 2010). Furthermore, ultrafine particles are typically bounded to polycyclic aromatic hydrocarbons (PAH) which are smaller than 100nm in diameter and particularly lethal because they can be absorbed by cells in the lungs and penetrate the circulatory system (Houston et al., 2008; Künzli et al., 2003). Additionally, PAH has been strongly associated with premature births and hindered fetal development yet they are not currently regulated (Choi, Rauh, Garfinkel, Tu, & Perera, 2008; Houston et al., 2008).

Literature gaps. Many air pollution monitoring studies have been conducted near freeways, but few studies have measured air pollution exposure along main arterials that may both carry heavy vehicle and foot traffic (Boarnet et al., 2011; Houston et al., 2013). Furthermore, there is limited knowledge on how particulate matter disperses in varying atmospheric conditions in urban street environments (Kumar, 2010). Among the studies that have examined pollution concentrations in varying microenvironments, more research is needed to analyze the scale of influence on air pollution of localized traffic, meteorological, and built environment factors compared to regional ambient conditions (Boarnet et al., 2011).

LITERATURE REVIEW

According to the Health Effects Institute (2010), traffic-related pollution concentrations depend on travel-activity patterns, vehicle volume and fleet composition, meteorological conditions, chemical behavior of the pollutant, and land-use characteristics. The following literature review will explore how previous studies have examined these factors.

Traffic Pollution Exposure. Kaur et al. (2006) monitored UFP levels for varying transportation modes (walk, bike, bus, taxi and car) through major and residential roads in London. Video footage of participants' movements reveals walking along the building side versus the curbside of the sidewalk may lead to a 10% reduction in UFP exposure (Kaur et al, 2006). This finding is consistent with the findings of Boarnet et al. (2011) which examined fine particulate matter (using mass-based measurements) in five southern California cities and found that sidewalk pollution concentrations are highly variable. Additionally, air monitoring equipment such as fast or scanning mobility particle sizer (FMPS or SMPS) and condensation particle counters (CPCs) can be used to measure particulate matter concentration spikes surrounding the traffic intersection environment (Klems et al., 2010; Westerdahl et al., 2005). Using this technique, Klems et al. (2010) found that concentration spikes largely generated from vehicle acceleration from a red to green light may last a few-tens of seconds and account for 6-25% of ambient exposure and up to 50% of ambient exposure on an hourly basis. However, other studies have removed short-term pollution spikes on the one second level basis when analyzing aggregated pollution averages (i.e., 1 minute to 5 minute intervals) using ultrafine particle fluctuations that indicate vehicle exhaust (Baldauf et al., 2013; Boarnet et al., 2011; Kowaza et al., 2012).

Traffic and Vehicle Emissions. Mean UFP concentrations may depend largely on location, road types, and truck traffic density (Westerdahl et al., 2005). In terms of traffic emissions collection methods, research studies use a variety of different monitoring instruments measuring different pollutants as vehicle tracers or health impact indicators. Wu et al. (2009) used a Gaussian diffusion line source model (that incorporates source strength, meteorology, and site geometry) and estimated the annual average exposure to the criteria pollutant PM2.5 and elemental carbon (EC) from gasoline and diesel exhaust near the Ports of Los Angeles and Long Beach. A meta-analysis on traffic exposure and associated health effects by Lipfert & Wyzga (2008) used the distance from major roads, traffic flow rate, high emitting vehicles, vehicle miles traveled, and vehicle age to gauge exposure to traffic pollution. Ambient daily traffic volume for land use regression analysis may also be retrieved from traffic databases compiled by state or regional transportation agencies (Wilton et al., 2013).

In order to monitor traffic-related air pollution, studies classify vehicles in different ways ranging from weight class, model, year and fuel source or content. Wu et al. (2009) used ARB’s Emissions Factors (EMFAC) model to compare emission rates between light and heavy duty vehicles. Bishop et al. (2012) uses remote infrared and UV sensors called Fuel Efficiency

Automobile Test (FEAT) to detect roadside tailpipe emissions (i.e., carbon dioxide, carbon monoxide, hydrocarbon, oxides of nitrogen, sulfur dioxide, and ammonia) in the form of mass ratios of the gases. Furthermore, video footage of license plates was used to retrieve vehicle registration information (e.g., vehicle make, model, and year) in addition to infrared beams that recorded vehicle speed and acceleration.

Meteorological Data. Typical meteorological data collected from weather stations collect wind direction and speed, ambient temperature, atmospheric pressure, and mixing heights with varying short temporal averages that tend to be less accurate especially at airport locations (Vardoulakis et al., 2003; Wilton et al., 2013). When examining meteorological conditions, studies generally collect temperature, wind speed, and direction from either portable sonic anemometers that may be placed on mobile monitoring platforms, air quality management district stations, or other secondary sources such as the National Weather Service (Wu et al., 2009; Baldauf et al., 2013). Boarnet et al. (2011) found fine particle concentrations were associated with lower wind speeds and higher temperatures. Wind flowing perpendicular to the roadway may also influence how pollution accumulates while a parallel wind flow may facilitate dispersion (Kowaza et al., 2012; Halger et al., 2012). Hu et al. (2009) also found UFP concentrations extended further away from major roadways by 1200-2600 meters pre-sunrise hours due to the inversion layer of cool, stagnant air trapping pollutants at the surface level throughout the night.

Air Dispersion Modeling. One common technique to assess air pollution exposure is to use air pollution dispersion models developed by the US EPA, which rely on the Gaussian-plume theory using mathematical equations to simulate a 3D continuous point source (typically within 20 kilometers) in a given meteorological context (MacDonald, 2003; Vardoulakis et al., 2003; Wu et al., 2009). More advanced Gaussian models could include terrain features, buildings, and multiple atmospheric layers (MacDonald, 2003). Mensink et al. (2008) utilizes the

Danish Operational Street Pollution Model (OSPM) to simulate dispersion of traffic emissions (e.g., particulate matter, volatile organic compounds, nitric oxide, and carbon dioxide) to both sides of a street canyon based on wind conditions in addition to using the Gaussian Model to provide background emissions (20-30 kilometers radius) based on surrounding street traffic and industrial sources. However, OSPM does not account for pollution that could be traveling into the street canyon from above the canopy air or the dynamic character of these particles (Kumar et al., 2011).

Another pollution dispersion model also using Gaussian plume theory is CALINE4 which relates a given wind direction and roadside traffic emissions as a line source to canyon or intersection scenarios (Vardoulakis et al., 2003). However, CALINE4 is generally tailored more for highway development than understanding concentrations in urban street microenvironments (e.g., small buildings, sound walls, and vegetation), and CALINE4 is limited in modeling low, parallel wind speeds, and different canyon configurations (Vardoulakis et al., 2003; Wu et al, 2009). These air pollution models focused on how source emissions disperse and are tested with receptor-oriented models which depend on pollution monitoring sites using emissions estimates and meteorological data. Full scale street canyon experiments could emit tracer gases to monitor pollution concentrations and retention at varying heights within the canyon.

Another approach to characterizing air pollution in the urban environment is with land-use regression (LUR) models that typically account for road types, elevation, land cover, and traffic counts which tend to be the most important factor explaining exposure (Ryan & LeMasters, 2007). Wilton et al. (2013) is an example of a comparative exposure study between the City of Los Angeles and Seattle that used a hybrid model of LUR and CALINE3 dispersion to increase their explanation from R^2=.45 to R^2=.79 for nitric oxide exposure. Computational fluid dynamics (CFD) models turbulence, small scale pollutant dispersion, and heat transfer based on computer simulations. Most standard, validated CFDs use the k-epsilon turbulence model that analyzes how kinetic energy in turbulence dissipates which deals with recirculating flows and large eddies (Vardoulakis et al., 2003).

Urban Street Canyon. Air pollution studies conducted in a narrow street canyon with tall buildings tend to find higher localized concentrations (Boarnet et al., 2011; Eeftens et al., 2013; Salmond et al., 2010). Boarnet et al. (2011) concluded that more open space and paving was associated with reduced fine particle concentrations in street canyons with 2-5 story buildings. Many studies have attempted to model air pollution dispersion in a street canyon of orthogonal winds blowing between tall buildings along a street canyon. Hunter et al. (1990/1991) characterized three types of flow regimes based on street canyon height (h) to width (w) ratios: skim flow (h/w = 1), wake interference flow (h/w = .5), and isolated roughness flow (h/w = .25-.33) ordered by increasing air flow conditions, respectively. These aspect ratios of building heights to street widths may have a larger effect in deeper street canyons (Eeftens et al., 2013). Salmond et al. (2010) found higher particle counts in narrower versus wider street canyons by studying particle exchange between the urban canopy and boundary layers; however, this air flow exchange had a limited effect on UFPs. Moeseke et al. (2005) found less air flow exchange the higher the degree of wind (i.e., 0, 45 and 90 degrees) blowing through a street canyon. Air pollution dispersion across a non-homogeneous street canyon has unpredictable wind flow regimes but perpendicular wind speeds higher of $4ms^{-1}$ were associated with twice as high concentrations on the leeward side than windward side. However, an off-center located traffic lane reversed findings to yield as much as 50-60% higher concentrations on the windward side than leeward. Therefore, street geometry locations of traffic lanes had a greater effect on pollution dispersion than flow regimes. Other high concentrations were found in the middle of the canyon, at the 1.5m height of a pedestrian level more than 2.5m. As a toolkit for sustainable street canyon geometries considering air quality, Chan et al. (2003) used a 3-D numerical model code CFX-6 to test whirling eddies, horse-shoe vortices, and the other conventional wind flow regimes that yielded results with little difference from expensive wind tunnel experiments.

Passive Control. An alternative method of managing air pollution dispersion is through passive controls. Microenvironment variables (also referred to as roughness coefficients when applied to street canyon models) such as green landscaping, vegetative barriers, sound walls, building reliefs, street grade and even curbside parking can reduce or exacerbate air pollution concentrations (Vardoulakis et al., 2003; Kumar et al., 2011). Ottele et al. (2010) describes how leaves on a wall of vegetation can act as an effective sink for particulate matter (i.e., PM10, fine and ultrafine particles) in order to improve air quality. However, thick or voluminous tree canopies could also act as an air pollution dispersion barrier. Gromke and Ruck (2007) used a 3-D wind tunnel model the effects of a row of trees along the center of a street canyon and determined larger tree crown diameters were correlated with up to 2.5 times higher pollution concentrations along the leeward building walls and a slight reduction in windward building side concentrations. Vegetative barriers have been variable in their effect on air pollution dispersion (Hagler et al., 2012). Other studies have been conducted on how street grade levels and configurations such as noise barriers and sidewalls may reduce up to 50% of traffic-related pollution concentrations (Heist & Perry, 2009; Hagler et al., 2012). Roads below grade with noise barrier walls (6-9 meters tall) had the largest reduction in surface level pollution concentrations while elevated roadways had the smallest reduction in concentrations (Heist & Perry, 2009). According to Gallagher et al. (2011), parked cars may act as passive controls for pedestrian pollutant exposure based on whether the parking spots are parallel, perpendicular, or angled at 45 degrees and depending on parking occupancy and wind conditions; the dispersion of air pollutants was modeled using a commercial computational fluid dynamics (CFD) code.

RESEARCH OBJECTIVE

The objective of this research study is to spatially and temporally characterize UFP concentrations in an urban street environment. Factors analyzed in this study that may be associated with high UFP concentrations include the following:

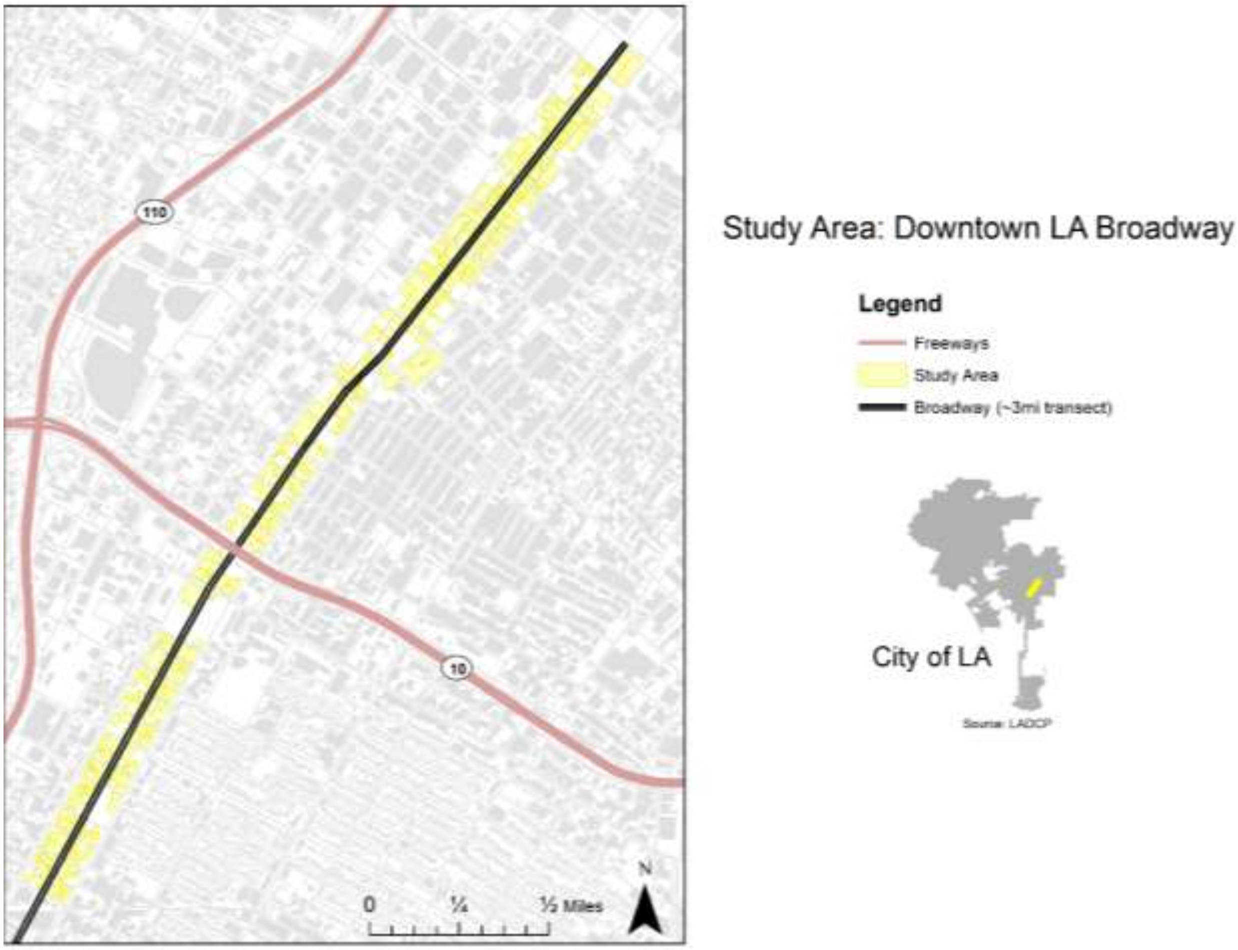
- Time of day (morning vs. afternoon measurements)
- Traffic queue length and acceleration
- Traffic proximity counts and high emitting vehicles by class and age
- Building morphology and the microenvironment (i.e., parking lots, trees)
- Meteorological context (e.g., wind speed)

RESEARCH METHODS

Data Collection & Study Area. Air pollution measurements were collected using a mobile monitoring platform (MMP) traveling down a fixed route during April-July 2008 in Downtown Los Angeles. The study area was roughly three miles along a transect on Broadway Street between 2nd Street and Jefferson Boulevard (see Figure 1). A total of 12 runs were completed which took about 10-12 minutes each run to drive through 32 intersections. Samples were collected on a second level basis totaling about 7,300 (n=7329) observations. Missing pollution observations (n=96) were excluded from the analysis.

Many of studies have chosen to aggregate their concentrations over at least minute intervals (Kumar et al., 2010; Boarnet et al., 2011; Kowaza et al., 2012; Houston et al., 2013). This study takes a highly resolved approach on the one-second level of analysis to examine which factors attribute to ultrafine particle spikes. These runs were conducted during the late morning (e.g., 9-10AM) and afternoon (e.g., 3-4:30PM) shifts (see Figure 2). Half of the runs were completed in the morning and the other half were completed in the afternoon. The final air pollution dataset was synchronized spatially and temporally with the built environment, meteorological, and traffic conditions (see Figure 3).

. Figure 1. Study Area Map



Air Pollution. The MMP collected outdoor air samples in a Toyota RAV4 SUV electric vehicle via an air inlet composed of a 6-inch wide in diameter steel duct located on the rear passenger's window which was positioned closest to the sidewalk in the case of this study (see Figure 2). This MMP was rented from the Air Resources Board and has been used similarly in other previous transect studies (Hu et al., 2009; Kozawa et al., 2009; Kozawa et al., 2012; Westerdahl et al., 2005). The air monitoring instrument used for this study was a Fast Mobility Particle Sizer (FMPS) spectrometer which monitors UFP levels in a 100 particles per cubic centimeters resolution. Since FMPS captures particle counts rounded to the hundreds place per cubic centimeter, the one second resolution of concentration levels is an estimate. FMPS uses multiple, low-noise electrometers for particle detection (TSI, 2014). The MMP carried the FMPS instrument along with several other air monitors for CO2, NOX, black carbon, PAH, and PM2.5 but these pollutants are not examined in the current study due to limited available samples.

Meta-Built Environment. Geographic Information Systems (GIS) were used to spatially relate the built environment measures (i.e., street widths, building height, and setbacks) to air pollution concentrations (ultrafine particles) at the one meter level using MMP latitude and longitude coordinates recorded from a portable GPS unit. Also using GIS, meta-built environment variables were referenced along the transect such as traffic signals, crosswalks, intersections, street trees, surface parking lots, parking garages, and bus stops (existing and proposed) using MMP video footage, Los Angeles Regional Imagery Acquisition Consortium (LAR-IAC), TIGER streets, and LA Metro bus data.

Meteorological Data. Hourly averages of the prevailing wind direction (radians) and speed (ms^{-1}) were retrieved from the closest Air Quality Management District (AQMD) station located at 1630 North Main Street in Los Angeles which is approximately 1.5 miles northeast of the start point of the Broadway transect.

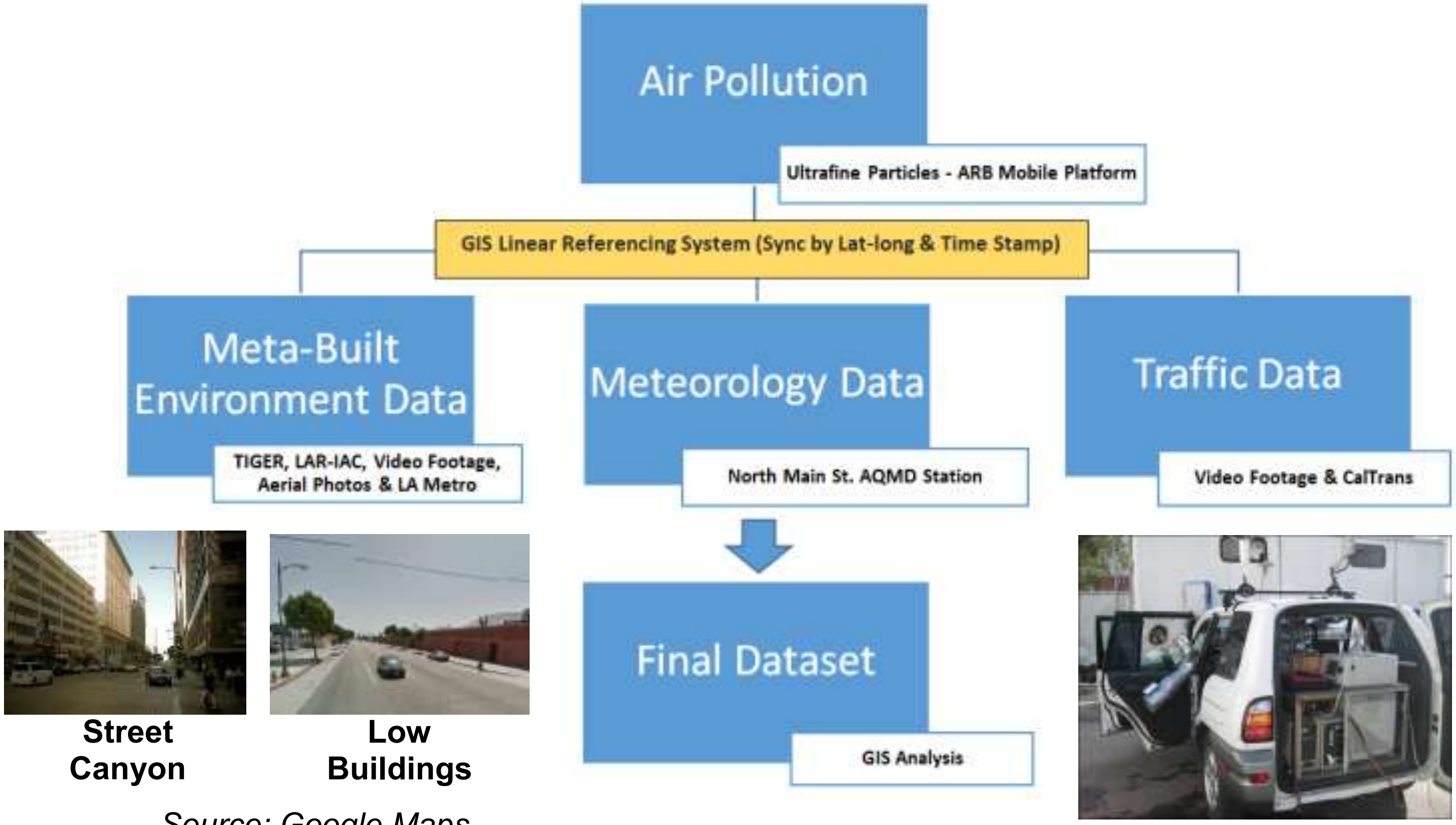
Traffic Data. Real-time traffic was recorded similarly to Hu et al. (2009) for ambient and local traffic conditions. Ambient traffic volume data was retrieved from the 110 and I-10 freeways using UC Berkeley Institute of Transportation’s database called the Freeway Performance Measurement System (PeMS). These freeways were selected for ambient analysis since the 110 is located about 1,000 meters away from the transect and the I-10 bisects the transect roughly 1,500 meters from the transect’s start and end points. Also, a video camera was mounted on the dashboard of the MMP to record footage of surface street traffic in front of the MMP that was later reviewed for manual traffic counts and queues. Vehicles were classified into passenger vehicles (e.g., light duty vehicles including heavy pickup trucks), medium, and heavy duty vehicles based on truck classifications by the US Department of

Transportation (see Figure 3). Refer to Table 1 below for how local traffic was coded at the one second resolution.

Figure 2. Field Measurements

Sampling Date/Shift	Sampling Time
04/03/08 AM	9:56:00-10:08:14
04/03/08 PM	4:03:04-4:14:00
04/04/08 AM	9:47:00-10:00:35
04/07/08 AM	9:42:14-9:54:53
04/07/08 PM	3:41:46-3:51-30
07/14/08 PM	4:11:53-4:21:10
07/16/08 AM	10:02:08-10:11:09
07/16/08 PM	4:10:05-4:21:27
07/18/08 AM	9:57:41-10:09:27
07/24/08 PM	3:50:57-4:00:28
07/28/08 AM	10:03:00-10:12:00
07/28/08 PM	4:13:03-4:19:52

Figure 3. Air Pollution Data Map



Source: Google Maps

ARB Mobile Monitoring Platform

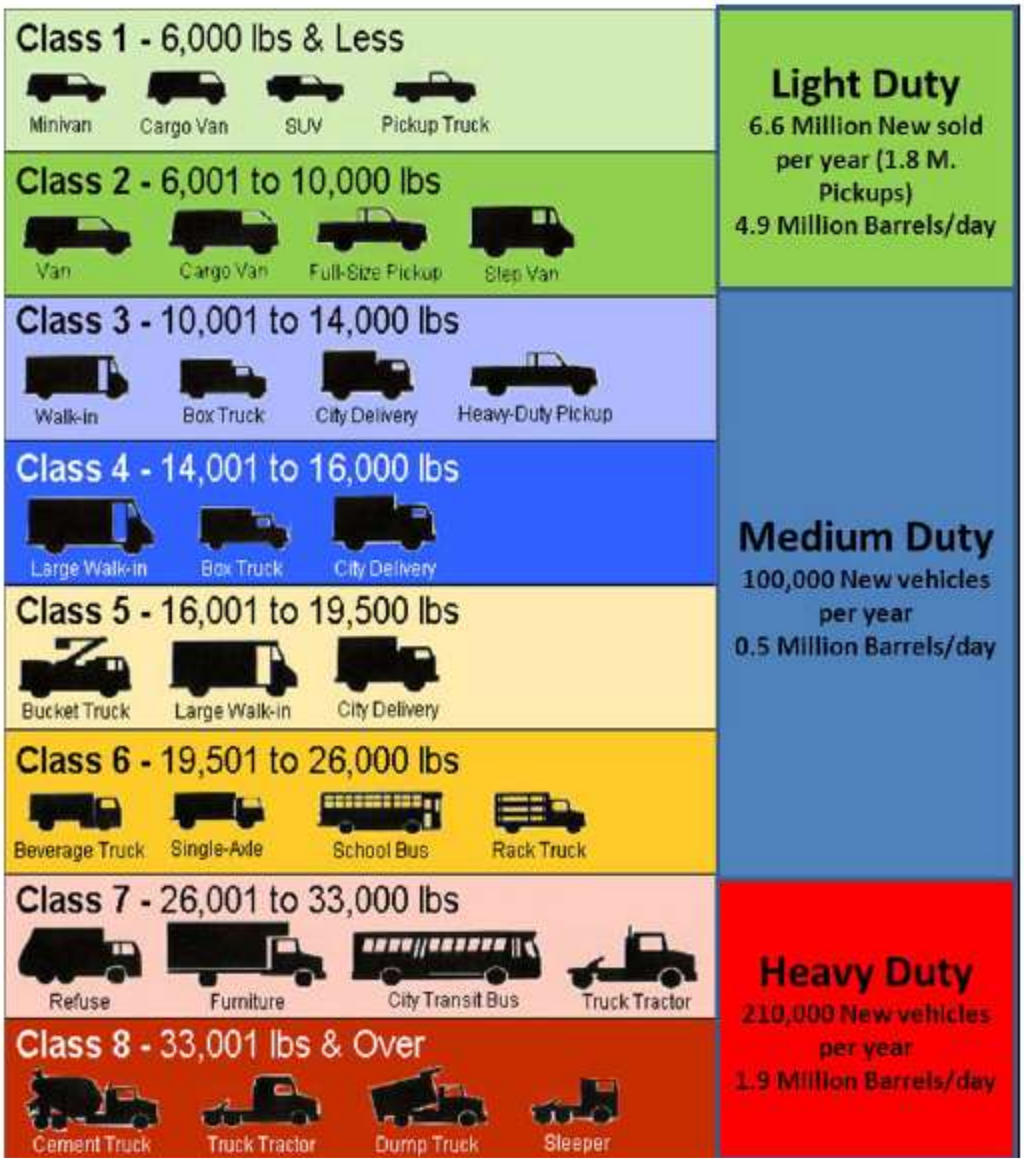


Figure 4. Truck Classification by the US Dept. of Transportation's Gross Vehicle Weight Rating (US Department of Energy, 2013).

Table 1A. Traffic Codebook

Variable [units]	Definition
FMPS [UFP/cm^3]	Fast Mobility Particle Sizer (FMPS) spectrometer collected ultrafine particle concentration levels in a 100 particles per cubic centimeters resolution
lane_mmp [1-3]	Location of mobile monitoring platform (MMP) in lanes numbered from right to left (1=right lane, 2=middle lane, 3=left lane)
queue_mmp [#]	The position of the MMP in a queue
accel (go, on, xr, xl) [0-1]	The second in time when the queue accelerates from stopped position at a red to green traffic light
Ongoing Traffic (go) [#]	Direction of traffic the MMP drove along (southbound). Vehicles were counted when visible (to the naked eye) in the video frame.
Oncoming Traffic (on) [#]	Opposite direction of traffic the MMP is driving along (northbound). Vehicles are counted when the MMP is immediately passing them.
Cross Traffic (xr vs. xl) [#]	Transverse direction of traffic coming from the left (westbound) and right (eastbound) side of the MMP. Vehicles were counted when passing through middle of the most immediate intersection.
Passenger Vehicles (pass) [#]	Consists of Class 1-2 vehicles used to transport passengers with a gross weight less than 10,000 pounds including sports utility vehicles, pickup trucks, and vans in addition to heavy duty pickups
Old Vehicle (ov) [#]	Passenger Vehicles that appear to be dated before 1986
Medium Duty Vehicle (med) [#]	Consists of Class 3-6 vehicles used for delivery typically with a gross weight between 10,000-26,000 pounds including walk-ins trucks, box trucks, city delivery trucks, bucket trucks, beverage trucks, single axle trucks, and rack trucks
Heavy Duty Truck (heav) [#]	Consists of Class 7-8 vehicles used for major goods movement typically with a gross weight over 26,000 pounds including refuse trucks, furniture trucks, truck tractors, cement trucks, dump trucks and sleepers.
Bus [#]	A large motor vehicle carrying passengers by road, esp. one serving the public on a fixed route and for a fare
Motorcycle (mcycle) [units]	Two-wheeled vehicle that is powered by a motor and has no pedals.

Table 1B. Traffic Codebook Continued

Variable [units]	Collection Method
FMPS [UFP/cm^3]	FMPS was transported in a zero emissions vehicle. Outdoor air was collected via a duct positioned through passenger's window
lane_mmp [1-3]	The lane position was determined from video footage taken from the MMP. Lane changing moment the platform completely changed lanes
queue_mmp [#]	A queue was determined by when the MMP had come to a complete stop (excluding inching forward after stopping).
accel (go, on, xr, xl) [0-1]	Regardless of whether the MMP was part of the queue, the acceleration of the first vehicle in the queue of the closest intersection from when a red light turned green was recorded
Ongoing Traffic (go) [#]	If the MMP was first in queue, any ongoing traffic beyond the most immediate intersection was counted until the vehicle became too blurry to be discerned by the video camera's resolution.
Oncoming Traffic (on) [#]	The vehicle was counted as oncoming the second the vehicle was halfway out of the video frame.
Cross Traffic (xr vs. xl) [#]	The vehicle was counted as right or left cross traffic the second the vehicle was passing through the most immediately visible intersection in the camera's view.
Passenger Vehicles (pass) [#]	These vehicle classifications were based on Truck Classification by the US Department of Transportation's Gross Vehicle Weight Rating and Vehicle Inventory Use Service (VIUS) Categories.
Old Vehicle (ov) [#]	Old vehicles were coded based on visual appearance and comparison to google searches that match the vehicles model year. Also audio from researchers driving the MMP who remarked seeing high particle concentrations from an old vehicle were recorded as well. At times, commentary from MMP drivers on high particle concentrations was used in labeling an old vehicle. Two researchers with prior experience classifying vehicles were selected to review this work.
Medium Duty Vehicle (med) [#]	These vehicle classifications were based on Truck Classification by the US Department of Transportation's Gross Vehicle Weight Rating and Vehicle Inventory Use Service (VIUS) Categories.
Heavy Duty Truck (heav) [#]	These vehicle classifications were based on Truck Classification by the US Department of Transportation's GVWR and Vehicle Inventory Use Service (VIUS) Categories.
Bus [#]	Buses were coded separate from vehicle classifications since they were potentially natural gas powered
Motorcycle (mcycle) [#]	Motorcycles were coded separately as potential high emitters of diesel exhaust

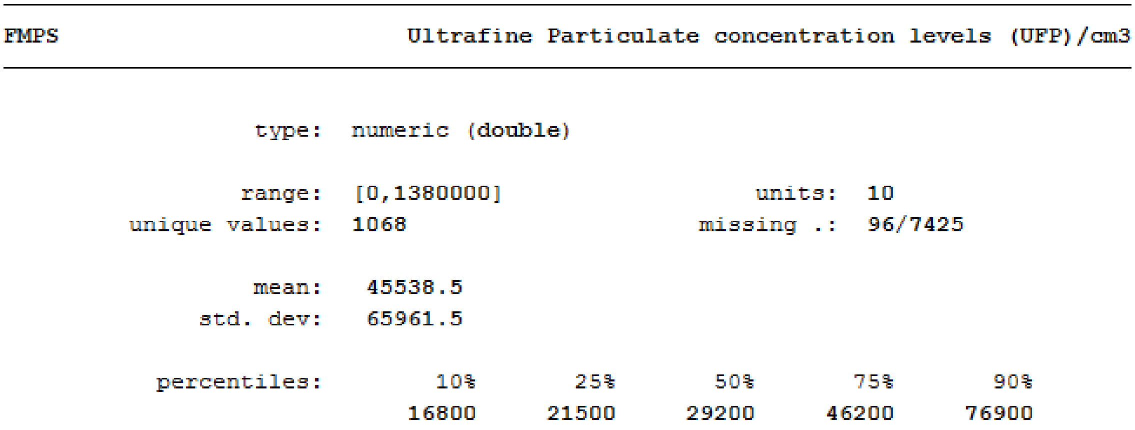
Table 1C. Traffic Codebook

Variable [units]	**Notes**
FMPS [UFP/cm^3]	FMPS uses multiple, low-noise electrometers for particle detection. Since FMPS could only capture particle counts rounded to the hundreds place per cubic centimeter, the 1 second resolution of concentration levels is an estimate
lane_mmp [1-3]	There were only 3 lanes throughout this Broadway transect hence why only 3 lane categories were assigned
queue_mmp [#]	The MMP was assumed to be in-motion if there was no queue order. Vehicles along the side of or behind the MMP may be out of the sight of the camera and therefore not counted. Queue length included vehicles in all ongoing lanes of traffic. Whenever a larger vehicle blocked the camera's field of vision from ongoing traffic ahead, an educated guess was made for the vehicle count.
accel (go, on, xr, xl) [0-1]	The inching forward of vehicles in a queue did not count as acceleration. Acceleration was only recorded from a traffic light turning red to green. Lone vehicles turning right while light was red, vehicles accelerating pass the MMP in free flow traffic, and the personal acceleration of the MMP was not counted. Cross traffic acceleration may be less precise if the MMP was approaching the intersection from afar.
Ongoing Traffic (go) [#]	This is the most subjective traffic count since there is no distance proxy and is reliant on some educated speculation on how many vehicles are driving ahead of the MMP at any given second.
Oncoming Traffic (on) [#]	These vehicles are counted once except the vehicles from right cross traffic turning left become oncoming traffic as well. Right cross traffic turning right are counted only as oncoming traffic.
Cross Traffic (xr vs. xl) [#]	The next immediate intersection of cross traffic was counted as vehicles crossed center of intersection regardless of whether MMP was in queue. Right cross traffic turning right or left cross traffic turning right were only counted as onging or oncoming vehicles. The left turning cross traffic were counted as they crossed and counted again as they became ongoing or oncoming traffic.
Passenger Vehicles (pass) [#]	See light duty vehicles and include heavy pickup trucks under Figure 3
Old Vehicle (ov) [#]	The pre-1986 was used as the criteria for an old vehicle as a proxy to high emitting vehicles that have yet to install On Board Diagnostics (OBD) that were used to better regulate emissions.
Medium Duty Vehicle (med) [#]	Unable to discern heavy duty pickups from regular picks up so all pickups were coded as light duty (see Figure 3). School buses were coded in the "Bus" vehicle category.
Heavy Duty Truck (heav) [#]	See Figure 3. City transit buses were coded under the "Bus" vehicle category.
Bus [#]	In note section, specified the color of metro bus or tour bus to possibly determine fuel source since vehicle fleets were in the process of being converted to natural gas. Notes also indicated whether bus idling at transit stop
Motorcycle (mcycle) [#]	Motorcycles were seldom observed in the study and therefore could not be used for meaningful analysis

RESEARCH FINDINGS

Pollution Descriptives. The average pollution concentration along this transect is approximately 45,000 UFP/cm^3 which is around twice the background levels of roughly 20,000 UFP/cm3. These ambient concentrations consisted of about a quarter of the study's pollution measurements (see Table 2; Hu et al., 2009). The mean is skewed by higher concentrations that are a few hundred thousands UFP/cm^3 (see Figure 4). When excluding outliers, the first quantile is around 20,000 UFP/cm^3, the median is just above 25,000 UFP/cm^3, and the third quantile is roughly 50,000 UFP/cm^3 (see Figure 5).

Table 2. UFP Summary Statistics



```
FMPS                              Ultrafine Particulate concentration levels (UFP)/cm3

                  type:  numeric (double)

                 range:  [0,1380000]                  units:  10
         unique values:  1068                     missing .:  96/7425

                  mean:   45538.5
             std. dev:    65961.5

           percentiles:        10%       25%       50%       75%       90%
                             16800     21500     29200     46200     76900
```

Figure 4. UFP Boxplot with Outliers

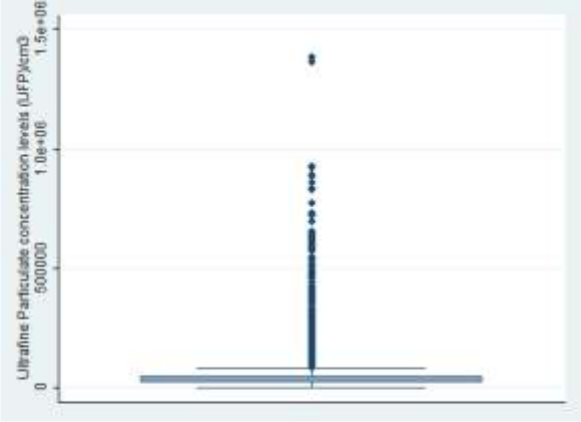
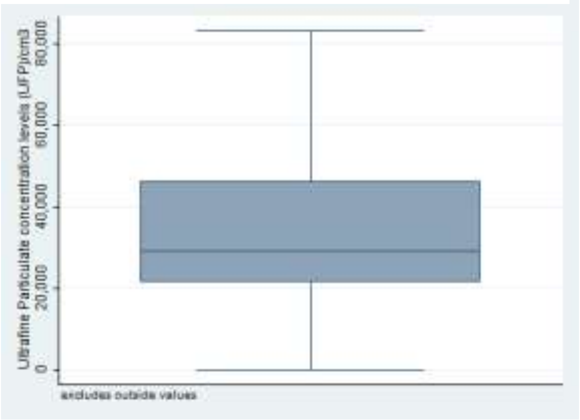
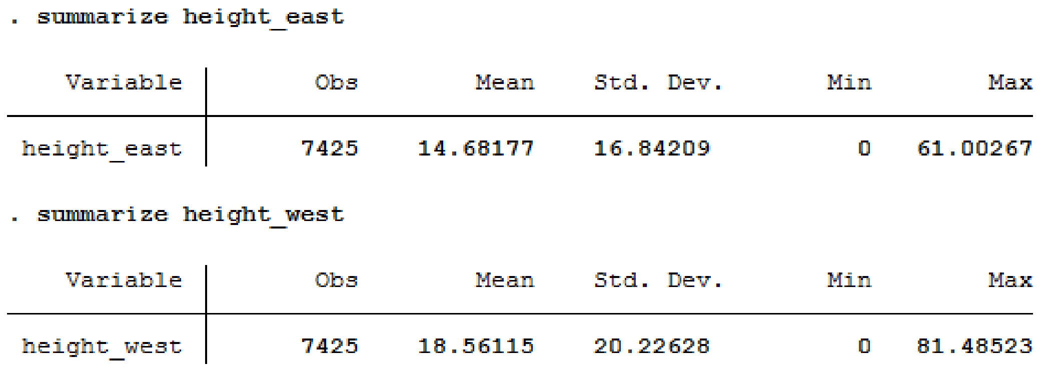


Figure 5. UFP Boxplot without Outliers



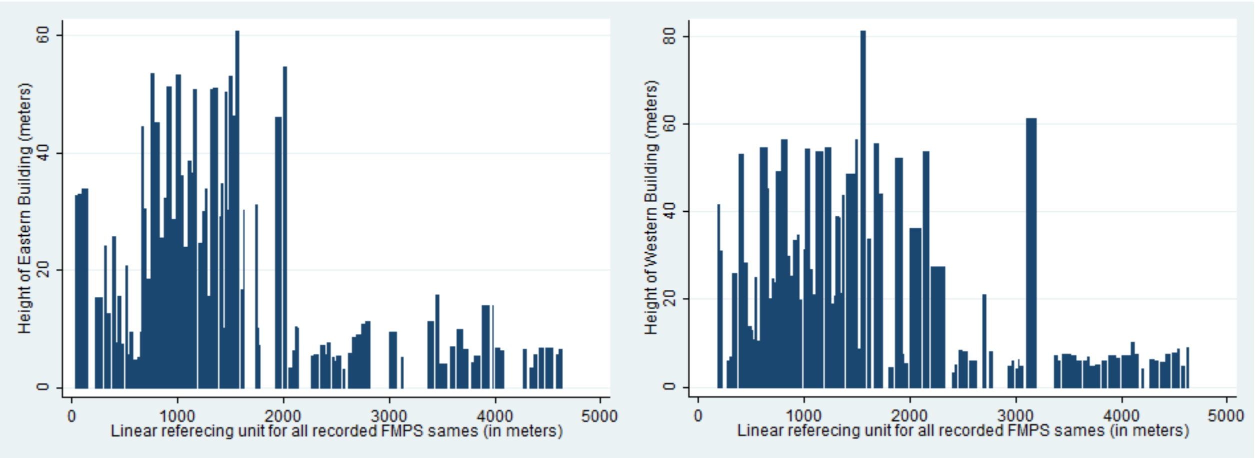
Built Environment Descriptives. On average, buildings are slightly taller on the west side of the transect (~19m vs. ~15m, respectively; see Table 3). The first half of the transect has taller buildings typically above 15m while the second half has lower buildings typically below 15m (see Figure 6). Therefore, the appropriate threshold for “tall” buildings was above 15m and “low” buildings were below 15m for comparing UFP concentrations (see Figure 8 and 9).

Table 3. Building Height Summary Statistics



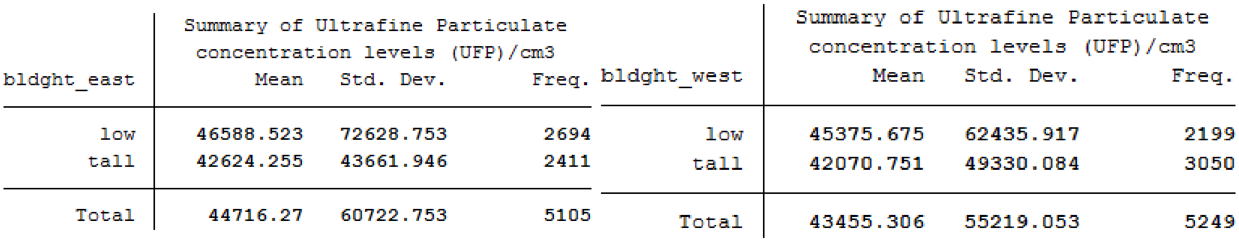
```
. summarize height_east

    Variable |        Obs        Mean    Std. Dev.       Min        Max
-------------+---------------------------------------------------------
 height_east |       7425    14.68177    16.84209          0   61.00267

. summarize height_west

    Variable |        Obs        Mean    Std. Dev.       Min        Max
-------------+---------------------------------------------------------
 height_west |       7425    18.56115    20.22628          0   81.48523
```

Figure 6. Building Heights Across Transect: East & West



Mean UFP concentrations for tall buildings were associated with at least a few thousand UFP/cm^3 lower than low buildings (see Table 4). However, east building heights were associated with slightly higher UFP concentrations at the 75th percentile (~50,000 UFP/cm^3 vs. ~45,000 UFP/cm^3, respectively). In contrast, the west buildings heights do not seem to differ in median UFP concentrations (~30,000 UFP/cm^3; see Figure 7).

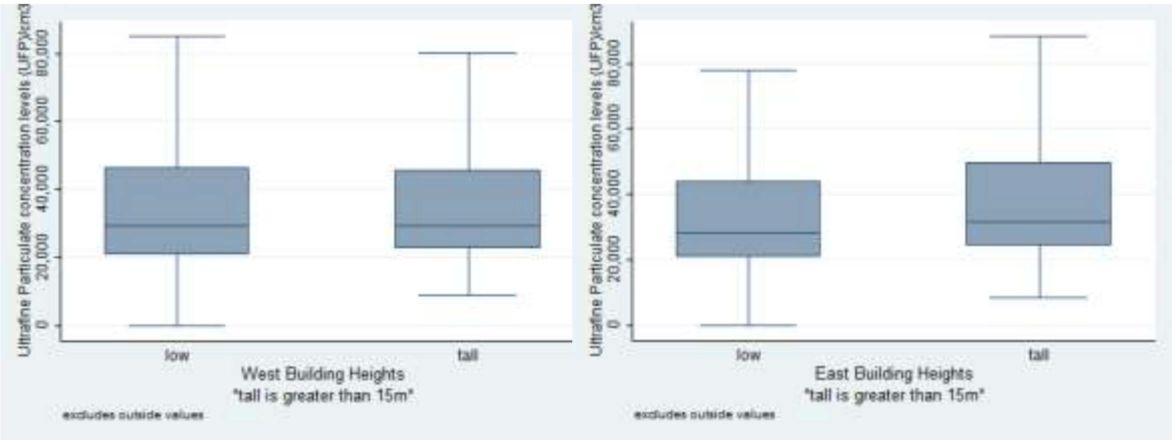
Table 4. Mean UFP Concentrations by Building Heights (Low vs. Tall)



```
            |    Summary of Ultrafine Particulate
            |     concentration levels (UFP)/cm3
bldght_east |        Mean   Std. Dev.       Freq.
------------+------------------------------------
        low |   46588.523   72628.753        2694
       tall |   42624.255   43661.946        2411
------------+------------------------------------
      Total |    44716.27   60722.753        5105
```

```
            |    Summary of Ultrafine Particulate
            |     concentration levels (UFP)/cm3
bldght_west |        Mean   Std. Dev.       Freq.
------------+------------------------------------
        low |   45375.675   62435.917        2199
       tall |   42070.751   49330.084        3050
------------+------------------------------------
      Total |   43455.306   55219.053        5249
```

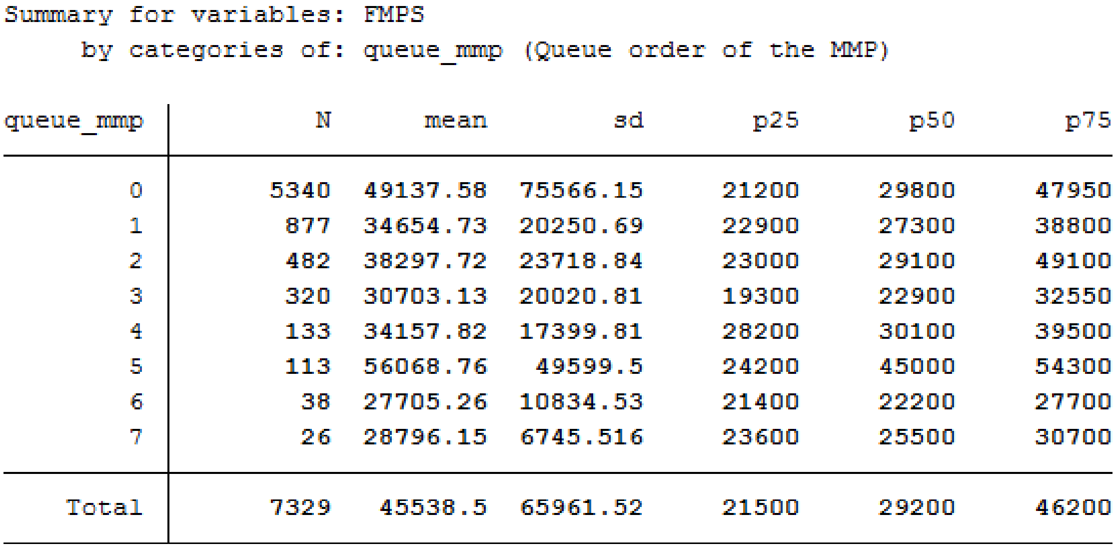
Figure 7. UFP Concentrations by Building Heights (Low vs. Tall) Boxplots



Traffic Descriptives. The queue positioning (queue_mmp) variable was a proxy for when the MMP was in motion or in queue. Whenever the queue position was zero (queue_mmp = 0), we assumed the MMP was in motion. The MMP was most prevalently first in queue at an intersection (12%) and less likely to be located further down the traffic queue (see Appendix A). As the MMP is positioned further down the queue, mean UFP concentrations generally declined (see Table 5). Similarly, higher counts of ongoing passenger vehicles corresponded with lower

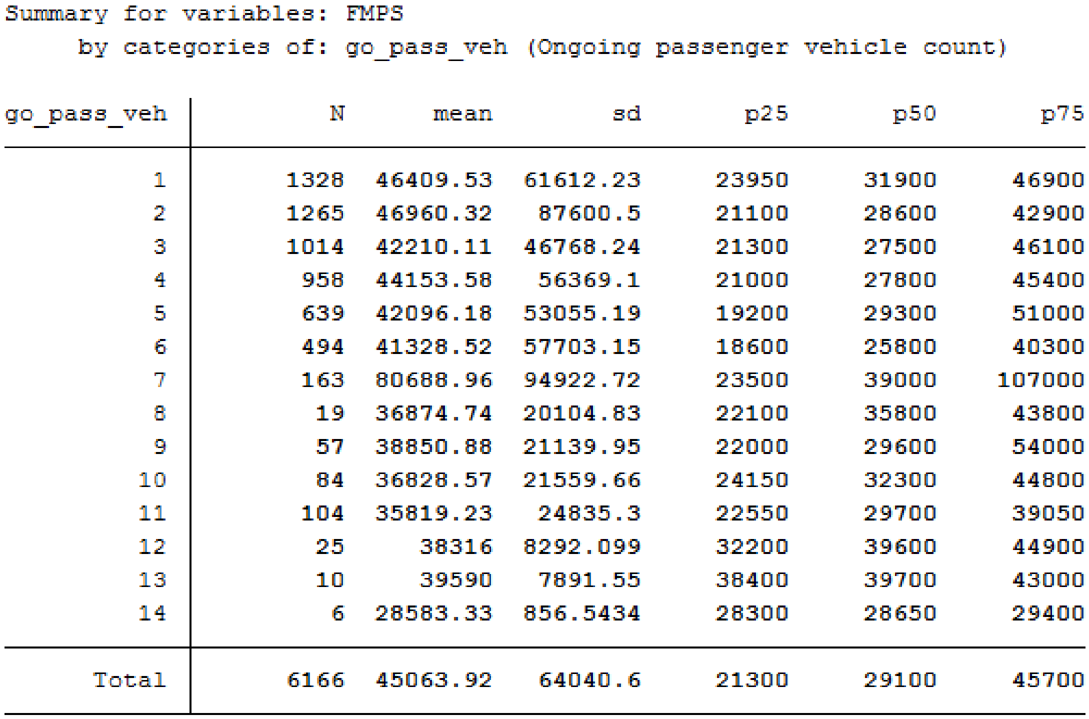
UFP mean concentrations. For instance, the MMP behind 1 ongoing passenger vehicle was associated with a mean UFP concentration that was over 1.5 times higher than the mean UFP concentration for when the MMP was behind 14 ongoing passenger vehicles (~46410 UFP/cm^3 vs. ~28583 UFP/cm^3, respectively; see Table 6).

Table 5. Mean UFP Concentrations by MMP Queue Position



```
Summary for variables: FMPS
     by categories of: queue_mmp (Queue order of the MMP)

queue_mmp |        N      mean        sd       p25       p50       p75
----------+------------------------------------------------------------
        0 |     5340  49137.58  75566.15     21200     29800     47950
        1 |      877  34654.73  20250.69     22900     27300     38800
        2 |      482  38297.72  23718.84     23000     29100     49100
        3 |      320  30703.13  20020.81     19300     22900     32550
        4 |      133  34157.82  17399.81     28200     30100     39500
        5 |      113  56068.76   49599.5     24200     45000     54300
        6 |       38  27705.26  10834.53     21400     22200     27700
        7 |       26  28796.15  6745.516     23600     25500     30700
----------+------------------------------------------------------------
    Total |     7329   45538.5  65961.52     21500     29200     46200
-----------------------------------------------------------------------
```

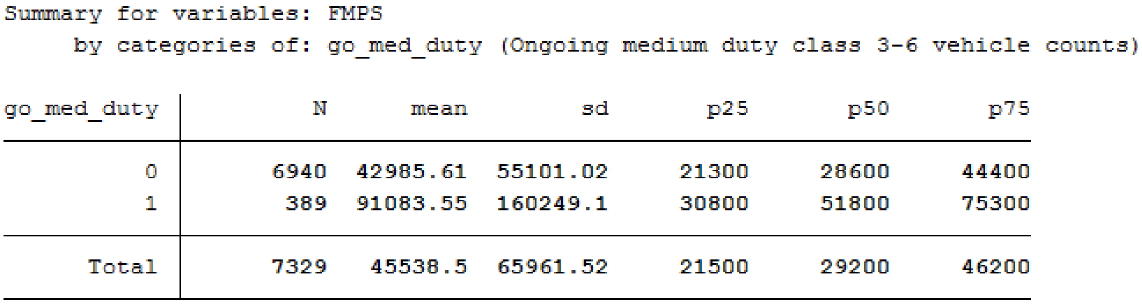
Table 6. Mean UFP Concentrations by Ongoing Passenger Vehicle Counts



```
Summary for variables: FMPS
     by categories of: go_pass_veh (Ongoing passenger vehicle count)

go_pass_veh |        N      mean        sd       p25       p50       p75
------------+------------------------------------------------------------
          1 |     1328  46409.53  61612.23     23950     31900     46900
          2 |     1265  46960.32   87600.5     21100     28600     42900
          3 |     1014  42210.11  46768.24     21300     27500     46100
          4 |      958  44153.58   56369.1     21000     27800     45400
          5 |      639  42096.18  53055.19     19200     29300     51000
          6 |      494  41328.52  57703.15     18600     25800     40300
          7 |      163  80688.96  94922.72     23500     39000    107000
          8 |       19  36874.74  20104.83     22100     35800     43800
          9 |       57  38850.88  21139.95     22000     29600     54000
         10 |       84  36828.57  21559.66     24150     32300     44800
         11 |      104  35819.23   24835.3     22550     29700     39050
         12 |       25     38316  8292.099     32200     39600     44900
         13 |       10     39590   7891.55     38400     39700     43000
         14 |        6  28583.33  856.5434     28300     28650     29400
------------+------------------------------------------------------------
      Total |     6166  45063.92   64040.6     21300     29100     45700
-------------------------------------------------------------------------
```

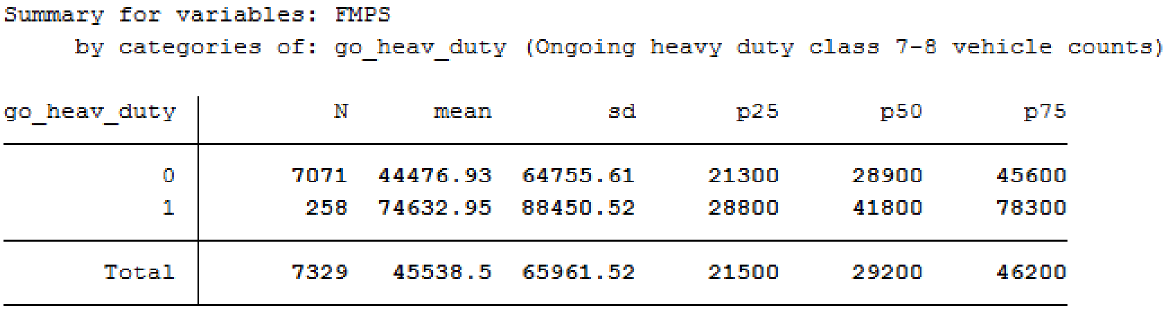
According to Table 7, the mean UFP concentration for when the MMP was traveling behind an ongoing medium duty truck was over twice as high than when there was no ongoing medium duty truck present (~91,000 UFP/cm^3 vs. 45,500 UFP/cm^3, respectively). In Table 8, ongoing heavy duty trucks were associated with over 1.5 times higher mean UFP concentrations than when there was not an ongoing heavy duty truck (~75,000 UFP/cm^3 vs. ~45,000 UFP/cm^3, respectively). The presence of two ongoing old vehicles corresponded with almost twice as high mean UFP concentrations than when there were no ongoing old vehicles (~77,600 UFP/cm^3 vs. ~42,000 UFP/cm^3, respectively; see Table 9).

Table 7. Mean UFP Concentrations by Ongoing Medium Duty Vehicle Counts



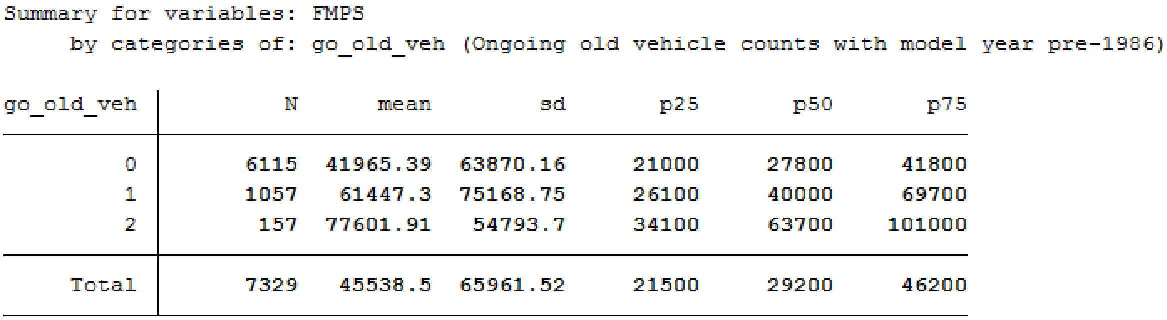
```
Summary for variables: FMPS
     by categories of: go_med_duty (Ongoing medium duty class 3-6 vehicle counts)

go_med_duty |         N      mean        sd       p25       p50       p75
------------+------------------------------------------------------------
          0 |      6940  42985.61  55101.02     21300     28600     44400
          1 |       389  91083.55  160249.1     30800     51800     75300
------------+------------------------------------------------------------
      Total |      7329   45538.5  65961.52     21500     29200     46200
-------------------------------------------------------------------------
```

Table 8. Mean UFP Concentrations by Ongoing Heavy Duty Vehicle Counts



```
Summary for variables: FMPS
     by categories of: go_heav_duty (Ongoing heavy duty class 7-8 vehicle counts)

go_heav_duty |         N      mean        sd       p25       p50       p75
-------------+------------------------------------------------------------
           0 |      7071  44476.93  64755.61     21300     28900     45600
           1 |       258  74632.95  88450.52     28800     41800     78300
-------------+------------------------------------------------------------
       Total |      7329   45538.5  65961.52     21500     29200     46200
--------------------------------------------------------------------------
```

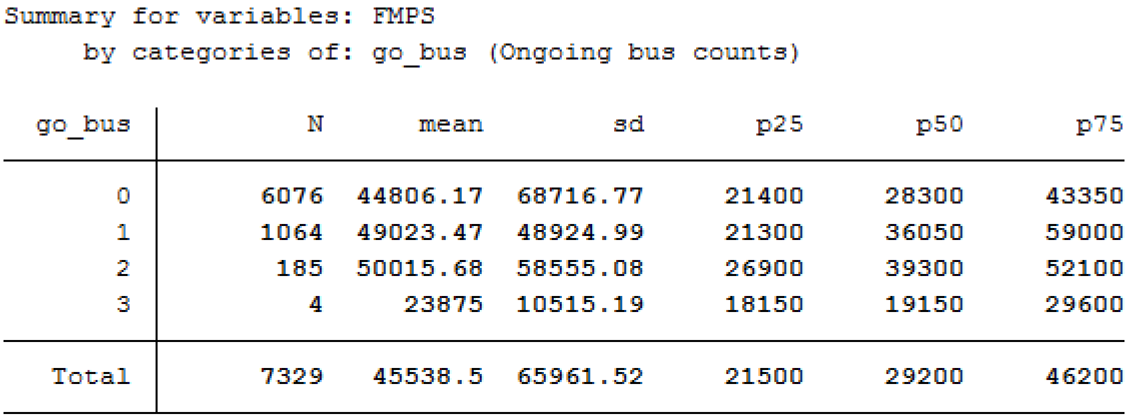
Table 9. Mean UFP Concentrations by Ongoing Old Vehicle Counts



```
Summary for variables: FMPS
     by categories of: go_old_veh (Ongoing old vehicle counts with model year pre-1986)

go_old_veh |         N      mean        sd       p25       p50       p75
-----------+------------------------------------------------------------
         0 |      6115  41965.39  63870.16     21000     27800     41800
         1 |      1057   61447.3  75168.75     26100     40000     69700
         2 |       157  77601.91   54793.7     34100     63700    101000
-----------+------------------------------------------------------------
     Total |      7329   45538.5  65961.52     21500     29200     46200
------------------------------------------------------------------------
```

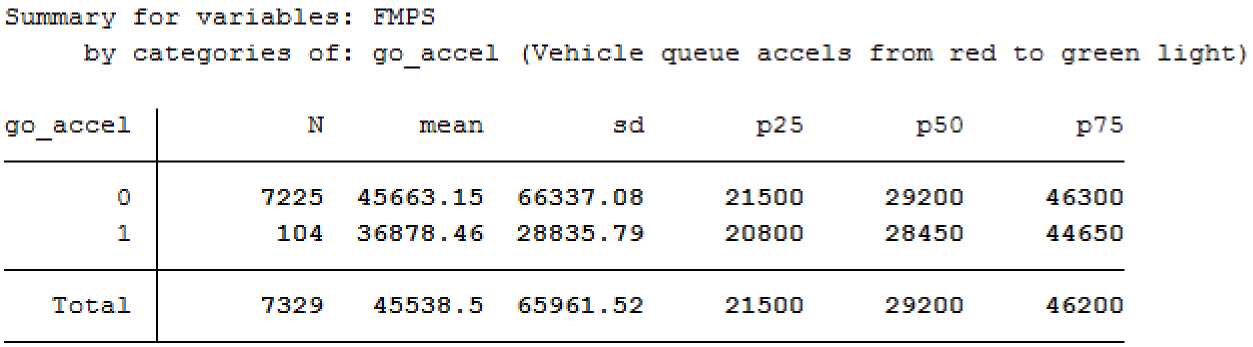
Ongoing bus counts were generally assoicated with slighty higher concentrations compared to no ongoing buses (~50,000 UFP/cm^3 vs. ~44,800 UFP/cm^3 , respectively). However, the exception was three observed ongoing buses corresponded with about half the mean UFP concentrations of when there are no ongoing buses (~24,000 UFP/cm^3 vs. ~44,800 UFP/cm^3, respectively; see Table 10). The instance of ongoing vehicle queues accelerating from a traffic light turning from red to green were associated with slightly lower mean UFP concentrations (~37,000 UFP/cm^3 vs. ~45,600 UFP/cm^3, respectively, see Table 11).

Table 10. Mean UFP Concentrations by Ongoing Bus Counts



```
Summary for variables: FMPS
     by categories of: go_bus (Ongoing bus counts)

  go_bus |         N      mean        sd       p25       p50       p75
---------+------------------------------------------------------------
       0 |      6076  44806.17  68716.77     21400     28300     43350
       1 |      1064  49023.47  48924.99     21300     36050     59000
       2 |       185  50015.68  58555.08     26900     39300     52100
       3 |         4     23875  10515.19     18150     19150     29600
---------+------------------------------------------------------------
   Total |      7329   45538.5  65961.52     21500     29200     46200
----------------------------------------------------------------------
```

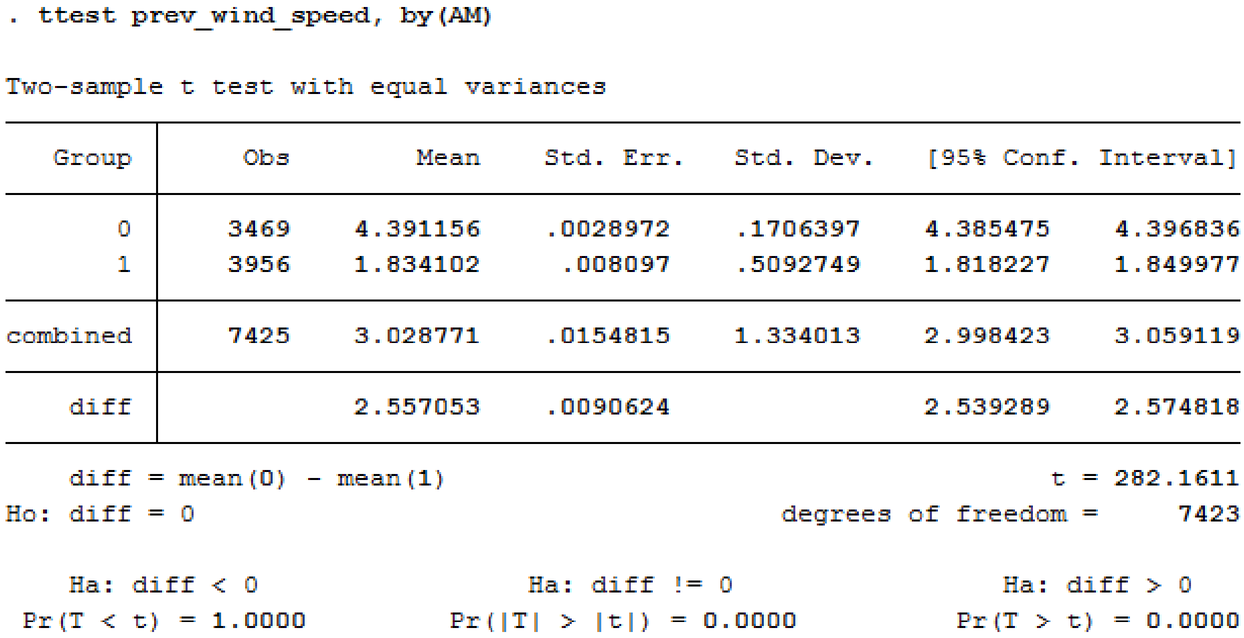
Table 11. Mean UFP Concentrations by Ongoing Acceleration Events



```
Summary for variables: FMPS
     by categories of: go_accel (Vehicle queue accels from red to green light)

go_accel |         N      mean        sd       p25       p50       p75
---------+------------------------------------------------------------
       0 |      7225  45663.15  66337.08     21500     29200     46300
       1 |       104  36878.46  28835.79     20800     28450     44650
---------+------------------------------------------------------------
   Total |      7329   45538.5  65961.52     21500     29200     46200
----------------------------------------------------------------------
```

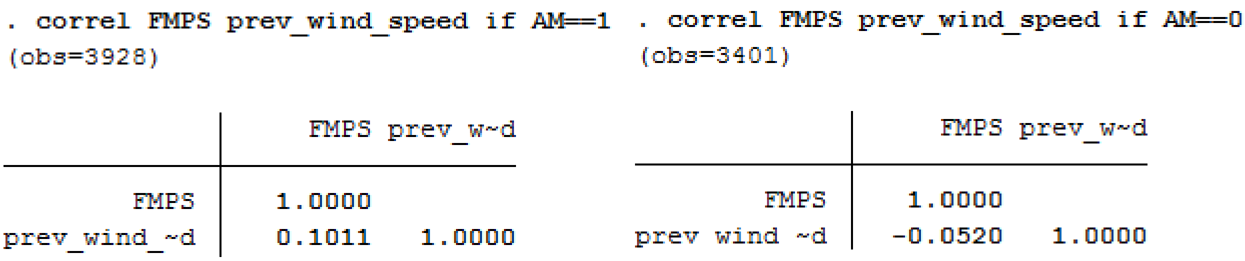
Meteorological Descriptives. The hourly average prevailing wind speed during sampling periods was around 3 m/s while mean UFP concentrations varied at higher and lower wind speeds (see Appendix B and C). The mean prevailing wind speed is more than twice as high in the afternoon than in the morning (~4.4 m/s vs. ~1.8 m/s, respectively; see Table 12). The correlation coefficient for prevailing wind speeds depending on UFP measurements (FMPS) is .10 while the afternoon wind speeds correlate with UFP concentrations with a coefficient of -.05 (see Table 13).

Table 12. Mean Prevailing Wind Speeds by Morning vs. Afternoon



```
. ttest prev_wind_speed, by(AM)

Two-sample t test with equal variances
------------------------------------------------------------------------------
   Group |     Obs        Mean    Std. Err.   Std. Dev.   [95% Conf. Interval]
---------+--------------------------------------------------------------------
       0 |    3469    4.391156    .0028972    .1706397    4.385475    4.396836
       1 |    3956    1.834102     .008097    .5092749    1.818227    1.849977
---------+--------------------------------------------------------------------
combined |    7425    3.028771    .0154815    1.334013    2.998423    3.059119
---------+--------------------------------------------------------------------
    diff |            2.557053    .0090624                2.539289    2.574818
------------------------------------------------------------------------------
    diff = mean(0) - mean(1)                                      t = 282.1611
Ho: diff = 0                                     degrees of freedom =     7423

    Ha: diff < 0                 Ha: diff != 0                 Ha: diff > 0
 Pr(T < t) = 1.0000         Pr(|T| > |t|) = 0.0000          Pr(T > t) = 0.0000
```

Table 13. UFP Concentrations by Prevailing Wind Speeds (AM vs. PM) Correlation

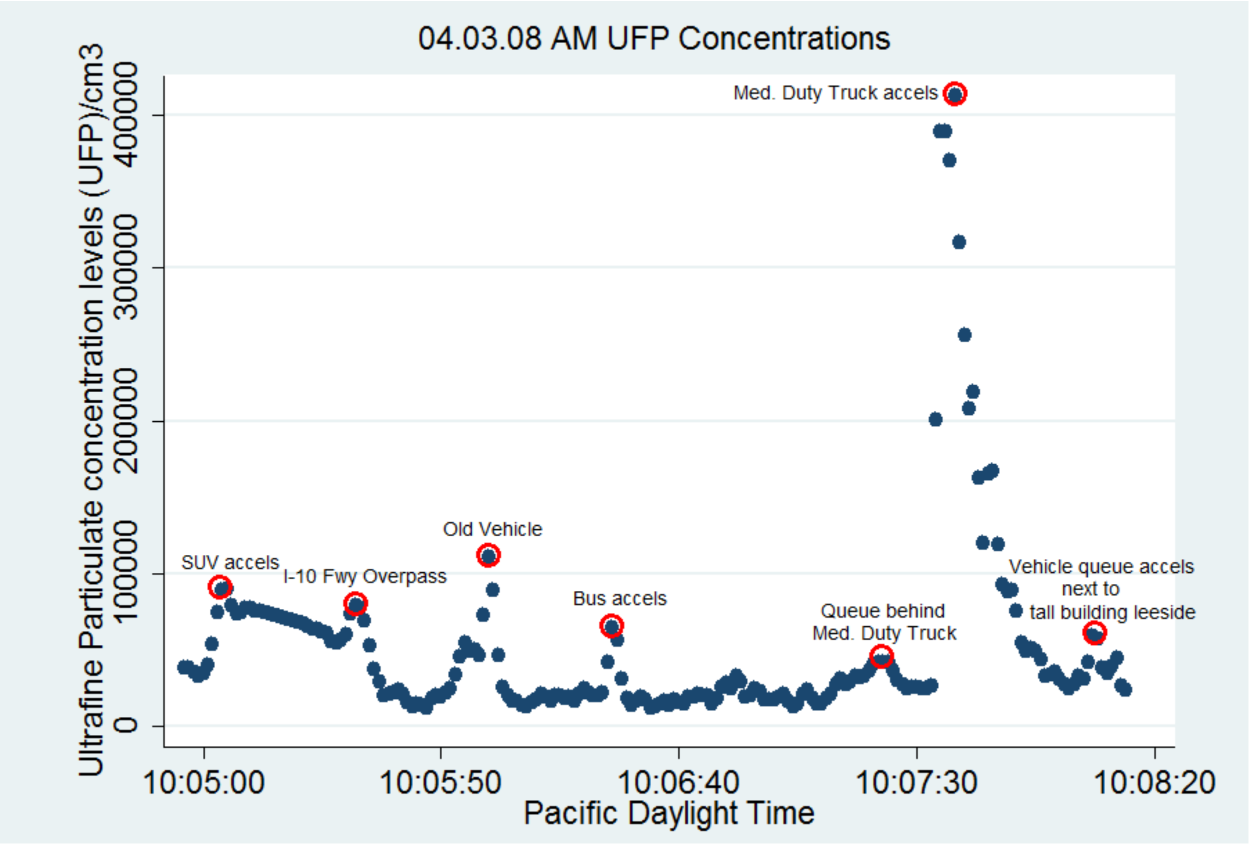


```
. correl FMPS prev_wind_speed if AM==1
(obs=3928)

             |     FMPS prev_w~d
-------------+------------------
        FMPS |   1.0000
prev_wind_~d |   0.1011   1.0000
```

```
. correl FMPS prev_wind_speed if AM==0
(obs=3401)

             |     FMPS prev_w~d
-------------+------------------
        FMPS |   1.0000
prev_wind_~d |  -0.0520   1.0000
```

1-Second Interval UFP Analysis. Below is a portion of a morning sampling period (n=199) that shows UFP concentrations at the one second resolution with conjectures on what (i.e., traffic, built environment, and meteorological) factors contribute to pollution spikes (see Figure 8). Most spikes were attributed to vehicle acceleration, old vehicles, diesel trucks, and the possible pollution build up against a tall building on the leeward side of the transect.

Figure 8. UFP Concentrations 1-Second Scatterplot

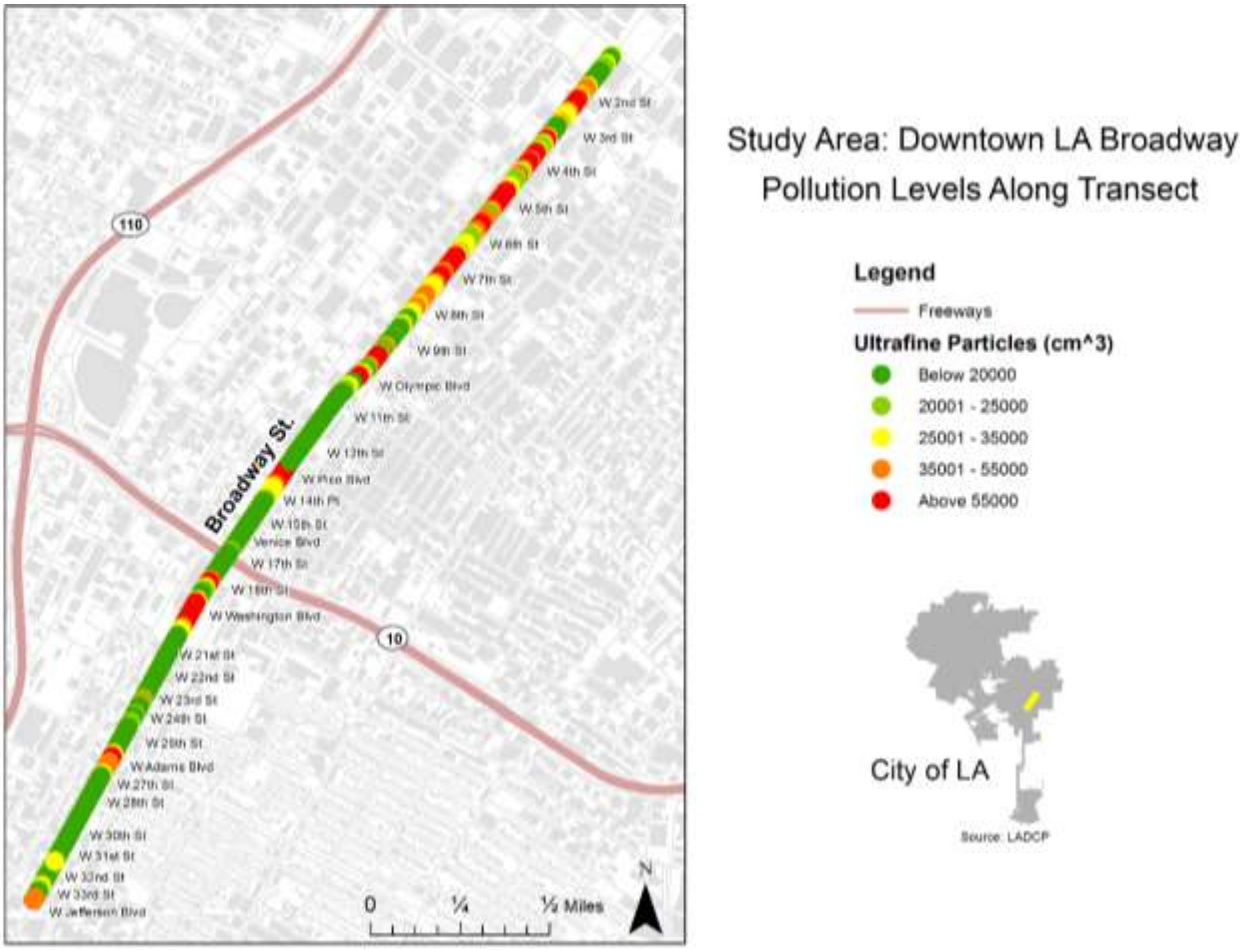


When conducting a spatial analysis, the transect has two distinct built environments (see Figure 9). The first portion (street canyon) of the transect visually has more observations of elevated UFP concentrations (above 55,000 UFP/cm^3) compared to the second portion (low buildings) of the transect that has more observations of background UFP concentrations (below 20,000 UFP/cm^3; see Figure 10).

Figure 9. 3-D Visual Broadway Transect

(*Source: ArcScene, LAR-IAC)*

Figure 10. UFP Concentrations 1-Second Scatterplot

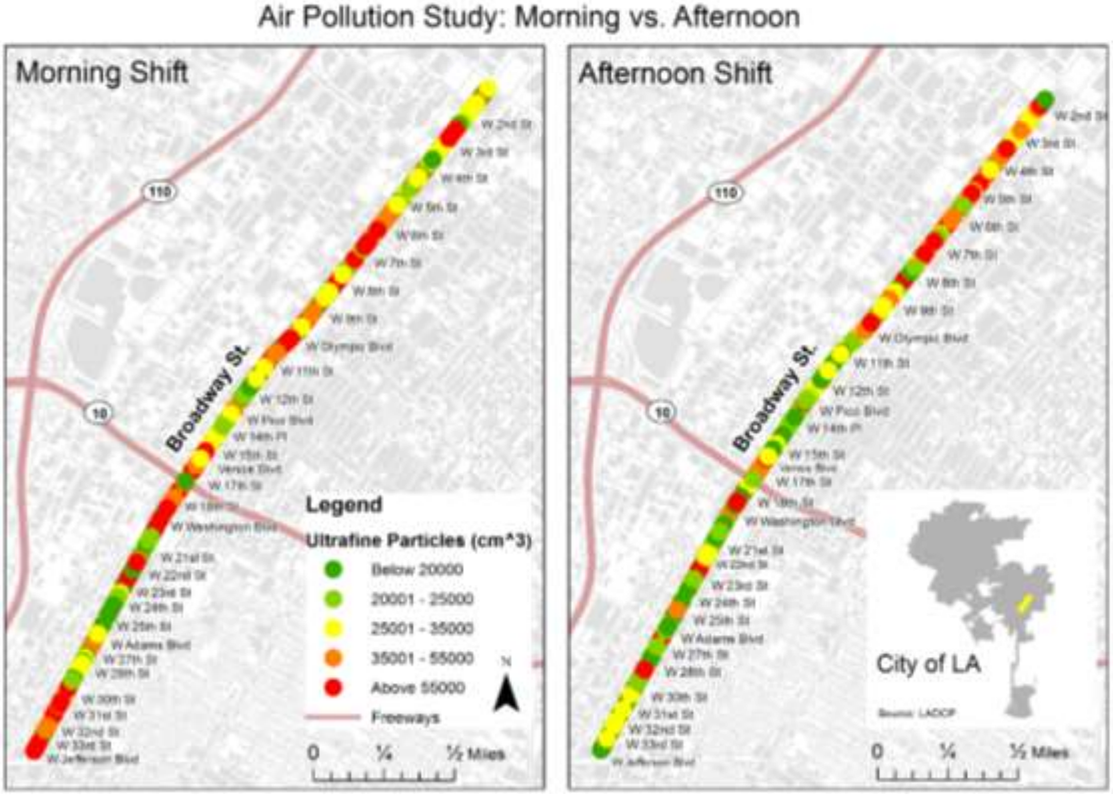


Morning vs. Afternoon Analysis. The remaining analysis is separated into morning and afternoon samples since the mean UFP concentration was higher in the morning than afternoon (~50,000 UFP/cm^3 vs. ~40,000 UFP/cm^3, respectively; see Table 14). When comparing the same spatial map divided into morning and afternoon samples, there are more elevated UFP concentrations (above 55,000 UFP/cm^3) in the morning than in the afternoon except in the street canyon portion (see Figure 11).

Table 14. Mean UFP Concentrations by Time of Day (AM vs. PM)

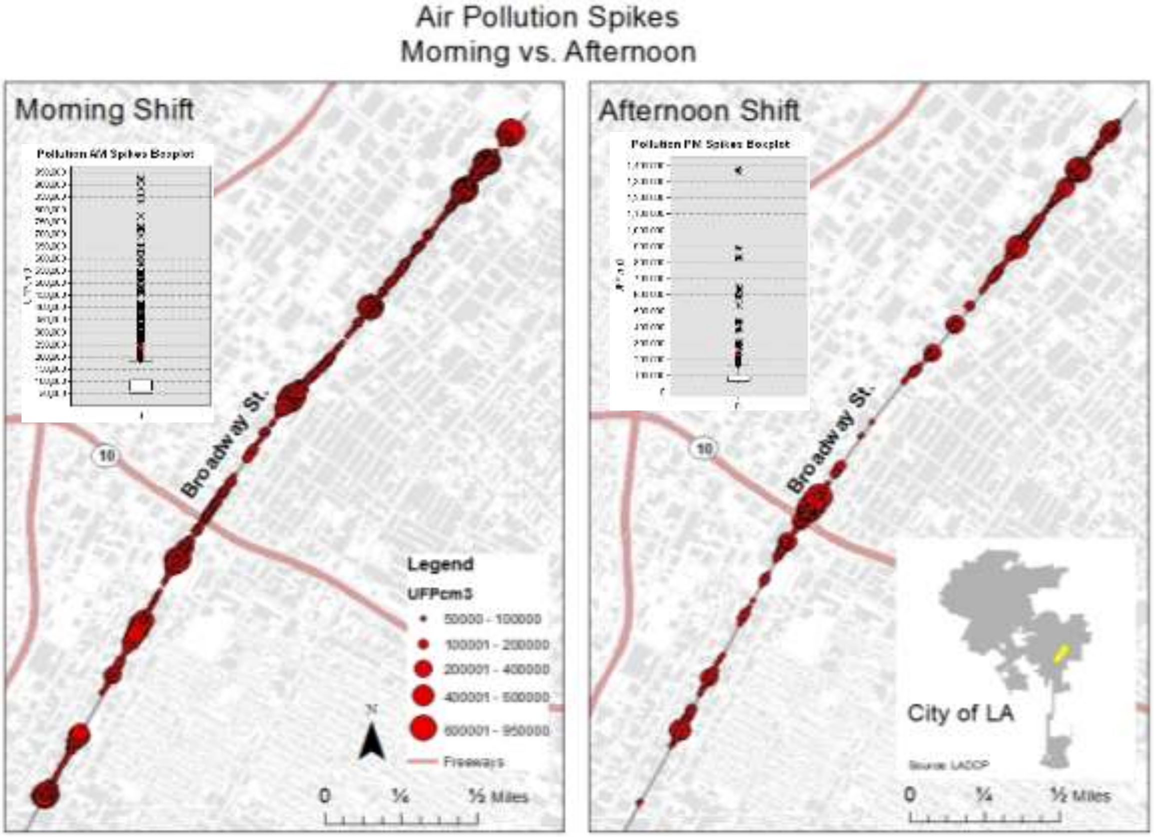
AM	N	mean	sd	p25	p50	p75
0	3401	40312.26	58343.36	20800	27200	41000
1	3928	50063.56	71608.55	22600	31600	51800
Total	7329	45538.5	65961.52	21500	29200	46200

Figure 11. UFP Concentrations by Time of Day (AM vs. PM)



When examining only the UFP pollution spikes (above 50,000 UFP/cm^3), the graduated symbol sizes corresponds with higher UFP concentrations. The box plots within the spatial maps convey that there are many more outliers in the morning measurements compared to the afternoon measurements. The morning shifts also has higher third quartile concentrations compared to the afternoon.There are more pollution spikes observed in the morning all throughout the transect compared to the afternoon samples that appear to be concentrated in the street canyon and near the I-10 freeway (see Figure 12).

Figure 12. UFP Pollution Spikes by Time of Day (AM vs. PM)



Based on Table 15, the difference in mean UFP concentrations among varying built microenvironment variables and vehicle acceleration were compared by different sides of the transect and times of the day for statistical significance using t-tests. The morning and afternoon mean UFP concentrations were significantly different such that morning concentrations are higher (p-value < .005). When comparing low and tall buildings, both east and west buildings had significantly higher mean UFP concentrations associated with low buildings (p-value < .05). However, when disaggregated by morning and afternoon measurements, only the morning average UFP concentrations for low east buildings showed significantly higher concentrations than tall buildings (p-value < .005). In terms of surface parking lots, east lots in the morning and afternoon were associated with significantly lower mean UFP concentrations compared to without eastern surface lots (p-value < .05). In contrast, west lots showed significantly higher mean UFP concentrations than without surface lots on the west side of the transect (p-value < .0005). When examining parking structures, none of the east side parking structures was significantly linked to mean UFP concentrations. West parking structures in both the morning and afternoon were significantly associated with lower mean UFP concentrations compared to when there was not a west parking structure (p-value < .005). Street trees were significantly associated with lower mean UFP concentrations in the afternoon only (p-value < .05). Ongoing vehicle acceleration was not significantly associated with mean UFP concentrations.

Table 15. Mean UFP Concentrations t-tests

UFP t-tests	Mean Values	Observed Mean Difference	t-value/p-value
AM vs. PM	50064 > 40312	9751	**2.64/.0084
Low vs Tall			
East Buildings	46589 > 42624	3964	*2.33/.0199
AM	51821 > 43984	7836	**3.27/.0011
PM	40472 > 40976	-504	-.21/.8333
West Buildings	45376 > 42071	3305	*2.14/.0324
AM	48758 > 46432	2325	.99/.32
PM	40373 > 37302	3071	1.66/.0955

Surface Parking Lot vs. ~Surface Parking Lot			
East Lots	38140 < 46497	-8357	***-3.45/.0005
AM	43592 < 50888	-7296	*-2.02/.04
PM	32043 > 41405	-9362	**-3.01/.0026
West Lots	49659 > 45155	4504	1.63/.1028
AM	47855 > 50268	-2413	-.59/.5564
PM	51723 > 39245	12478	***3.49/.0005
Parking Structure vs. ~Parking Structure			
East Structures	48539 > 45331	3208	1.03/.3054
AM	49254 < 50126	-872	-.20/.8443
PM	47512 > 39874	7638	-1.78/.0759
West Structures	31214 > 46825	-15611	****-5.58/.0000
AM	35880 < 50757	-14877	**-2.75/.0061
PM	29186 > 41884	-12698	****4.19/.0000
Trees vs. ~Trees	42967 < 46306	-7329	-1.82/.0684
AM	48850 < 50444	-1594	-.59/.5520
PM	35571 < 41645	-6074	*-2.51/.0120
Ongoing Accel vs. ~Ongoing Accel	36878 < 45663	-8785	-1.35/.1775
AM	39211 > 50221	-11009	-1.14/.2534
PM	34156 > 40400	-6244	-.74/.4617

UFP Concentrations by Intersection Analysis. Spatial analysis of UFP concentrations at intersections with 20m buffers show that most intersections in the street canyon have elevated UFP levels (above 55,000 UFP/cm^3) except at the 7th Street in the morning measurements which has low UFP concentrations (below 20,000 UFP/cm^3; see Figure 13). Most of the second half transect intersections in the morning except W 21st Street, W 27th Street, and W 28th Street have higher UFP concentrations (above 35,000 UFP/cm^3). When examining the box plots of UFP concentrations by intersection, W Adams Blvd has the highest 75th percentile and maximum UFP concentrations when excluding outliers (see Figure 14).

Figure 13. Spatial Analysis of UFP Concentrations by Intersection (AM vs. PM)

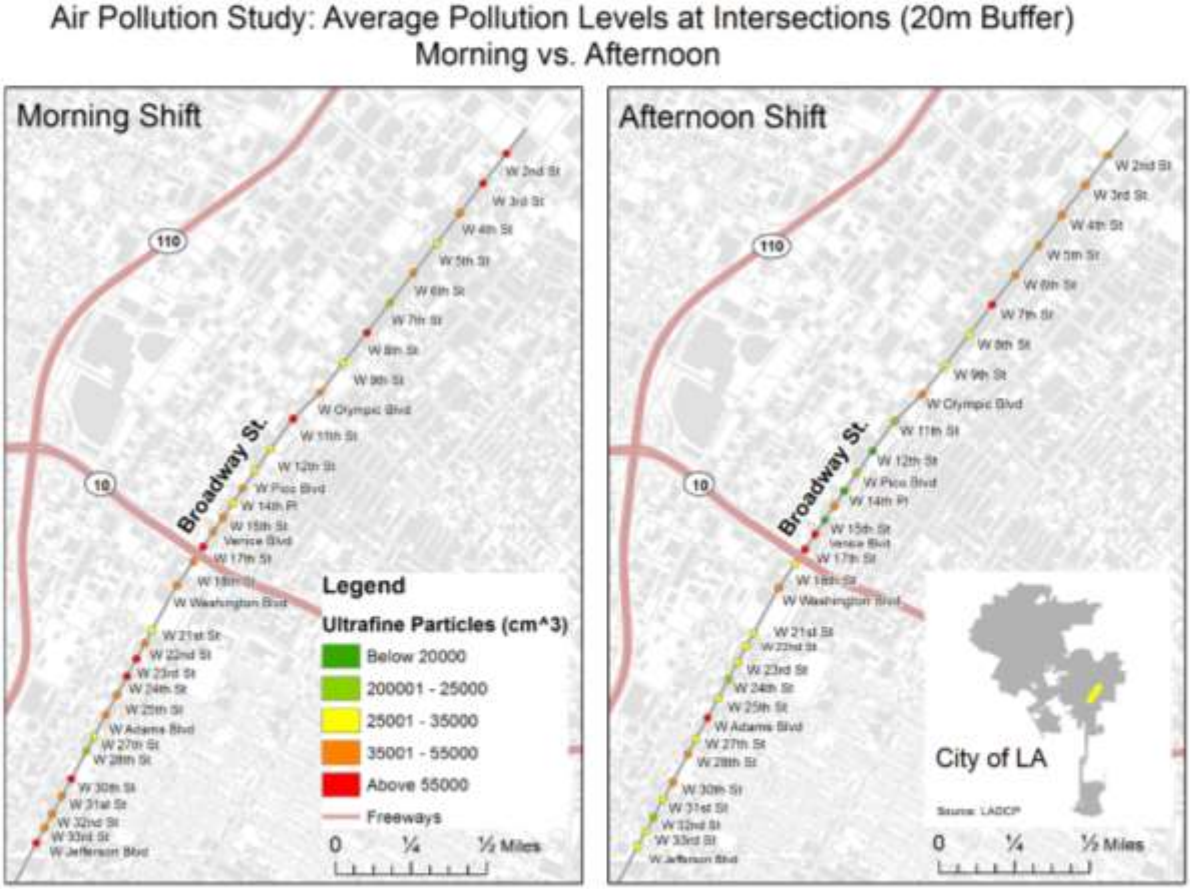
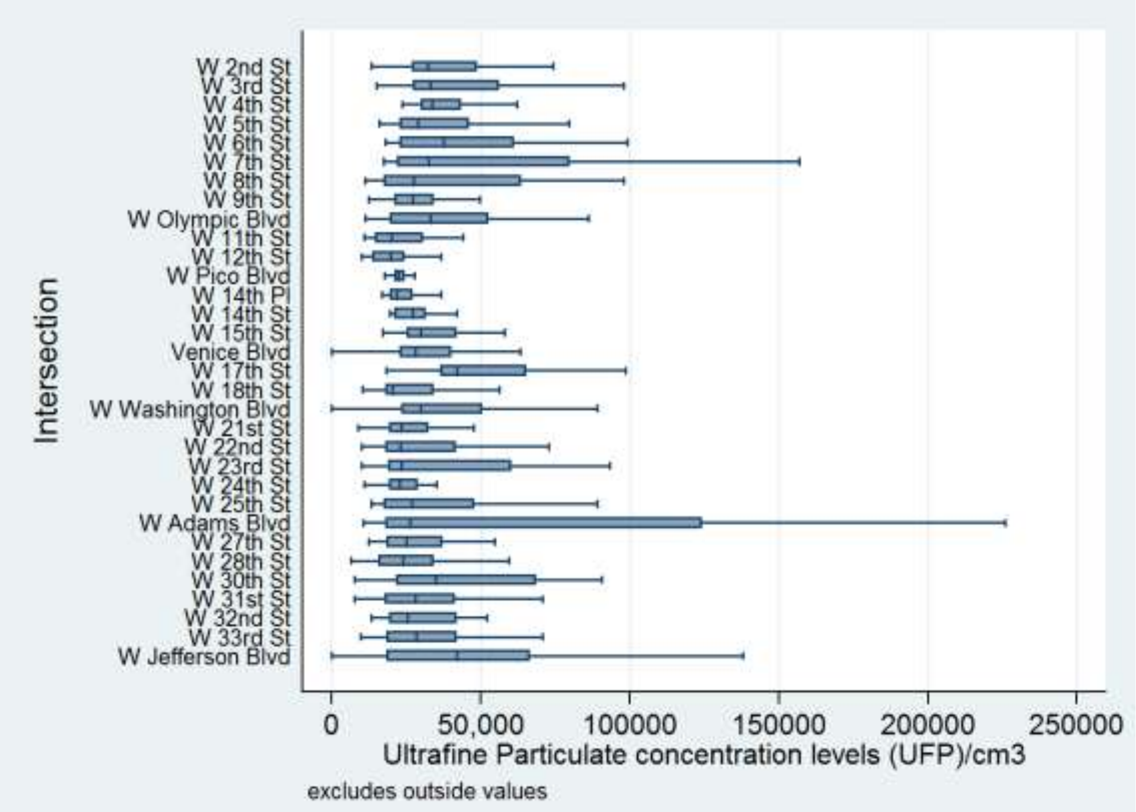


Figure 14. Box Plot of UFP Concentrations by Intersection



When comparing mean UFP concentrations using t-tests by an intersection indicator variable, intersections in the morning were significantly associated with higher average UFP concentrations than measurements not at the intersection (p-value < .0005). When a 20 meter buffer was added around intersections, elevated morning concentrations were still significantly associated with intersections (p-value < .005; see Table 16).

Table 16. UFP Mean Concentrations t-tests by Intersection

UFP t-tests	Mean Values	Observed Mean Difference	t-value/p-value
Intersection vs. ~Intersection	51109 > 44394	6715	**3.28/.0010
AM	59274 > 48281	10993	***3.55/.0004
PM	42611 > 39808	2803	1.08/.2818
Intersection (20m) vs. ~Intersection (20m)	47103 > 44817	2286	1.38/.1679
AM	55466 > 47632	7834	**3.18/.0015
PM	37792 > 41509	-3717	1.74/.0826

Inclusion of Outliers. There are two outlying pollution concentrations that are above a million ultrafine particle numbers per cubic centimeters and roughly 20 standard deviations away from the mean concentration. These points occurred jointly after “hard acceleration” of a utility truck immediately ahead of the MMP as mentioned (in the recorded traffic video footage field conversation) by Emeritus UCLA Professor Arthur Winer (A. Winer, personal communication, April 3, 2008). The pollution spike may also be attributed to a school bus (most likely diesel run and outdated by appearance) that crossed the intersection 12 seconds beforehand. However, these two outliers did not drastically change the outcomes of the results, and therefore, were included in the study.

CONCLUSION

Mean UFP concentrations along the transect is about twice the background concentrations which is skewed most likely by high emitting vehicles and acceleration events. Lower mean UFP concentrations were associated with the MMP being positioned farther down the vehicle queue at an intersection which was similarly reflected by the increasing number of ongoing passenger vehicle counts. Elevated mean UFP levels were associated with ongoing old vehicles and medium and heavy duty trucks. Prevailing wind speeds were calmer in the morning compared to afternoon measurements. Significantly higher UFP concentrations and pollution spikes were found in morning compared to afternoon measurements. Spatially speaking, higher pollution concentrations occurred more frequently in the street canyon section of the route than in the lower buildings section. At first glance, taller buildings corresponded with lower mean UFP concentrations more than low buildings; however, only lower morning UFP concentrations were significantly associated with tall east buildings. Surface parking lots were significantly associated with lower mean UFP concentrations compared to when there were no parking lots. The only exception was west parking lots in afternoon measurements were significantly associated with higher mean UFP concentrations. In terms of parking structures, west structures were significantly associated with both lower (in the morning) and higher (in the afternoon) mean UFP concentrations. The intersection level of UFP concentrations results were consistent with findings in the 1-second interval analysis with spatially higher concentrations in the street canyon and significantly higher mean UFP concentrations at intersections than when not at intersections.

DISCUSSION

Explanation of Results. Although other directions of (oncoming and cross) traffic data were collected in this study, the analysis was focused on ongoing traffic because it is the most direct source of tail pipe emissions exposed to the MMP. Longer queues generally declined in mean UFP pollution concentrations most likely due to the MMP positioned farther away from moving and accelerating traffic at the intersection that are associated with higher UFP levels (Klems et al., 2010). The bus counts were flagged as uncertain sources of UFP matter because LA Metro was in the process of converting their bus fleet from diesel exhaust to natural gas (Littman & Ortiz-Gilstrap, 2011).

Ongoing passenger vehicle counts may also be reflective of a long queue while MMP is still in motion either approaching or navigating down the street next to a lane with a vehicle queue. Counterintuitive (although mostly insignificant) findings that lower UFP concentrations were associated with tall buildings and higher concentrations were associated with low buildings must be explored further in multivariate regression analyses that control for other factors such as high emitting vehicles, prevailing and surface level wind conditions, and microenvironment variables (Bishop et al., 2012; Boarnet et al., 2011). Morning concentrations were significantly higher most likely because the winds were calmer which impeded air flow mixing and also because of build up of UFP concentrations due to inversion layer that forms over night (CARB, 2012; Hu et al., 2009). Prevailing southwesterly winds may suggest a trapping of concentrations on the leeward (downwind) side of tall buildings within the street canyon (Moeseke et al., 2005). The elevated UFP concentrations at intersections surrounded by low buildings such as W Adams Bldv may be attributed to tall trees with dense canopies lining either side of the street that may trap pollution at the surface level.

Limitations. Although this study has taken a highly resolved look at UFP concentrations in the built and meteorological context, this transect study's air pollution concentrations are not generalizable to the rest of Los Angeles since each site of analysis varies by meteorological, built environment, and traffic conditions. Since the prevailing southwesterly winds may run parallel to this transect that runs north and south, this study may not be comparable to other studies analyzing street canyon effects. Even within the study area, concentrations measured during the summer months will not be representative of other months in the year due to seasonal changes (Boarnet et al., 2011; Hu et al., 2009). This study's collection methods of mobile pollution measurements has been repeated in previous air pollution studies that have also used the Air Resources Board MMP vehicle (Hu et al., 2009; Kozawa et al., 2009; Kozawa et al., 2012; Westerdahl et al., 2005). In addition to the limited samples available for other pollutants due to equipment malfunction, ultrafine particulate matter was selected as the study's measure of traffic-related air pollution because it serves as a highly resolved tracer of vehicle exhaust and is linked with adverse health outcomes (Kumar et al., 2010; Kumar et al., 2011; HEI, 2012). However, ultrafine particle concentrations tend to reduce drastically with distance from tailpipe sources (HEI, 2012).

The MMP's air inlet being positioned towards the sidewalk and not facing forward at the front of the vehicle may have changed the observed pollution concentrations. Therefore, exposure levels may be better simulated for a pedestrian and less so for a cyclist. Even when relating to exposure, there was a disconnect between travel activities of a pedestrian (e.g., walking along the sidewalk, waiting at a bus stop or corner of an intersection) and the travel activities of the MMP in terms of speed and spatial location in a queue. It is also important to consider secondary sources of UFP emissions such as from restaurant vents or cigarette smoke. Overall, the volatile nature of ultrafine particulate matter makes it difficult to spatially and temporally characterize exposure pathways (HEI, 2012; Kowaza et al., 2012; Kumar et al., 2011).

Another drawback was that traffic counts could not be collected at a fixed point since the video footage moved with the flow of traffic. Also we had a limited ability to see the full queue length at an intersection since only vehicles in the view of the camera were counted. There was no guarantee that any old vehicle was necessarily a high emitting vehicle. There was also a chance that poorly maintained vehicles from the 1990s or early 2000s could be high emitters. Additionally, the poor video quality made it challenging to discern how many and what type of vehicles were traveling ahead of the MMP in the distance. In general, the traffic data was subject to human error and discretion in classifying vehicles by weight, age, and queue accelerations. Although this study attempts to make direct traffic observations, this proximity model does not directly account for how ultrafine particles disperse based on its physical and chemical properties (HEI, 2012). Furthermore, dispersion behavior from traffic-induced turbulence or surface level wind conditions was not measured because the data from the sonic anemometer mounted to the MMP was limited and unavailable. In terms of other technological errors, the GPS tracking unit was subject to signal drift whenever the MMP was in queue therefore quality assurance measures were taken to check if geographic coordinates showed a logical progression through the transect by time. While this study tried to include other microenvironment variables such as an indicator for street trees, the influence of the tree as a carbon sink or dispersion hindrance could not be determined since the species of trees and canopy sizes were not measured (Ottele et al, 2010; Hagler et al., 2012; Grome & Ruck, 2007).

Future research. While many studies focus on pollution concentrations near freeways, there has also been a growing interest in examining ultrafine particulate concentrations along major arterials given varying surface roughness factors at the microenvironment scale (Zhu et al., 2002; Hu et al., 2009; Hudda & Fruin, 2013). Future studies should combine methods of examining arterials and major intersections across varying built environments, traffic management strategies, exposure by travel modes, and levels of social economic status neighborhoods (Klems et al., 2010; Boarnet et al., 2011; Kaur et al., 2006; Houston et al., 2004). Multiple air monitoring instruments (i.e., DiSCmini, CPC, FMPS) should be used to test internal validity of both mobile and stationary pollution measurements (Westerdahl et al., 2005; Klems et al., 2010; TSI, 2014). Mobile measurements should be taken both in-vehicle and pedestrian mounted to test exposure through different travel modes (Kaur et al., 2006). Air monitors should also be placed indoors to capture secondary sources of emissions of such as from stovetop cooking. Studying indoor concentrations is also important because people may spend a majority of their time inside where they are chronically exposed to pollutants over long periods of time (Houston et al., 2013). Especially within this street canyon portion of the transect, many units had open air store fronts that may be easily accumulating traffic-related air pollution.

Future studies should also make sure to compare ambient and local measurements of traffic volume and wind conditions in terms of prevailing and surface street level (Boarnet et al., 2011; Wu et al., 2009; Baldauf et al., 2013). Particularly studies should be conducted at sites with different wind orientations of parallel and especially perpendicular flows through a street canyon (Moeseke et al., 2005). Studies sampling at different times of the day including pre-sunrise hours and seasons including cold winters may be able to better inform how to reduce exposures to extended localized concentrations for long-term land uses such as residential areas (Hu et al., 2009; Boarnet et al., 2011). Further exploration surface roughness variables such as street tree species, crown sizes, sound walls, and even curbside parking occupancy as possible pollution barriers should be examined as well (Ottele et al., 2010; Vardoulakis et al., 2003; Kumar et al., 2011; Gromke & Ruck, 2007; Hagler et al., 2012; Heist & Perry, 2009; Gallagher et al., 2011). Air pollution dispersion and land use regressions models coupled with computational fluid dyanmics should be used to incorporate traffic-related, spatial, microenvironment, and meteorological factors influencing air pollution concentrations (Vardoulakis et al., 2003; MacDonald et al., 2003, Mensink et al., 2003; Wu et al., 2009; Ryan & LeMasters, 2007; HEI, 2010). However, these models may be very data and computational intensive and robustness of simulations depend heavily on the model assumptions (HEI, 2010). Therefore, direct measurement studies must continue to be conducted to inform these simulations and dispersion models (Kumar et al., 2010). Additionally, statistical models using multivariate regression and panel analyses may incorporate lag structures to capture how air pollution disperses from a tailpipe after vehicle acceleration events.

Due to more efficient fuel and cleaner vehicle technological advancements, future studies may want to direct their attention on to how to reduce resuspended road dust, tire and break wear, and other sources of noncombustion particulate emissions from motor vehicles that will increasingly become a larger proportion of traffic-related air pollution (HEI, 2010).

Policy Recommendations. Future planning of transit-oriented developments (TOD) must be examined for air pollution exposure on a case by case basis. In general, a TOD toolkit of best practices learned from this study and literature review would recommend the following:

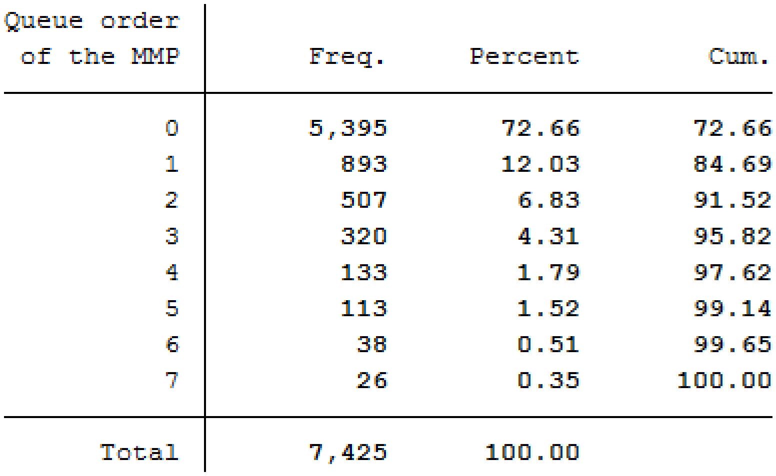
- TOD designs should consider existing and projected contexts of the surrounding built-environment, traffic, and meteorological conditions.
- Vary building heights in dense developments to lessen street canyon effect.
- Orient buildings to facilitate air dispersion based on prevailing winds.
- Encourage traffic management strategies that avoid acceleration of long queues.
- Avoid placing developments that generate heavy foot traffic and outdoor pedestrian dwelling times in the morning (i.e., coffee shops) on the leeward (downwind) side of busy intersections.

- Place bus stops on the far-side (after crossing intersection) to reduce exposure to vehicle plumes due to acceleration from traffic lights.
- Design bus shelters that minimize trapping of air pollutants.
- Mindful green landscaping (i.e., street tree's canopy size as carbon sink vs. concentrating pollution) that suits streetscape context.
- Mandate (not recommend) siting sensitive (i.e., school, hospital, residential) land uses 500ft away from major freeways.
- Use Cap and Trade proceeds to fund further research to inform SB 375's smart growth strategies of environmental justice and public health implications.

To enhance our understanding of traffic-related air pollution exposure, the Air Resources Board should accelerate their adoption of an extensive, air monitoring network at the local level where population density and pollution concentrations are variably high (HEI, 2010). These air monitoring networks should implement standardized air monitor instruments that expand the particle size distribution analyzed and focuses on particle number counts as unit of analysis for consistent regulatory purposes and comprehensive validiation of particle dispersion models (Kumar et al., 2011).

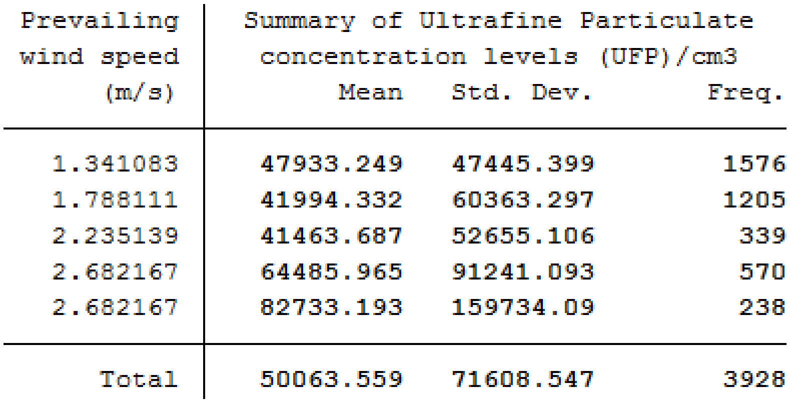
APPENDIX

A. Frequency and cumulative percentage of MMP queue position



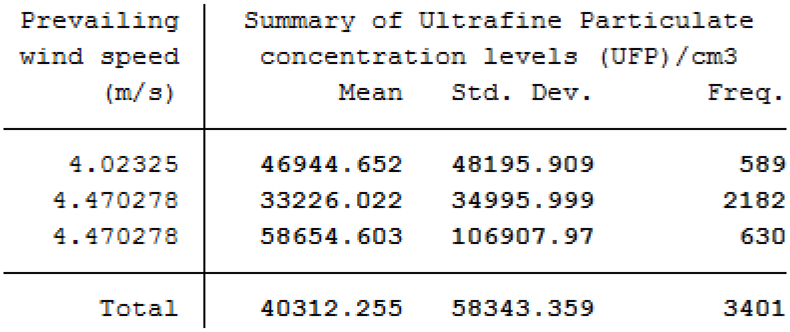
```
Queue order |
 of the MMP |      Freq.     Percent        Cum.
------------+-----------------------------------
          0 |      5,395       72.66       72.66
          1 |        893       12.03       84.69
          2 |        507        6.83       91.52
          3 |        320        4.31       95.82
          4 |        133        1.79       97.62
          5 |        113        1.52       99.14
          6 |         38        0.51       99.65
          7 |         26        0.35      100.00
------------+-----------------------------------
      Total |      7,425      100.00
```

B. Mean UFP Concentrations by Prevailing Wind Speeds (AM)



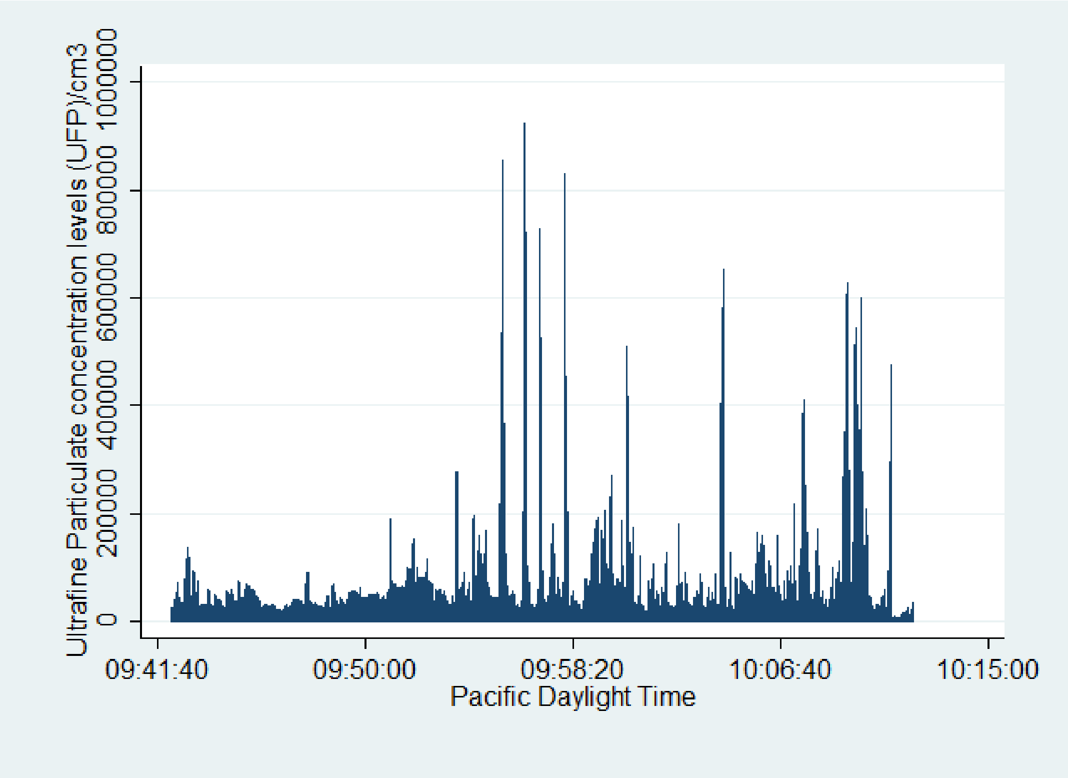
```
 Prevailing |  Summary of Ultrafine Particulate
 wind speed |   concentration levels (UFP)/cm3
      (m/s) |        Mean   Std. Dev.       Freq.
------------+------------------------------------
   1.341083 |   47933.249   47445.399        1576
   1.788111 |   41994.332   60363.297        1205
   2.235139 |   41463.687   52655.106         339
   2.682167 |   64485.965   91241.093         570
   2.682167 |   82733.193   159734.09         238
------------+------------------------------------
      Total |   50063.559   71608.547        3928
```

C. Mean UFP Concentrations by Prevailing Wind Speeds (PM)

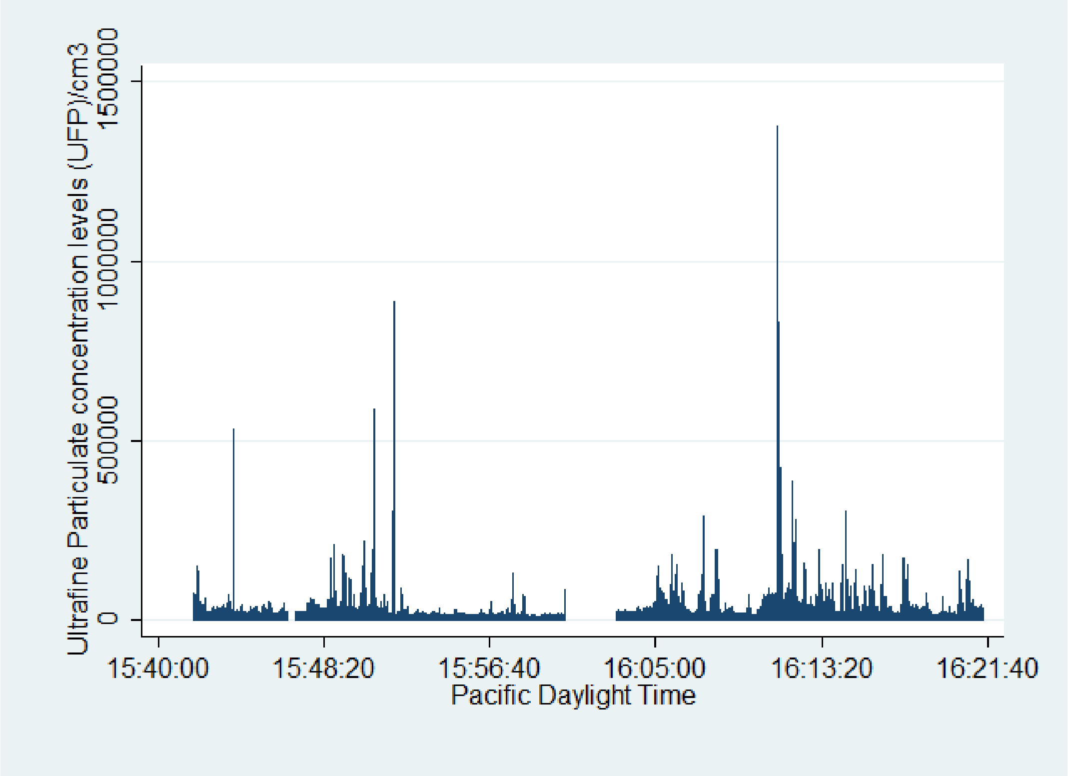


```
 Prevailing |  Summary of Ultrafine Particulate
 wind speed |   concentration levels (UFP)/cm3
      (m/s) |        Mean   Std. Dev.       Freq.
------------+------------------------------------
    4.02325 |   46944.652   48195.909         589
   4.470278 |   33226.022   34995.999        2182
   4.470278 |   58654.603   106907.97         630
------------+------------------------------------
      Total |   40312.255   58343.359        3401
```

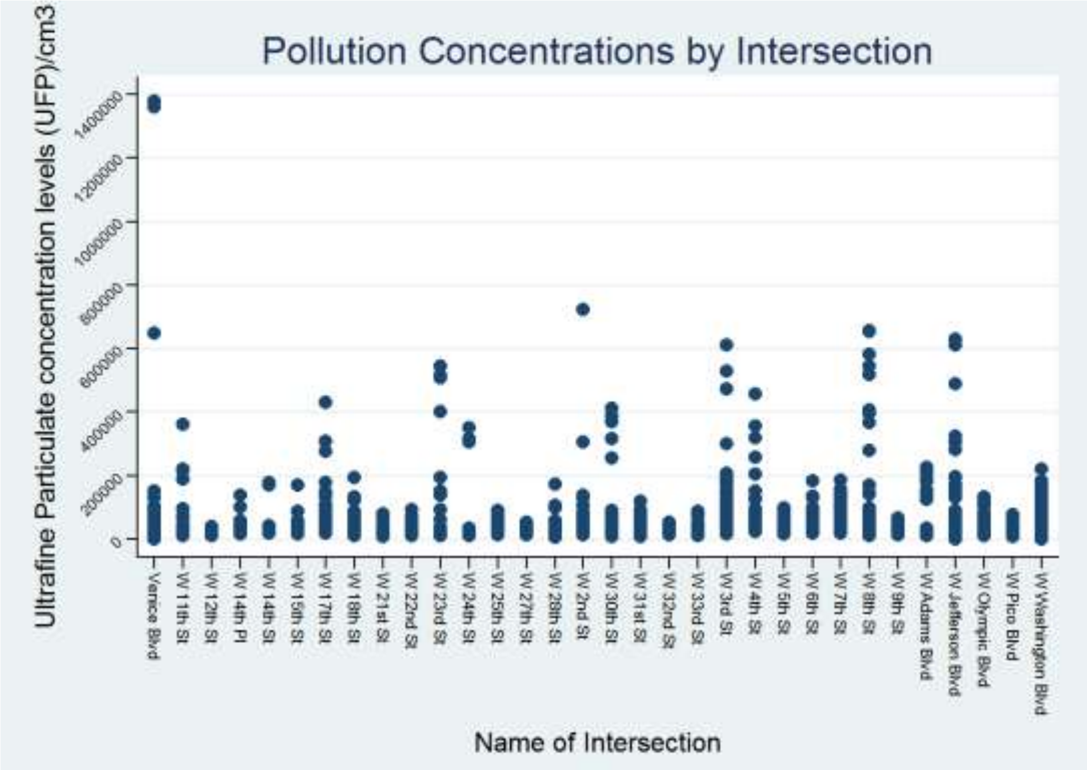
D. UFP Concentrations by 1-Second Intervals for Morning Measurements



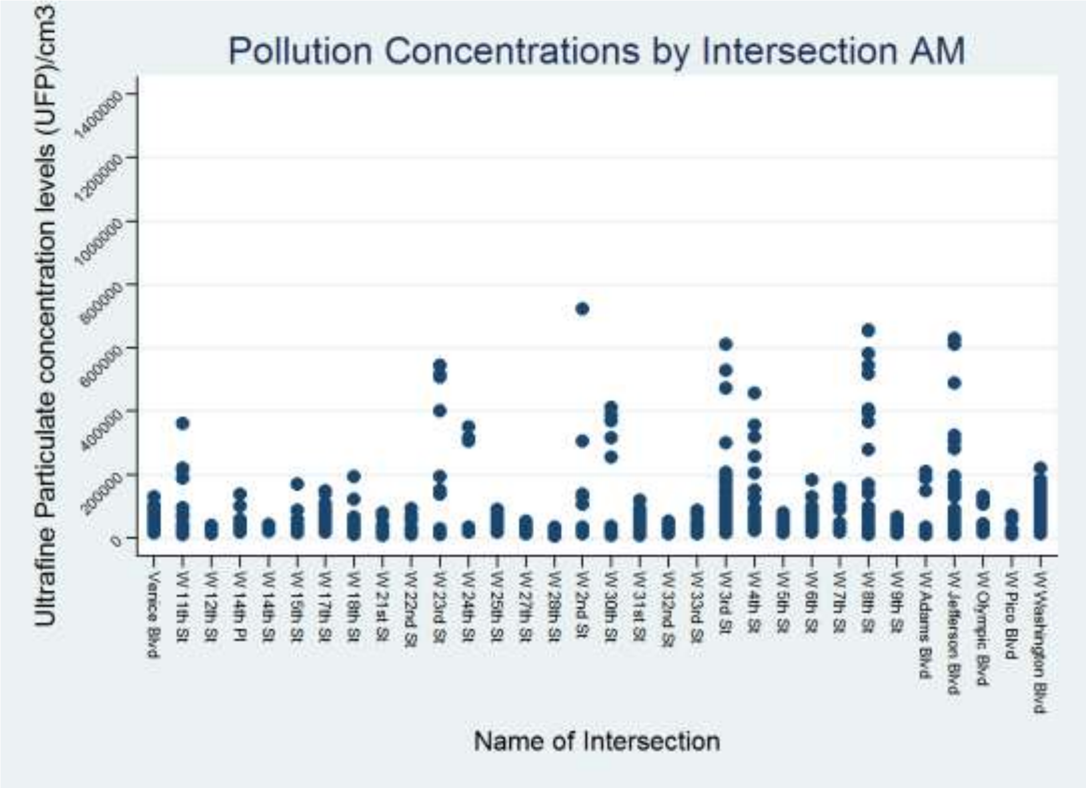
E. UFP Concentrations by 1-Second Intervals for Afternoon Measurements



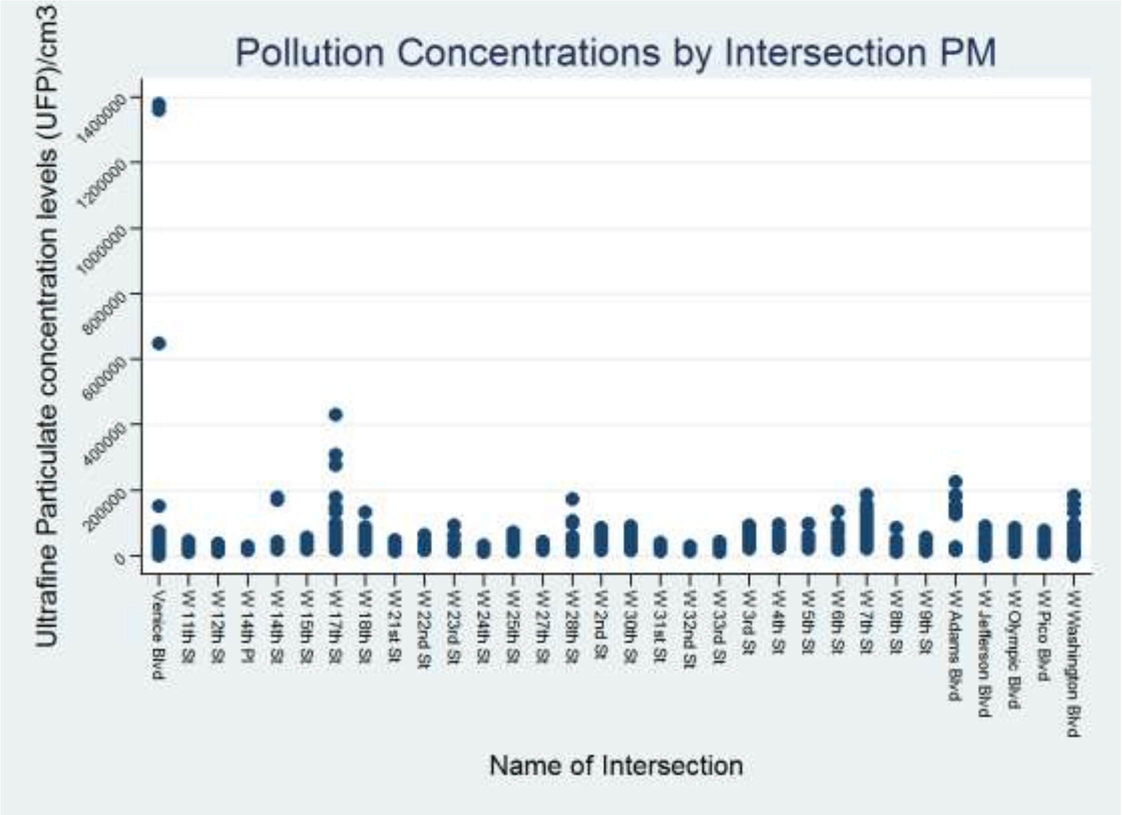
F. UFP Concentrations by Intersection



G. UFP Concentrations by Intersection (AM)



H. UFP Concentrations by Intersection (PM)



REFERENCES

Air Quality Management District. (2014, May 8). *Near roadway air monitoring network.* Retrieved from http://www.aqmd.gov/tao/AQ-Reports/AQMonitoringNetworkPlan/NearRoadMonitoring2.htm

Andersen, Z.J., Wahlin, P., Raaschou-Nielsen, O., Ketzel, M., Scheike, T., Loft, S. (2008). Size distribution and total number concentration of ultrafine and accumulation mode particles and hospital admissions in children and elderly in Copenhagen. *Occupational and Environmental Medicine, 65*(7), 458-466.

Araujo, J. A. and Nel, A.E. (2009). Particulate matter and atherosclerosis: role of particle size, composition and oxidative stress. *Particle And Fibre Toxicology*, *6*, 19.

Baldauf, R.W., Heist, D., Isakov, V., Perry, S., Hagler, G.S.W., Kimbrough, S., Shores, R., Black, K., & Brixy, L. (2013). Air quality variability near a highway in a complex urban environment. *Atmospheric Environment, 64*, 169-178.

Bishop, G.A., Schuchmann, B.G., Stedman, D.H., & Lawson, D.R. (2012). Multispecies remote sensing measurements of vehicle emissions on Sherman Way in Van Nuys, California. *Journal of the Air & Waste Management Association*, *62*(10), 1127-1133. doi:10.1080/10962247.2012.699015

Boarnet, M.G., Houston, D., Edwards, R., Princevac, M., Ferguson, G., Pan, H., & Bartolome, C. (2011). Fine particulate concentrations on sidewalks in five Southern California cities. *Atmospheric Environment, 45*, 4025-4033.

Brugge, D., Durant, J.L., & Rioux, C. (2007). Near-highway pollutants in motor vehicle exhaust: a review of epidemiologic evidence of cardiac and pulmonary health risks. *Environmental Health, 6*, 23.

California Air Resource Board. (2012). Key events in the history of air quality in California. *ARB.* Retrieved from http://www.arb.ca.gov/html/brochure/history.htm

California Air Resources Board (2013). Sustainable communities. Retrieved from http://www.arb.ca.gov/cc/sb375/sb375.htm

Chan, A.T., Au, T.A., So, E.S. (2003). Strategies guidelines for street canyon geometry to achieve sustainable street air quality. *Atmospheric Environment*, *35*, 4089-4098.

Choi, H., Rauh, V., Garfinkel, R., Tu, V., & Perera, F.P. (2008). Prenatal exposure to airborne polycyclic aromatic hydrocarbons and risk of intrauterine growth restriction. *Environmental Health Perspectives, 116,* 658-665.

Eeftens, M., Beekhuizen, J., Beelen, R., Wang, M., Vermeulen, R., Brunekreef, B., Huss, A., & Hoek, G. (2013). Quantifying urban street configuration for imporvemetns in air pollution models. *Atmospheric Environment, 72*, 1-9.

Ewing, R. & Cervero, R. (2001). Travel and the built environment - synthesis. *Transportation Research Record, 1780,* 87-106.

Faust, J., August, L.M., Alexeff, G., Bangia, K., Cendak, R., Cushing, L., . . . Zeise, L. (2013). California communities environmental health screening tool, version 1.1. *Office of Environmental Health Hazard Assessment.* Retrieved from http://oehha.ca.gov/ej/pdf/CalEnviroscreenVer11report.pdf

Gallagher, J., Gill, L.W., McNabola, A. (2011). Optimizing the use of on-street car parking system as a passive control of air pollution exposure in street canyons by large eddy simulation. *Atmospheric Environment, 45*, 1684-1694.

Gromke, C. & Ruck, B. (2007). Influence of trees on the dispersion of pollutants in an urban street canyon—Experimental investigation of the flow and concentration field. *Atmospheric Environment, 41*, 3287–3302.

Hagler, G.S., Lin, M., Khlystov, A., Baldauf, R.W., Isakov, V., Faircloth, J. & Jackson, L.E. (2012). Field investigation of roadside vegetative and structural barrier impact on near-road ultrafine particle concentrations under a variety of wind conditions. *Science of the Total Environment*, *419*, 7-15.

Health Effects Institute. (2010). Traffic-related air pollution: A critical review of the literature on emissions, exposure, and health effects. *Health Effects Institute, 17.* Boston, Massachusetts.

Heist, D.K. & Perry, S.G. (2009). A wind tunnel study of the effect of roadway configurations on the dispersion of traffic-related pollution. *Atmospheric Environment, 43*, 5101–5111.

Houston, D., Wu, J., Ong, P., & Winer, A.M. (2004). Structural disparities of urban traffic in southern California: Implications for vehicle-related air pollution exposure in minority and high-poverty neighborhoods. *Journal of Urban Affairs, 25,* 565-592.

Houston, D., Krudysz, M., & Winer, A.M. (2008). Diesel truck traffic in port-adjacent low-income and minority communities: Environmental justice implications of near-roadway land use conflicts. *Transportation Research Record: Journal of the Transportation Research Board, 2076,* 38-46.

Houston, D., Wu, J., Yang, D., & Jaimes, G. (2013). Particle-bound polycyclic aromatic hydrocarbon concentrations transportation microenvironments. *Atmospheric Environment, 71,* 148-157.

Hu, S. S., Fruin, S., Kozawa, K., Mara, S., Paulson, S. E., & Winer, A.M. (2009). A wide area of air pollutant impact downwind of a freeway during pre-sunrise hours. *Atmospheric Environment, 43*(16): 2541-2549.

Hudda, N. & Fruin, S.A. (2013). Models for predicting the ratio of particulate pollutant concentrations inside vehicles to roadways. *Environmental Science & Technology, 47*, 11048-11055.

Hunter, L.J., Watson, I.D., & Johnson, G.T. (1990/91). Modelling air flow regimes in urban canyons. Energy and Building, *15–16*, 315–324.

Karra, S., Malki-Epshtein, L., Neophyton, M. (2011). The dispersion of traffic related pollutants across a non-homogeneous street canyon. *Procedia Environmental Sciences*, *4*, 25-34.

Kaur, S.S., Clark, R.R., Walsh, P.T., Arnold, S.J., Colvile, R.N., & Nieuwenhuijsen, M.J. (2006). Exposure visualization of ultrafine particle counts in a transport microenvironment. *Atmospheric Environment,* 40(2), 386-398. doi:10.1016/j.atmosenv.2005.09.047

Klems, J.P., Pennington, M.R., Zordan, C.A., & Johnston, M.V. (2010). Ultrafine particles near a roadway intersection: Origin and apportionment of fast changes in concentration. *Environmental Science & Technology, 44*, 7903-7097.

Kozawa, K.H., Winer, A.M., Fruin, S.A. (2012). Ultrafine particle size distributions near freeways: Effects of differing wind directions on exposure. *Atmospheric Environment, 63*, 250-260.

Kumar, P., Robins, A., Vardoulakis, S., Britter, R. (2010). A review of the characteristics of nanoparticles in the urban atmpshere and the prospects for developing regulatory controls. *Atmospheric Environment, 44*, 5035-5052.

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., & Britter, R. (2011). Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment—A review. *Journal of Aerosol Science*, *42*, 580-603.

Künzli, N., McConnell, R., Bates, D., Bastain, T., Hricko, A., Lurmann, F., & Peters, J. (2003). Breathless in Los Angeles: The exhausting search for clean air*. American Journal of Public Health, 93*, 1494-1499.

Li, N., Sioutas, C., Cho, A., Schmitz, D., Misra, C. , Sempf, J., Wang, M.Y., Oberley, T., Froines, J., & Nel, A. (2003). Ultrafine particulate pollutants induce oxidative stress and mitochondrial damage. *Environmental Health Perspectives*, *111*(4): 455-460.

Lipfert, F.W., Wyzga, R.E. (2008). On exposure and response relationships for health effects associated with exposure to vehicular traffic. *Journal of Exposure Science and Environmental Epidemiology*, *18*, 588–599. doi:10.1038/jes.2008.4

Littman, M. & Ortiz-Gilstrap, H. (2011, January 12). Metro retires last diesel bus, becomes world's first major transit agency to operate only clean fuel buses. *LA Metro*. Retrieved from http://www.metro.net/news/simple_pr/metro-retires-last-diesel-bus/

Los Angeles County Metropolitan Transit Authority. (2013). Developer: Metro's official blog of transit data and technology. Retrieved from http://developer.metro.net

Los Angeles County Metropolitan Transit Authority. (2013). Measure R. Retrieved from http://www.metro.net/projects/measurer/

MacDonald, R. (2003). *Theory and objectives of air dispersion modelling* [PDF document]. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.409.9932&rep=rep1&type=pdf

Mensink, C., Cosemans, Guido. (2008). From traffic flow simulations to pollutant concentrations in street canyons and backyards. *Environmental Modeling & Software*, *23,* 288-295.

Moeseke, G.V., Gratia, E., Reiter, S., & Herde, A.D. (2005). Wind pressure distribution influence on natural ventilation for different incidences and environment densities. *Energy and Buildings*, *37*, 878–889.

Oszlanczi, G., Vezer, T., Sarkozi, L., Horvath, E., Szabo, A., Konya, Z. & Papp, A. (2010). Metal deposition and functional neurotoxicity in rats after 3-6 weeks nasal exposure by two physicochemical forms of manganese. *Environmental Toxicology and Pharmacology, 30*(2): 121-126.

Ottele, M., Bohemen, H.D., & Fraajj, A.L. (2010). Quantifying the deposition of particulate matter on climber vegetation on living walls. *Ecological Engineering, 36,* 154-162.

Pope, C.A. III, & Dockery, D.W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of Air and Waste Management Association*, *56,* 707-742.

Ryan, P.H. & LeMasters, G.K. (2007). A review of land-use regression models for characterizing intraurban air pollution exposure. *Inhal Toxicol*, *19*, 127-133.

Salmond, J. A., Pauscher, L., Pigeon, G., Masson V., & Legain, D. (2010). Vertical transport of accumulation mode particles between two street canyons and the urban boundary layer. *Atmospheric Environment, 44*(39): 5139-5147.

TSI (2014). *Fast mobility particle sizer spectrometer 3091.* Retrieved from http://www.tsi.com/fast-mobility-particle-sizer-spectrometer-3091/

U.S. Environmental Protection Agency. (2013). Green Book: Currently designated nonattainment areas for all criteria pollutants. Retrieved from http://www.epa.gov/oaqps001/greenbk/ancl.html

Vardoulakis, S., Fisher, BE., Pericleous, K., Gonzalez-Flesca, N. (2003). Modelling air quality in street canyons: a review. *Atmospheric Environment*, *37*, 155-182.

Veronesi, B., Makwana, O., Pooler, M. & Chen, L.C. (2005). Effects of subchronic exposure to concentrated ambient particles: VII. Degeneration of dopaminergic neurons in Apo E-/- mice. *Inhalation Toxicology, 17*(4-5): 235-241.

Westerdahl, D., Fruin, S., Sax, T., Fine, P.M., & Sioutas, C. (2005). Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles. *Atmospheric Environment, 39,* 3597-3610.

Wilton, D., Szpiro, A., Gould, T., & Larson, T. (2013). Improving spatial concentration estimates for nitrogen oxides using a hybrid meteorological dispersionland use regression model in Los Angeles, CA and Seattle, WA. *Science of the Total Environment, 408*, 1120-1130.

Winer, A. (2008, April 3). Field conversations. [Sound recording]. Air Resources Board Mobile Monitoring Platform, Los Angeles, California.

Wu, J., Houston, D., Lurmann, F., Ong, P., Winer, A. (2009). Exposure of PM2.5 and EC from diesel and gasoline vehicles in communities near the Ports of Los Angeles and Long Beach, California. *Atmospheric Environment*, *43*, 1962-1971.

Zhu, Y., Hinds, W.C., Kim, S., Shen, S., & Sioutas, C. (2002). Study of ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment*, *36*, 4323-4335.