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Assessing Potential Diesel Exhaust Exposure in Truckers Resting at Truck Stops

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ASSESSING POTENTIAL DIESEL EXHAUST EXPOSURE IN TRUCKERS RESTING AT TRUCK STOPS

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INDUSTRIAL HYGIENE

ABSTRACT

The nature of long haul truck driving places workers in this occupation in a peculiar setting for chronic exposure to diesel exhaust which is a known carcinogenic. These drivers endure exposure to diesel exhaust in traffic and potentially greater exposure at truck stops where they park for rest breaks as mandated by DOT regulations. This study looked at the potential exposure to diesel exhaust in long haul truck drivers resting at truck stops where up to two hundred trucks are left idling for air conditioning and other reasons. Two different trucks were used consecutively over the 21 days of sampling. Descriptive statistics and relevant comparisons for elemental carbon (EC), organic carbon (OC), total carbon (TC) and particulate matter (PM2.5) were determined. Area sampling was conducted inside and outside of the truck cabs. Exposure levels for EC, (the surrogate for diesel exhaust) were found to be way below the MSHA PEL of 160µg/m3 and the ACGIH suggested limit of 20µg/m3. Diesel particulate concentration was significantly higher inside than outside of the truck cab (geometric mean = 4.4 µg/m3, 2.0 µg/m3 respectively), $p = 0.007$. PM2.5 concentration inside the truck was 30% higher than it was outside. There was no clear association between diesel particulate concentration inside and outside of the truck ($r = 0.4$, $p = 0.081$). Meteorological parameters seem not to influence diesel particulate concentration and PM2.5 inside the truck. It was concluded that diesel exhaust pollution in the truck stop environment is not

the prime source of the driver's exposure to diesel particulates inside the truck. Self-pollution by the truck appears to contribute a greater proportion of the diesel particulate concentration inside of the truck.

Keywords: elemental carbon, organic carbon, total carbon, particulate matter, long haul truck driver

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LIST OF ABBREVIATIONS

ACH	Air Changes per Hour
ACGI	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
DE	Diesel Exhaust
DPM	Diesel Particulate Matter
EC	Elemental Carbon
NIOSH	National Institute for Occupational Health and Safety
PM2.5	Particulate matter with an aerodynamic diameter not greater than 2.5 µm
PELs	Permissible Exposure Limits
REL	Recommended Exposure Limit
OC	Organic Carbon
OSHA	Occupational Safety and Health Administration
TC	Total Carbon
THS	Third hand smoke
TWA	Time Weighted Average

GLOSSARY OF TERMS

Aerodynamic Equivalent Diameter (AED)

The diameter of a unit density sphere having the same terminal settling velocity as the particle in question.

Organic carbon (OC)

The complex carbon compounds found in diesel particulate, including hydrocarbons such as aldehydes and polycyclic aromatic hydrocarbons (PAHs). Organic carbons do not include elemental carbon and inorganic substances such as sulfates.

Elemental carbon (EC)

The pure carbon particles that are the basic building blocks of diesel particulate.

Long Haul Truck Drivers

Truck drivers who go on trips covering several hundreds of miles across state lines while transporting goods

Total carbon (TC)

The combination of organic and elemental carbon found in diesel emissions. This excludes inorganic substances such as sulphates and usually makes up about 85% of diesel particulate matter.

Diesel particulate matter (DPM)

The portion of diesel exhaust which is made up of solid carbon particles and the attached chemicals including organic chemicals such as polycyclic aromatic hydrocarbons (PAHs) and inorganics such as sulfate compounds.(CANMET, 2001)

Self-Pollution

Vehicle self-pollution occurs when a vehicle's emissions migrate to inside that vehicle's passenger compartment (Marshall, 2005).

Pollution Hot Spot

A location where emissions from specific sources may expose individuals and population groups to elevated risks of adverse health effects including but not limited to cancer and contribute to the cumulative health risks of emissions from other sources in the area (California Air Resources Board [CA,ARB])

Third-hand smoke

Third-hand smoke (THS) is the residual tobacco smoke contaminant that remains after a cigarette is extinguished.

INTRODUCTION

According to The Bureau of Labor Statistics 1,625,290 workers in the United States are employed as heavy and tractor-trailer truck drivers (bls.gov, 2013). Commercial truck driving is among occupations with potential exposure to high levels of diesel exhaust (DE) or diesel particulate matter (DPM). The list includes miners, construction workers, heavy equipment operators, bridge and tunnel workers, railroad workers, loading dock workers, farmworkers, auto, truck and bus garage workers. While most Americans are subjected to unacceptable levels of DE, workers in these occupations experience much greater exposures (CARB, 2002). Long haul truck drivers (LHTD) spend many hours on the road and in truck stops where they take their rest breaks. Studies have shown that current exposures to DE in the trucking industry are generally low compared to occupational like underground mining (Zaebst, 1991). Notwithstanding these findings, DE exposure in LHTDs is still a matter of concern due to chronic nature of the exposure experienced by these workers. The truck doubles as a work station and a mobile home for this segment of drivers. As such, LHTDs are potentially inhaling DE during work and rest periods. An extensive review of literature on truck driver exposure to DE showed that little research has been done in assessing diesel particulate matter (DPM) exposure in long haul drivers resting at truck stops. This pilot project will use repeated measurements of DPM levels inside and outside of a single truck parked at a truck stop near Birmingham, Alabama. This study is an attempt to answer the question, “Does parking at a large truck stop for DOT mandatory breaks and other rest periods increase a driver’s exposure to DE when most trucks at that truck stop are idling?” A comparison between the two sets of measurements will be used to determine whether there is an association between the concentration of DE inside of the truck and the concentration of DE in the immediate environment outside of the truck. DE concentration inside and outside of the truck will be compared to average occupational exposures in the trucking industry as well as the U.S. national average outdoor DE concentrations from other studies.

BACKGROUND

Based on population level exposure estimates, diesel pollution poses a cancer risk approximately 7 times greater than the combined risk of all other air toxics tracked by EPA (Schneider and Hill, 2005). In 2012, the National Cancer Institute released two of the most important studies ever undertaken linking miners' exposures to elemental carbon in diesel exhaust to lung cancers and lung cancer mortality (Silverman, 2012). The two decade long studies that tracked the same 12,000 U.S. mining industry workers exposed to diesel carbon particles found a 3-fold increased risk of both lung cancer and premature mortality (Attfield, 2012). Other studies show that lifetime exposures to DE concentrations of 2-6 $\mu g/m^3$ can result in a 50 percent increase in risk of lung cancer for people exposed. The workers with the greatest exposures had a 5-fold risk of lung cancer death, and those that never smoked a 7-fold risk after taking into account other cancer risk factors (CA, ARB, 1998).

A NIOSH Teamsters (truckers) study concluded that the lifetime excess risk for truckers was 10 times higher than the 1/1000 excess risk allowed by OSHA in occupational settings (CATF, 2008). The increased risk for cancer falls on a segment of the working population that is already burdened with other health comorbidities such as obesity, diabetes and cardiovascular disorders. The U.S. Department of Transportation (DOT) has the primary health and safety jurisdiction in the case of drivers engaged in interstate truck transportation. OSHA covers these workers when they are at trucking terminals or customer’s premises loading and unloading goods. However neither of these government agencies have regulations to protect truck drivers from harmful diesel particulate matter in their work environment. The U.S. Environmental Protection Agency (EPA) regulates $PM_{2.5}$ levels in the air as well as other criteria pollutants that constituent DE. In 2007 the EPA mandated that all diesel engines used in heavy-duty highway vehicles comply with more stringent emission standards (EPA, 2001). Although these rules were designed to provide cleaner air for the general public, they also benefit LHTDs who spend countless hours in the proximity of a major source of at least 2 criteria pollutants ($PM_{2.5}$ and NOx). In many ways, the sleeper truck resembles a mobile home for the long haul driver. The same space also doubles as a work station. It is this work-sleep configuration that potentially places long haul truck drivers at a higher risk for exposure to DE and related chronic adverse health effects. Drivers working local routes and workers in other occupations have 8 to 12 hour occupational exposures to harmful substances. However for LHTDs, exposure to DE extends beyond hours on duty (14 hours). These drivers are likely to have DE exposures around the clock, whether be it in traffic or at truck stops where they take rest breaks. Federal regulations mandate truck drivers to take a 10 hour break after every 14 hours on duty (FMCSA, 2012). These breaks are often taken at truck stops where the driver, as well as fellow truckers, idle their vehicles for air conditioning or heating, emitting a considerable amount of DE.

Diesel exhaust is a complex mixture of many gases and fine particles that contains more than 40 toxic air contaminants (EPA, 2002). Some of DE constituents are known or suspected cancer-causing substances, such as benzene, arsenic and formaldehyde (CARB, 2002). In this pilot project, one driver was assessed for exposure to the fine particles in

DE or diesel particulate matter (DPM) inside the truck cabin at a truck stop near Birmingham, Alabama. The scope of this research will be limited to quantifying area exposure to DPM of which the elemental carbon (EC) component will be used as surrogate for total DE exposure. The elemental fraction stems from fuel droplet pyrolysis, while the organic fraction originates from unburned fuel, lubricating oil, and combustion byproducts. EC is currently the preferred surrogate for DE in industries other than coal mines since it is relative simple to measure, has few chemical interferences and is the major component of diesel particulate matter (Pronk, 2009).

Composition of Diesel Exhaust

DPM contains EC, OC, and small amounts of sulfate, nitrate, metals, trace elements, water, and unidentified compounds. A typical composition has 25-60% of EC, with estimates ranging from 5 to 90% and 20-50% of OC of total mass. Sulfate and nitrate may account for up to 12% and 4%, respectively, of total mass (Diaz, 2008). Polyaromatic hydrocarbons generally constitute less than 1% of the DPM mass. Metal compounds and other elements in the fuel and engine lubrication oil are exhausted as ash and typically make up 1%-5% of the DPM mass (EPA, 2002).The OC portion of DPM originates from unburned fuel, engine lubrication oil, and low levels of partial combustion and pyrolysis products. The EC part of DPM is formed by the pyrolysis (removal of hydrogen) of partially burned fuel at temperatures above 1,300 K (EPA, 2002). DPM consists of particles with a diameter $<2.5\mu m$ (fine particles), as well as a subgroup with a large number of ultrafine particles (particles with a diameter $<0.1\mu m$). These fine particles are highly respirable which makes them a major health concern

(EPA, 2002). Gaseous components of DE include carbon dioxide, oxygen, nitrogen, water vapor, carbon monoxide, nitrogen compounds, sulfur compounds, and numerous low-molecular-weight hydrocarbons. Many of the organic compounds present on the particle and in the gases are individually known to have mutagenic and carcinogenic properties (EPA, 2002).Toxicologically relevant constituents are the aldehydes (e.g. formaldehyde, acetaldehyde, acrolein), benzene, 1,3-butadiene, and polycyclic aromatic hydrocarbons (PAHs) and nitro-PAHs.

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$PM_{2.5}$

$PM_{2.5}$ is particulate matter with an aerodynamic mass median diameter less than or equal to a nominal 2.5µm. Airborne particulate matter represents a complex mixture of organic and inorganic substances. Sources of fine particles include all types of combustion activities (motor vehicles, power plants, wood burning, etc.) and certain industrial processes. Common chemical constituents of PM include sulfates, nitrates, ammonium, other inorganic ions such as ions of sodium, potassium, calcium, magnesium and chloride, organic and elemental carbon, crustal material, particle-bound water, PAHs and metals (including cadmium, copper, nickel, vanadium and zinc) (WHO, 2000). It should be noted that the list contains some of the same constituents that make up DE. Also referred to as "fine" particles, $PM_{2.5}$ is believed to pose the largest health risks. Because of their small size (less than one-seventh the average width of a human hair), fine particles can lodge deeply into the lungs where they can cause short and long term respiratory and cardiovascular morbidity (WHO,2000). $PM_{2.5}$ is one of the 6 criteria pollutants regulated by the EPA’s National Ambient Air Quality Standards (NAAQS).

The other 5 are ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead (EPA, 2011).

Permissible Exposure Limits (PELs)

OSHA does not have a PEL for diesel exhaust particulates nor does NIOSH have a REL. The American Conference of Governmental Industrial Hygienists (ACGIH), proposed a recommended workplace exposure limit of 20 $\mu g/m^3$. (ACGIH, 2001). The only occupational exposure limit available is the Mining Safety and Health Administration (MSHA) permissible exposure limit for TC which is 160 $\mu g/m^3$. MSHA does not use EC as a surrogate because there is insufficient evidence for an appropriate conversion factor (MSHA, 2008). The EPA's inhalation Reference Concentration, which estimates a safe daily exposure level during a lifetime, is 5 $\mu g/m^3$ for diesel exhaust particulates.

Based on the risk assessment performed by Cal/EPA's Office of Environmental Health Hazard Assessment, exposure to 2$\mu g/m^3$ of diesel particles over a working lifetime would create an excess lung cancer risk of one in a thousand, which is often used as an upper limit of acceptable workplace risk (CA, ARB, 2002). In Europe, a method similar to the NIOSH method is used to measure elemental and organic carbon. In German tunneling, for example, elemental carbon is used as a measure of exposure to DPM and it is limited to 100 $\mu g/m^3$ (CANMET, 2001).

Description of the Occupation

Most tractor-trailer drivers are long-haul drivers and operate trucks with a gross vehicle weight (GVW) capacity of more than 26,000 pounds. These drivers deliver goods over intercity routes, sometimes spanning several states. As such these workers may spend up to 3 weeks at a time away from home. When not driving, their trucks serve as mobile homes parked at truck stops and rest areas along the highways where these drivers take rest breaks. In addition to constant exposure to vehicular air toxicants, LHTDs are disproportionately represented in statistics for highway crashes.

In 2012, large trucks accounted for 4 percent of all registered vehicles and 9 percent of the total vehicle miles traveled. In the same year, these large trucks accounted for 8 percent of all vehicles involved in fatal crashes (NHTSA, 2014). The nature of this occupation contributes to long haul truck driving having one of the highest rates of injury and illnesses of all occupations. According to a study, truck drivers in the US were seven times more likely to die on the job, and two and half times more likely to suffer an occupational injury or illness, than the average worker (NIOSH, 2003). Federal regulations mandate that drivers may not work more than 14 straight hours comprising up to 11 hours spent driving and the remaining time spent doing other work, such as unloading cargo. A 10 hour break is required between working periods (FMSCA, 2013). As stated in the introduction, LHTDs mostly utilize truck stops for these rest breaks.

LITERATURE REVIEW

An extensive review of literature produced just a hand full of studies examining potential exposure to DE in LHTD resting at truck stops. A literature search on the existence and magnitude of a relationship between DE concentration inside and outside a truck parked at a truck stop did not yield any results. However some studies explored similar concerns in different settings.

Relationship between Indoor and Outdoor Airborne Particles

Researchers in Australia conducted a study to assess the relationship between indoor and outdoor airborne particles in residential houses located in a suburban area of Brisbane. Findings from the study suggest that for normal ventilation conditions, outdoor particle concentrations could be used to predict instantaneous indoor particle concentrations but not for minimum ventilation (Morawska, 2001). As stated in the introduction, trucks used for by LHTDs serve a dual purpose. First they are the drivers' workstations and it is from this end that questions about occupational exposures need to be addressed. On the other hand, when the driver retires for the day, the truck also serves as a home. This study examines the driver's exposure to DE in the latter. Although not as extensive as the reference literature, the current study asks a similar question posed by Morawska et al., "Is there an association between indoor and outdoor concentrations of pollutants?" In the current study the investigator seeks to address similar concerns with regards to a sleeper cab truck parked at a truck stop.

Studies in elderly subjects in the Dutch cities of Helsinki and Amsterdam, reported that outdoor measurements of EC were highly correlated with indoor and personal exposure measurements of EC, supporting the position that short-term increases in outdoor EC concentrations are reflected in increased personal exposures even for those who spend much of their time indoors (EPA. 2002).

In a different study, Liu et al hypothesized that in-vehicle $PM_{2.5}$ concentration can be estimated more accurately based on ambient concentration immediately outside the vehicle rather than by reference to ambient concentration (Liu, 2009).

When driving and rest periods are considered, a typical long haul truck driver will spend considerably longer periods inside his or her truck compared to local drivers. This adds more risk for DE exposure to LHTDs who use their trucks as homes each time they stop to rest at a truck stop than the average person who retires to a real house/home after a work day. The SHEDS (Stochastic Human Exposure and Dose Simulation) model for PM predicts that although the typical person spends only about 5% of his or her time in a vehicle, this microenvironment can contribute on average 20% and as much as 40% of a person's total PM exposure (EPA. 2002).

Liu et al, list key factors influencing in-vehicle $PM_{2.5}$ exposure as; traffic conditions, wind speed, wind direction, air exchange, vehicle types, and time spent in-vehicles (Liu, 2009). All mentioned variables will be considered in the final data analysis of the current study.

A study by the EPA estimated that, DE from vehicles on the nearby freeway contributed from 0.7 $\mu g/m^3$ to 4.0 $\mu g/m^3$ excess DPM above background concentrations, with a maximum of 7.5 $\mu g/m^3$ (EPA. 2002). It is against this background that concerns about excessive exposure to DPM in LHTDs resting at truck stops arise. Location of the truck stop used in the current study near a busy freeway has a potential to exacerbate air pollution caused by DE emissions from trucks idling for the driver's comfort.

An investigation on DE exposure in truck drivers who serve ports, discovered that the air in newer trucks tends to be slightly cleaner than the air in older trucks, implying that some portion of the diesel particulate matter (DPM) that the drivers inhale comes from their own trucks (NRDC, 2007). The same study showed that DPM levels inside the cabs of newer, cleaner trucks remained high across model years. Variations in DPM concentration depended on the location. It was concluded that most of the exposure was from surrounding diesel sources in the port environment (NRDC, 2007). This project assumes that the truck stop environment presents a similar source of pollution for drivers taking their rest break there.

A study at The Buffalo Peace Bridge in Buffalo NY, demonstrated that a concentration of motor vehicles resulted in elevated levels of mobile-source-related emissions downwind, to distances of 300 m to 600 m. (Spengler, 2011). The inside of a truck can represent a microenvironment within which air pollutant concentrations are relatively uniform or can be well-characterized. One study found out that in-vehicle $PM_{2.5}$ concentration can be higher than other microenvironments, such as houses (Liu, 2009). The current study attempts to link concentrations of DE in the truck stop environment to concentrations measured inside of a truck parked at that location.

The truck stop with many trucks idling to provide air condition for drivers, presents a potential pollution hot spot, hence the concern for increased DE exposure to drivers resting in such environments (EPA, 2002). Investigators in one study found that diesel emissions can enter the cabins of nearby school buses. High in-cabin air pollutant levels were observed at the bus transfer station and the school parking lot where many school buses were idling simultaneously (Zhang, 2013). Motivation for the current research partly comes from recognizing that, the truck presents a similar exposure scenario to drivers resting in the truck's bunk at these locations. On a typical cold or hot and humid night, most trucks are idled for extended periods in order to operate the HVAC system. Trucks are closely parked with about 1.5 meter gaps in-between them. This creates a situation whereby the driver is potentially exposed to DE from neighboring trucks.

Occupational DE Exposure Levels

Information regarding DPM in occupational environments suggests that exposure ranges up to approximately 1,280 $\mu g/m^3$ for miners, with lower exposure measured for railroad workers (39-191 $\mu g/m^3$), firefighters (4-748 $\mu g/m^3$), public transit personnel who work with diesel equipment (7-98 $\mu g/m^3$), mechanics and dockworkers (5-65 $\mu g/m^3$), truck drivers (2-7 $\mu g/m^3$), and bus drivers (1-3 $\mu g/m^3$) (EPA, 2002). Work area concentrations at fixed sites, especially for mining operations or other enclosed spaces are often higher than exposures in mobile settings (EPA. 2002). Although DE in truck drivers is generally low, LHTDs resting in the bunk of a truck idling at a truck stop are potentially exposed to higher concentrations of DE than drivers on the roadway.

Two large industrial hygiene surveys in the trucking industry reported significantly higher levels of EC and $PM_{2.5}$ in trucks when windows were open vs closed (1.5 vs 1.3 and 19.9 vs 18.5 $\mu g/m^3$), respectively (Pronk, 2009). The current study assumes drivers will typically keep windows fully closed when idling the truck for heat on cold nights. As such sampling for EC and $PM_{2.5}$ was conducted with the truck windows closed.

In a different study on DPM exposure to railroad train crews, Liukonen et al. concluded that open windows and exhaust stack(s) in front of the locomotive cab have a significant effect on EC. The same study also found that EC levels are highly predictive of diesel exhaust exposure whereas OC levels are not (Liukonen, 2002).

Methods (Reviewed Literature)

NIOSH built on the MSHA findings by publishing data from four underground metal/nonmetal mines and an isolated zone on the relationship between EC and TC. This study concluded that EC and DPM demonstrated a good correlation.Data from Australian coal mines also demonstrated a strong relationship between TC and EC in nine underground mines. It showed that TC, and therefore DPM, for these nine coal mines can be determined within 19% from using EC as a surrogate for at least concentrations of 50 $\mu g/m^3$ EC and greater (Noll, 2015).

In principle, non-DPM sources of elemental carbon (e.g., coal, carbon black) can positively interfere with EC analyses, while non-DPM sources of organic species (e.g. oil mist, cigarette smoke, pollen) and carbonates can interfere positively with OC analyses. Although the possibilities of such interferences are recognized, few reports have described their magnitude and potential to confuse and confound compliance-driven workplace exposure assessments (Sirianni, 2003). Although this study did not control for cigarette smoking by prior occupants of the trucks used, it is not expected to significantly impact results for DPM samples obtained from these trucks.

The NIOSH 5040 method was used to analyze DPM collected via active sampling in the current study. Total carbon (as OC and EC) is determined by the method, but EC was recommended as a measure of workplace exposure because OC interferences may be present. PM2.5 is a less suitable surrogate for DE since it is generated from more non-diesel sources, i.e. oil and grease mists, cigarette smoke, emissions from other combustion sources, and respirable inorganic matter such as mechanically aerosolized geological and fibrous materials (Hammond, 1988).

Comparison of the time series of indoor to outdoor particle concentrations showed a clear positive relationship for many normal ventilation conditions (estimated to be 2 ACH or greater, but not under minimum ventilation conditions estimated to be 1 ACH or less. These results, unless air exchange rate is known (Morawska, 2001). An air exchange rate of 2 ACH inside the truck was used for this project. The truck was left to idle with all windows closed and ventilation blower set at the second position in order to achieve the desired ACH. These conditions were designed for the investigator's comfort considering that he was to spend the entire sampling period (10 hours) in the truck. It was also assumed that a typical long haul truck driver would use similar settings while taking his or her DOT mandated 10 hour break.

The selection of sampling instruments was based on cost effectiveness and practicality (portability). It was expected that real time measurements of particulate matter would be related to the magnitude of total carbon concentrations obtained via gravimetric analysis of particulates collected by active sampling. A study showed that PM2.5 measurements from the DustTrak™ monitor are well correlated and highly predictive of measurements from the gravimetric sampling method for the aerosols in work environments (Kim, 2004). Other studies have also used the DustTrak is a very practical, compact, and relatively low-priced instrument.

In another study to compare two direct-reading aerosol monitors with the federal reference method (FRM) for $PM_{2.5}$ in indoor air, investigators concluded that though the DustTrak™ monitor provides precise measurements of $PM_{2.5}$ and that the accuracy of the measurements can be improved through statistical adjustment (MacIntosh, 2002).

The DustTrak aerosol monitor was also employed for PM2.5 sampling in a study to determine the relationship between indoor and outdoor airborne particles in the residential environment. The sub-micrometer particle numbers were measured using the Scanning Mobility Particle Sizer (SMPS), the larger particle numbers using the Aerodynamic Particle Sizer and an approximation of $PM_{2.5}$ was also measured using a DustTrak™ monitor (Morawska, 2001).

Concurrent sampling for $PM_{2.5}$ and or DPM with aerosol monitors and personal pumps (gravimetric method) is seen elsewhere in literature. In a study examining indoor and outdoor, measurements of 15-min average $PM_{2.5}$ concentrations were made with a real-time light-scattering instrument at both outdoor and indoor locations over two seasons in the Minneapolis-St. Paul metropolitan area. These data are used to examine within-day variability of $PM_{2.5}$ concentrations indoors and outdoors, as well as matched indoor-to outdoor (I/O) ratios. Concurrent gravimetric measurements of 24-hr average $PM_{2.5}$ concentrations were also obtained as a way to compare real-time measures with this more traditional metric (Ramachandran, 2000).

The current study to assess potential DE exposure in LHTDs resting at truck stops, gravimetric analysis and real-time sampling will be used concurrently. This enables the researcher to make an immediate assessment or estimation of DE levels in the truck. The use of a filter cassette requires submission of the sample to an analytical laboratory, creating a lag time before data on DE concentrations is available to the investigator. Albeit the DustTrak does not provide a breakdown of the $PM_{2.5}$ constituents, it gives a crude estimate of DE concentrations inside and outside of the truck in real time (Kyle, 2012).

Researchers investigating DE exposure in school buses concluded that, diesel emissions from idling school buses could reach children through different routes. First, diesel emissions from one school bus could migrate into the cabin of buses parked in close proximity. Secondly DE can penetrate into the vehicle's own cabin through cracks, doors, and windows. This so-called "self-pollution" increases the exposure of children on board, and has been quantified by the tracer gas method. Both scenarios are plausible in the truck stop setting where trucks are idled in close quarters for extended periods of time. Due to limitations of the current study, the proportion of EC/DE inside the truck originating from the truck's own engine could not be ascertained. Studies have employed an intentional marker to quantify entry of DE into school bus cabins. In one instance, a tracer gas [sulfur hexafluoride (SF6)] was injected into the bus exhaust system. The concentration of SF6 was later measured inside the bus. In yet another study, an organic iridium compound (tris[norbornadiene] iridium[III] acetylacetonate) was added to the diesel fuel. The iridium is incorporated into carbon based particles emitted in engine exhaust. Samples of TC collected inside the bus were then analyzed for levels of iridium (Borak, 2007). Using SF6 as a tracer. Behrentz et al. (2004) estimated that up to 0.3% of in-cabin air came from a bus's own exhaust. Using iridium as a fuel-based tracer, self-pollution was estimated to contribute 0.1% of in-cabin $PM_{2.5}$ (Ireson et al., 2004, 2011; Liu et al., 2010). In a different study tracer measurements showed that bus self-pollution contributed approximately 50% of total $PM_{2.5}$ concentrations with windows closed and 15% with windows open, with over three-quarters of these contributions attributed to crankcase emissions (Ireson, 2011). In these studies, researchers were able to apportion the concentration of DE originating from the vehicle's own engine.

Statement of Problem and Its Relevance

In June, 2012, the International Agency for Research on Cancer (IARC) classified diesel exhaust (DE) including diesel particulate matter (DPM) as a known human carcinogen (Group 1) (IARC, 2012). The two largest industrial groups exposed are truck transportation and transit and ground passenger transportation. The two largest occupational groups exposed are truck drivers and heavy equipment operators (CAREX, 2015). According to the Bureau of Labor Statistics (BLS), over 1.5 million workers are employed as heavy-duty truck drivers. These drivers comprise a significant portion of the US work force. Diesel pollution poses a cancer risk approximately seven times greater than the combined risk of all other air toxins tracked by EPA. Studies have linked DE exposure an increased risk for cancer. The cancer risk posed by DE exposure is an additional health burden in a profession already faced with other significant and interrelated health risks. These include high stress levels, cardiovascular diseases, sleep apnea, obesity and eating disorders, as well as injury resulting from vehicular accidents.

Purpose of the Study

The purpose of this study was to assess potential exposure to DE in a trucker (LHTD) resting inside of his/her truck while parked at a truck stop with the truck idling. In this study sets of EC, OC, TC and $PM_{2.5}$ concentrations inside and outside of the truck were obtained from the sampled air. Results from the study were evaluated to see whether there is an association between the two measurements.

Specific Objectives of the Study

In order to make a comparison between inside and outside DE concentration, the experiment was designed to concurrently conduct area sampling for diesel particulate matter (DPM) inside the truck cabin and collect samples of DPM in the immediate environment outside of the truck cabin. Real time measurements $PM_{2.5}$ inside the truck and the immediate environment outside of the truck were taken simultaneously. The final goal of the study was to evaluate the truck driver's potential exposure to DE based on area sampling inside of the truck.

METHODS AND MATERIALS

Apart from the investigator, the experimental design outlined in this section did not involve any other human subjects during sampling for DE from a truck parked at a truck stop. Permission to carry out the study was granted by the Institutional Review Board at the University of Alabama at Birmingham (UAB), IRB Protocol # N150112001. A copy of board's letter is in appendix A.

Description of the Equipment

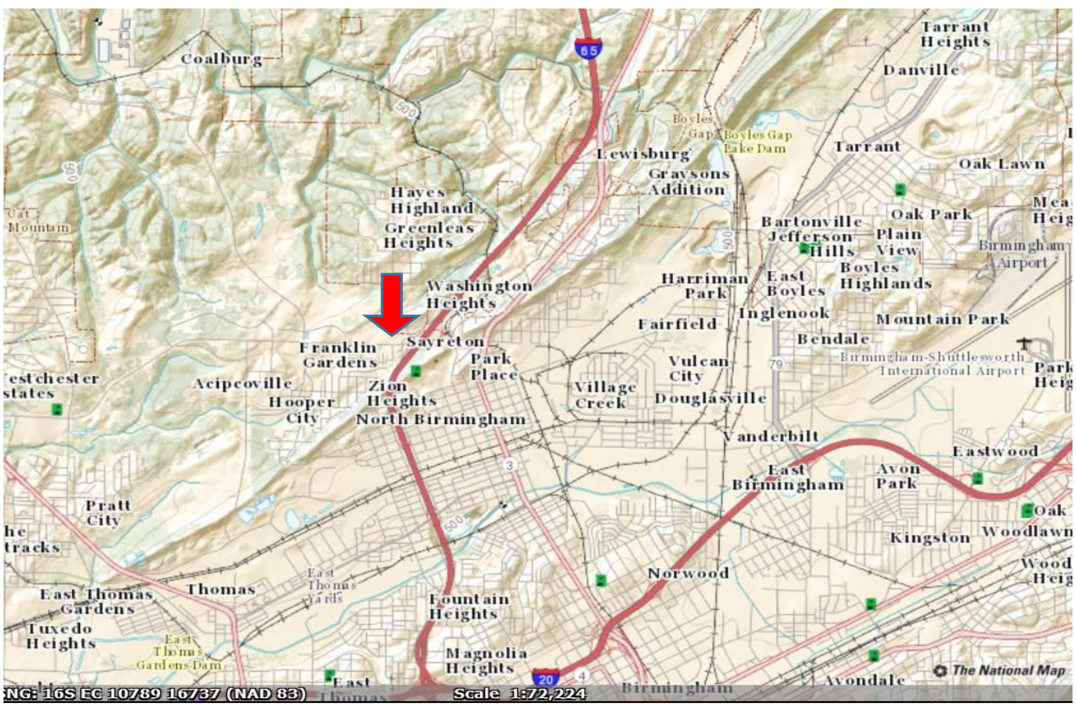
In order to control for variability in equipment (trucks), all sampling was to be conducted using one truck (shown in Figure 1.) However, due to circumstances beyond the researcher's control, two rental trucks were used consecutively for this project. The trucks are classified by the EPA as Heavy-duty diesel vehicles (HDDV), Class (8b) with a gross vehicle weight (GVW) greater than 60,000 lbs. (EPA, 2001). Both trucks had a conventional configuration (engine in the front) and were equipped with sleeper cabs. The trucks had similar engines and cabin configurations. Both truck used low sulfur diesel fuel and were both equipped with diesel exhaust filters to reduce emissions. The first 9 days of sampling were carried out using a 2011 model with 400,000 miles (truck 1). Sampling for the last 12 days was conducted in a 2013 model truck with 350,000 miles on the odometer (truck 2). The last periodic maintenance was performed in January, 2015 and December, 2014 on truck 1 and truck 2 respectively. Neither of the trucks had any visible cracks or openings inside of the cabin and appeared to be in good mechanical condition. The trucks' heating, ventilation, and air conditioning (HVAC) system incorporated 2 cab air filters, one located under the bunk bed and the other in the engine compartment (see photos in Appendix C). More photographic descriptions of the trucks are presented in Appendices B & D.

Figure1. Conventional heavy duty tractor used for the study

Description of the Truck Stop

The truck stop is located 6 miles north of downtown Birmingham, AL along Interstate 65 (Figure 3). It is accessed by a busy highway leading to trucking terminals and residential neighborhoods. The truck stop has 157 parking spots and is usually filled to capacity on most nights (Figure 2 & Appendix E).

Figure 2. South facing parking spots at the truck stop



USGS Image

Figure 3. Location of truck stop just north of downtown Birmingham on Interstate 65

DPM Sampling- The NIOSH 5040 Method

OSHA has no sampling method specifically for diesel exhaust. Reviewed literature claims that elemental carbon is the most reliable overall measure of exposure to diesel exhaust. This is because selecting an extractable organic compound or class of compounds as a reliable surrogate of exposure is difficult. The soluble organic fraction (SOF) associated with diesel exhaust aerosol is highly variable in composition and chemically complex, and uncertainty exists about the compounds responsible for mutagenic and carcinogenic activity. Also, low concentrations and the presence of interfering chemical compounds make analysis difficult. These factors make SOF an unreliable measure of diesel exposure (Cantrell, 1997). For this reason this study will use the concentration of EC inside the truck to represent potential exposure to DPM. Sampling and analysis of DPM will be conducted as prescribed in the NIOSH 5040 method (NMAM, 2003). At the analytical laboratory samples are analyzed for OC and EC content using the evolved gas analysis technique with thermal-optical analyzer as specified in NIOSH Method 5040. Elemental and organic carbon content of the sample are added to obtain the total carbon concentration (NMAM, 2003). EC and OC mass on a blank is subtracted from the EC and OC on a sample filter. The net carbon mass is divided by the volume of air drawn by the pumps to give a concentration in mg/m^3.

The concentration of elemental carbon is obtained by using equation (1) (NMAM, 2003)

$$C_{EC} = \frac{W_{EC} - W_b}{V}, mg/m^3 \qquad \text{Equation (1)}$$

Where:

EC = Elemental Carbon

C_{EC} = EC concentration

W_{EC} = total mass, µg, of EC on each filter sample

W_b = mass found in the average field blank

V = volume of air sampled in liters

Total carbon (as OC and EC) is determined by the same method, but EC was recommended as a measure of workplace exposure because OC interferences may be present. Cigarette smoke and carbonates ordinarily do not interfere in the EC determination. Less than 1% of the carbon in cigarette smoke is elemental. (NMAM, 2003). $PM_{2.5}$ is a less suitable surrogate for DE since it is generated from more non-diesel sources, i.e. oil and grease mists, cigarette smoke, emissions from other combustion sources (Hammond, 1988). Historical weather data from the closest weather station was archived from an online source (Weather Underground, Inc., Ann Arbor, Mich.).

Sampling Objectives

The primary goal of this study was to assess the concentration of DE inside and outside of a truck parked at a truck stop and determine whether there was an association between the two measurements. This was accomplished by:

1. Collecting the samples of total carbon from DE inside the truck cabin.

2. Obtaining real-time measurements of fine particulate concentration inside the truck cabin;[particulate matter with an aerodynamic equivalent diameter (AED) not greater than 2.5 µm ($PM_{2.5}$)].
3. Collecting the samples of total carbon from the background (the truck stop immediate environment).
4. Obtaining real-time background measurements of fine particulates ($PM_{2.5}$) concentrations.
5. Identifying variables that have the greatest influence in the truck driver's exposure to DPM.

Preliminary work done

There were 8 DPM samples and 10 respirable particulate matter ($PM_{2.5}$) samples collected during the preliminary phase of the study. DPM samples, collected April, July-September and November of 2014, came from different locations across the United States including Florida, Texas, Louisiana and Tennessee. The geographical and meteorological landscape differed widely for each sampling location. Different trucks were used for every sampling session. The filter location for each sample was inside of the truck. See Appendix N for listings of all preliminary data.

$PM_{2.5}$ samples were collected from Illinois, Nebraska, Wyoming, Louisiana, Texas, Florida and Missouri in the same time frame. Filter locations for samples included both inside and outside of the truck. See appendix L for listings of all preliminary data. Table 1. presents average DPM concentrations of preliminary sampling data. Mean (standard deviation) EC, OC, and TC concentrations were 3.3 µg/m^3 (4.13), 33.5 µg/m^3

(10.52) and 36 μg/m^3 (14.66) respectively. EC, OC, and TC concentrations captured from the inside of the cabin ranged from 1.4-13 μg/m^3, 25-52 μg/$m^3$and 25-67 μg/m^3 respectively.

Table 1

Average DPM (EC,OC,TC) Concentrations (μg/m^3) of Preliminary Sampling Data

Analyte Conc. (μg/m^3)	Filter Location	N	Mean (SD)	Median (Min. Max)
EC	Inside	8	3.3 (4.13)	1.4 (1.4,13)
OC	Inside	8	33.5 (10.52)	28.5 (25,52)
TC	Inside	8	36 (14.66)	31 (25,67)

EC=Elemental Carbon, OC=Organic Carbon, TC=Total Carbon
LOD=1.4 μg/m^3
Values < LOD were replaced with 1.4 μg/m^3
SD=Standard Deviation, Min=Minimum Value, Max=Maximum Value

Table 2. presents average $PM_{2.5}$ concentrations of preliminary sampling data. $PM_{2.5}$ concentrations collected from inside and outside of the truck cab ranged from 1.0 to 50.0 μg/m^3 and 1.0 to 81.0 μg/m^3 respectively. The limit of detection (LOD) was < 1.0 μg/m$^{3.}$ Values reported as LOD were replaced with 1.0 μg/m^3 for the analysis. The mean (standard deviation) for inside and outside $PM_{2.5}$ concentrations were 14.6 (14.12) and 24.2 (26.06) respectively.

Table 2

Average $PM_{2.5}$ Concentrations (μg/m^3) of Preliminary Sampling Data

Filter Location	N	Mean (SD)	Median (Min, Max)
Inside	10	14.6 (14.12)	12.5 (1,50)
Outside	10	24.2 (26.06)	16.5 (1,81)

LOD =1.0 μg/m^3
Values < LOD were replaced with 1.0 μg/m^3
SD=Standard Deviation, Min=Minimum Value, Max=Maximum Value

Interpretation of Preliminary Data

There are appreciable spatial differences in $PM_{2.5}$ background as well as in-cabin concentration. The DustTrak aerosol monitor recorded lower outside concentrations in the Midwest plains and Rockies (Little America, WY; less than 1.0 μg/m^3). The South East had higher concentrations, more so in the Mississippi delta (Tallulah, LA; 81 μg/m^3). It is yet to be ascertained whether this difference in outside $PM_{2.5}$ concentrations is a function of weather which is invariably influenced by the location.

As shown in figure 4, preliminary data seem to show a correlation between $PM_{2.5}$ concentrations inside and outside of the truck ($r = 0.46$, $p = 0.03$).

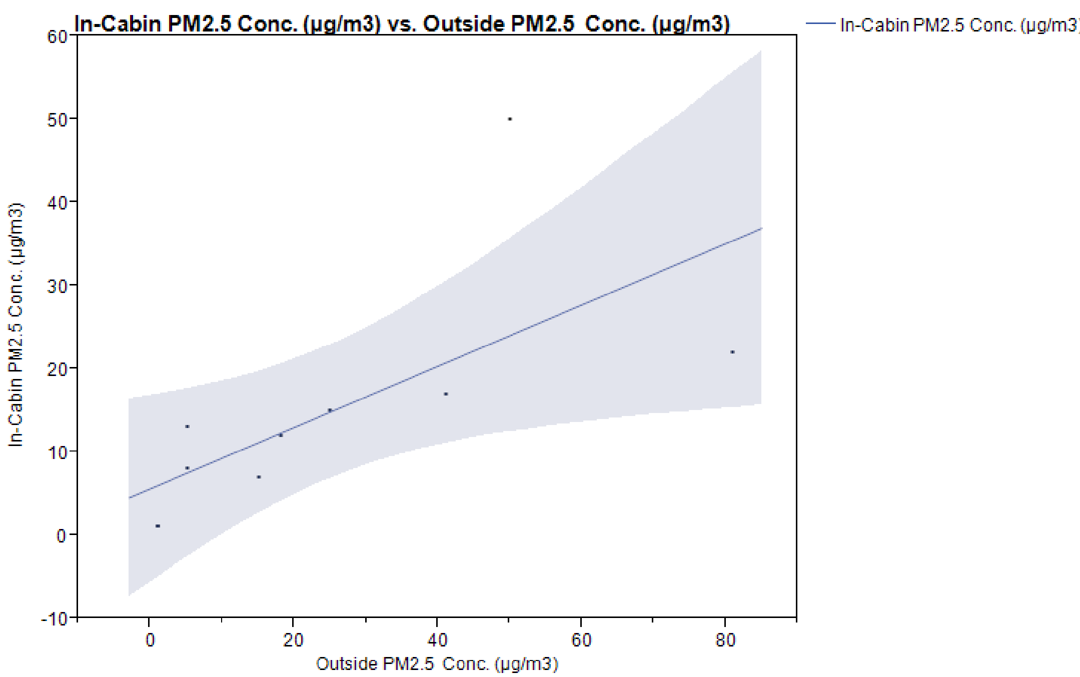


Figure 4. $PM_{2.5}$ concentration inside the truck in relation to the outside $PM_{2.5}$ concentration.

Potential covariates such as geographical location and weather (which can be a function of location) were not analyzed. Neither were variations in DE inside the truck cab resulting from the use of different trucks. Preliminary data comes from a sampling period covering several months and different seasons. Logistics involved in the transportation of goods lead to wide variations in sampling times (time of day) and size of truck stops where sampling was conducted.

Limitations

As stated earlier potential covariates such as geographical location and weather (which is can be a function of location) were not controlled for. Neither were variations in DE inside the truck cab resulting from the use of different trucks. Temporal variations resulting from a sampling period covering several months and different seasons were also not accounted for. Different trucks models were used in the preliminary phase of this project introducing yet another variable that was not controlled for.

Current Study

In order to control for seasonal, diurnal, geographical and truck model variables the following modifications were made in the later phase of the study.

A rented diesel powered conventional tractor (engine in the front) with a sleeper cab was used for the study. The truck was driven from the leasing company's yard to a local truck stop where it was parked for a 10-hour sampling period. All sampling sessions were conducted with the truck parked in the same area. The same parking orientation was assumed every time with the engine end facing southward (Figure 6.). The distance between the research truck and neighboring trucks on either side was almost consistent at approximately 1.5 m apart. Sampling was conducted during night time when the truck stop was at full capacity. All the sampling was conducted in winter over a period of 25 days beginning on January 26 and ending on February 19, 2015. Sampling was carried out daily for the first 9 days using the same truck (truck 1). Due to circumstances beyond the researcher's control, the rest of the samples (12) were collected from a different truck (truck 2). In all, 21 sets of samples were collected. Truck 1 had no detectable smell of tobacco. However there was a strong tobacco odor in truck 2 leading to the assumption that a smoker had used the truck previously. The study attempted to simulate conditions whereby a driver along with the majority of other drivers idled their trucks continuously while taking the 10 hour break required by DOT regulations. Sampling was conducted during the winter when it was assumed that on cold nights, most drivers would leave their engines running for warm air. In order to estimate area exposure under such conditions, 10-hour samples from the trucks were collected while the engine idled. Once sampling instruments started running and patency checks were made, the investigator went into the truck bunk to rest or sleep for 10 hours like a typical long haul truck driver. The researcher holds a commercial driver's license and abided by all DOT regulations which include maintaining a log book to show his duty status. A sample log sheet is shown in Appendix G. Sampling started between 6:30 and 7:30 pm, lasting till 4:30 to 5:30 the following morning. The study was designed to measure a typical LHTD's DE exposure at a time when pollution at the truck stop peaks, representing worst case exposure scenario. The following conditions were necessary: 1) Parking at a relatively large truck stop (a least 100 parking spaces); 2) Truck stop filled to capacity; 3) Weather conditions that necessitated idling trucks in order to use the HVAC system; 4). Weather conditions or phenomena which limited dispersion of air pollutants. Preliminary research has shown an elevated concentration of $PM_{2.5}$ outside of the truck in the early morning hours at different locations in the South East of the U.S. The graph in Figure 4. shows a notable rise in concentration around 3:00 am indicating a possible temperature inversion at that location. Data used to construct the graph were obtained from a DustTrak® aerosol monitor used in preliminary work done prior to this project .This observation was recorded at a truck stop in Louisiana. A similar trend was observed in a study on DE exposure in school buses which showed that background air pollutant levels varied by time of day. In that study, fine particle counts were more than double during morning than afternoon runs. (Borak and Sirianni, 2007). A temperature inversion occurs when warm air forms a layer on top of cooler air. There are two types of temperature inversions: surface inversions that occur near the Earth's surface, and aloft inversions that occur above the ground. Surface inversions are the most important in the study of air quality (noaa.gov). Picture in Appendix M illustrate such an occurrence at the truck stop where data used to construct the graph in Figure 4. were obtained.

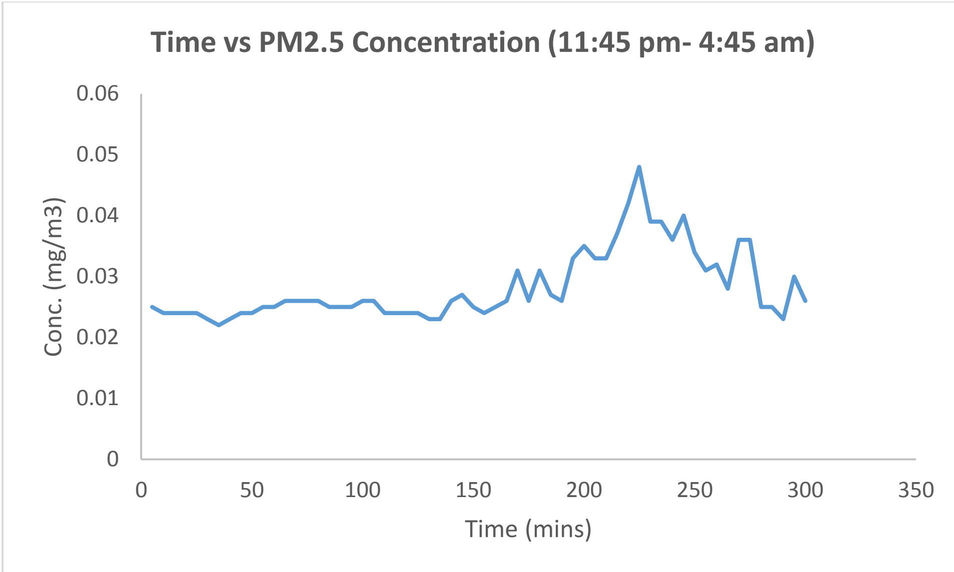


Figure 5. Elevated $PM_{2.5}$ concentration in the early morning hours resulting from a possible temperature invesrion around the truck stop

Data for prevailing weather conditions at the time of sampling was recorded and later verified with archived weather reports from Weather Underground, an online source. Table 3 represents a summary of values for the meteorological parameters of interest.

Table 3

Summary Statistics for archived Meteorological Data

Parameter	N	Mean (STD)	Range
Temp ^{o}F	21	34.6 (7.7)	20.0 - 50.0
Humidity (%)	21	65.4 (15.4)	36.0 - 97.0
Wind (mph)	21	12.9 (7.7)	0.0 - 26.0

A total of 21 samples of DPM inside the truck cab and 21 samples of DPM outside of the truck cab were collected for gravimetric analysis. 20 samples of Real time concentrations for $PM_{2.5}$ for inside as well as outside of the truck cab were collected simultaneously with the DPM samples. The missing DPM data (20 instead of 21 samples) was due to an improperly charged DustTrak. The problem was rectified the following day.

Figure 6. Truck used for study (indicated with arrow) parked facing southward with several other trucks

Sampling Equipment

- DustTrak™ II Aerosol Monitor 8530 for $PM_{2.5}$ monitoring inside the truck cab
- DustTrak™ Aerosol Monitor 8520 for $PM_{2.5}$ concentration outside the truck cab

- Sampling trains comprising of SKC AirChek® XR5000 personal sampling pumps and pre-fitted 37 millimeter quartz fiber filters used as the collection media
- Duct tape for sealing off a 10 mm gap opening in the passenger window after allowing flexible tubes assess to sample air outside of the truck
- TSI's Model 8360A VelociCalc® Plus Multi-Parameter Ventilation Meter to measure ventilation parameters
- Bios® DryCal DC-Lite primary air flow calibrator for pre and post sampling calibration of the SKC pumps

Sampling

Assumptions

This study assumed that truck drivers typically keep windows fully closed while their trucks idle for heating or cooling. As such, all windows were fully closed for this study.

Based on visual inspection and truck maintenance records, it was assumed that trucks used for this study were in a good mechanical condition. There were no visible holes or cracks inside the truck cab. Seals around windows and doors appeared to be intact. All the 157 parking spots at the truck stop were occupied during all 21 nights of sampling. General weather conditions at the truck stop were recorded at each sampling session. Archived weather reports were retrieved online from Weather Underground for data quality control purposes. Over the entire 21 days of sampling the average humidity outside the truck was 40%, and it rained on two occasions. Wind speeds ranged from 0 mph/calm to 26 mph/strong with an average speed of 10 mph. The wind direction was variable over the entire sampling period. The average outside temperature during the 10 hour sampling sessions was 39°F. With the exception of 2 nights, when the average outside temperature was 50°F, about 90 % of trucks in the truck stop were idling when sampling was being conducted.

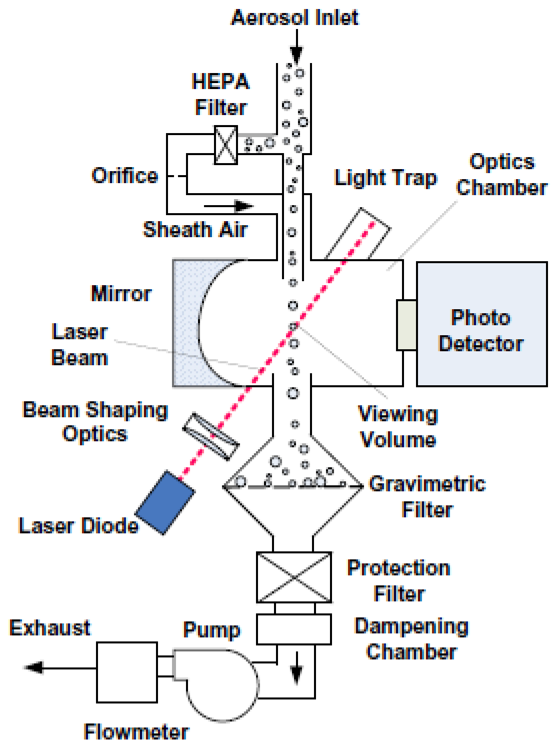
Truck's Internal Climate

The truck's mechanical ventilation was used to provide fresh air at 2.6 air changes per hour (ACH). The recommended air change rate for residences is 1-2 ACH (Engineering ToolBox, 2015). In one study, a comparison of indoor to outdoor particle concentrations showed a clear positive relationship for many normal ventilation conditions (estimated to be 2 ACH or greater, but not under minimum ventilation conditions estimated to be 1 ACH or less). These findings suggest that for normal ventilation conditions, outdoor particle concentrations could be used to predict instantaneous indoor particle concentrations but not for minimum ventilation, unless air exchange rate is known (Morawska, 2001). Ventilation parameters such as temperature, velocity and pressure inside the truck were measured using a TSI Model 8360A VelociCalc® Plus multi-parameter ventilation meter (Appendix G). The inside humidity ranged from 26 to 30 %, while temperature ranged from 70 - 75°F. The average air velocity at 100 cm from the dashboard air vents and 100 cm from the cab floor was 5 ft/min.

Real-time Aerosol Monitoring

Inside and outside $PM_{2.5}$ concentration were measured in real time using two DustTrak aerosol monitors, simultaneously running side by side. The DustTrak aerosol monitors were fitted a with cascade-impactor pre-collector at the inlet nozzle to remove particles larger than 2.5µm. The aerosol monitors were set log data at 5-minute intervals for the 10 hour sampling period. The 5-minute logging interval was selected in order to create a manageable set of data points over the 10- hour sampling period. Data from the DustTrak were downloaded to a computer and where it was manipulated using Excel spread sheets. Graphs were constructed from the captured data to illustrate variations in $PM_{2.5}$ concentration over the 10 hour sampling period. Inside and outside $PM_{2.5}$ concentration were compared to concentrations of EC, OC and TC obtain by gravimetric analysis. A study to compare gravimetric and real-time sampling of $PM_{2.5}$ concentrations inside truck cabins showed that the association between average real-time and gravimetric $PM_{2.5}$ measurements on moving trucks was fairly consistent (Spearman rank correlation of 0.63), with DustTrak measurements exceeding gravimetric measurements by approximately a factor of 2 (Kim, 2004).

The DustTrak® aerosol monitor theory of operation



Source: TSI Incorporated

Figure 7. The DustTrak aerosol monitor theory of operation

The Model 8530 version of DustTrak™ II Aerosol Monitor is single channel basic photometric instrument used to determine the mass concentration of aerosols in real time. The DustTrak II Model 8530 is capable of sampling high concentration up to 400 mg/m^3. In the schematic shown in Figure 6, the aerosol is drawn in to the sensing chamber in a continuous stream using a diaphragm pump. Part of the aerosol stream is split ahead of the sensing chamber, passed through a HEPA filter and injected back in to the chamber around the inlet nozzle as sheath flow. The remaining flow, called the sample flow passes through the inlet entering the sensing chamber. A gold coated spherical mirror captures a significant fraction of the light scattered by the particles and focuses it on to a photo detector. The voltage across the photo detector is proportional to the mass concentration of the aerosol over a wide range of concentrations. (TSI, 2012).

Active Sampling /Gravimetric Analysis

Active sampling was used to collect DPM from inside and outside of the truck. Sampling trains comprising of a 37 mm cassette, flexible tubing and an SKC personal sampling pump were used for this purpose. The pre-weighed quartz fiber filters as well as the 37mm cassettes which housed them, were obtained from an AIHA accredited laboratory (Bureau Veritas) where they were returned for post sampling analysis.

Personal sampling pumps were calibrated before and after each sampling exercise using the DryCal® DC-Lite Primary Flow Meter Air Flow Calibrator. A representative 37 mm cassette was placed in line between the calibrator and the pump. The NIOSH 5040 method recommends a flow rate of 2-4 L/min. (NMAM, 2003). A flow rate of 2.4 L/min was chosen for this study to reduce overloading of the filter considering the 10 hours of sampling required. All the sampling equipment was set on the passenger side seat for convenience and easy access (Figures 8 & 9).

The DustTraK® aerosol monitors were calibrated annually with Arizona Test Dust (ISO 12103-1, A1 test dust) at the factory and zero checked daily before sampling (TSI, 2012). Outside concentrations for $PM_{2.5}$ and TC were obtained by extending tubing from the instruments to the outside of the truck cabin via a 10 mm gap in the passenger side window. The remaining gap in the window was sealed using duct tape as shown in Appendix J. Once the driver (investigator) had settled into a parking space at the truck stop, the SKC personal pumps were calibrated and set to run at 2.4 L/min. The aerosol monitors and personal pumps were observed for proper function in the first 30 minutes and as needed thereafter. The SKC pumps and DustTrak aerosol monitors operated concurrently over the 10-hour sampling period.

Active Sampling for DPM

There are three methods by which air borne diesel particulate samples can be collected. These methods include total dust samples (open face or cassette without a preclassifier), respirable dust (collected with a respirable preclassifier), and submicron dust (collected with both a respirable preclassifier and a submicron impactor). The choice of sample collection method considers the cost and the potential interferences that can result from the method. Regardless of the sampling method, the sampling media (filter) must be one that does not interfere with the analysis (MSHA). For this reason a pre-fired quartz fiber filter was chosen. The quartz fiber filter is capable of withstanding the temperatures from the analytical procedure. The filter is pre-fired to remove residual carbon, attached to the filter during manufacturing (MSHA). In this study samples for EC were collected using a sampling train consisting a pre-fired quartz fiber filter mounted in a 37-mm plastic cassette. The decision to exclude a respirable preclassifier (cyclone) in the sampling train was based on 2 reasons. Firstly, most samples obtained from preliminary work in similar settings yielded an EC mass less the 2μg limit of detection. Secondly, judging from preliminary results, heavy loading of carbonate was not anticipated in this experiment. Figure 8 shows a setup in the preliminary phase of the study where a Dorr-Oliver cyclone (Zefon International, Ocala, Fla.) was included in the sampling train.

Figure 8. Set-up showing a cyclone in the sampling train to collect DPM samples inside the truck cab.

Figure 9. Set-up excluding a cyclone in the sampling train for inside and outside gravimetric assessment of EC, OC and TC.

Calibration of Instruments

Determination of instrument agreement between the TSI DustTrak™ model 8530 and TSI

DustTrak™ model 8520. Due to logistical reasons two different models of TSI DustTrak™ aerosol monitors were used for this study. Instrument agreement was determined in the industrial hygiene lab at UAB. The 2 instruments were setup to simultaneously sample particulates from a smoldering match inside an enclosed chamber. A flexible tube with a 6 mm diameter measuring 87 cm in length was attached to the inlet port at each instrument. A 2.5µm size discriminating impactor was used on both instruments. As shown in figure 8, the flexible tubes were extended into the chamber at the same height and instruments were simultaneously set to run. $PM_{2.5}$ concentration displayed on both instruments was recorded at 1 minute intervals over 25 minutes of sampling. A comparison of time versus concentration plots for both instruments was made (Figure 12). It was observed that the DustTrak™ model 8520 instrument displayed lower $PM_{2.5}$ concentrations the over the entire 25 minutes of sampling (Figure 10). Using the slope of the line on the plots, a correction factor of 1.3 was determined to make concentrations obtained from the 2 instruments as uniform as possible (Figure 13).

Figure 10. Instruments displaying different $PM_{2.5}$ concentrations from the same chamber.

Figure 11. Aerosol monitors simultaneously sampling particulates inside the chamber.

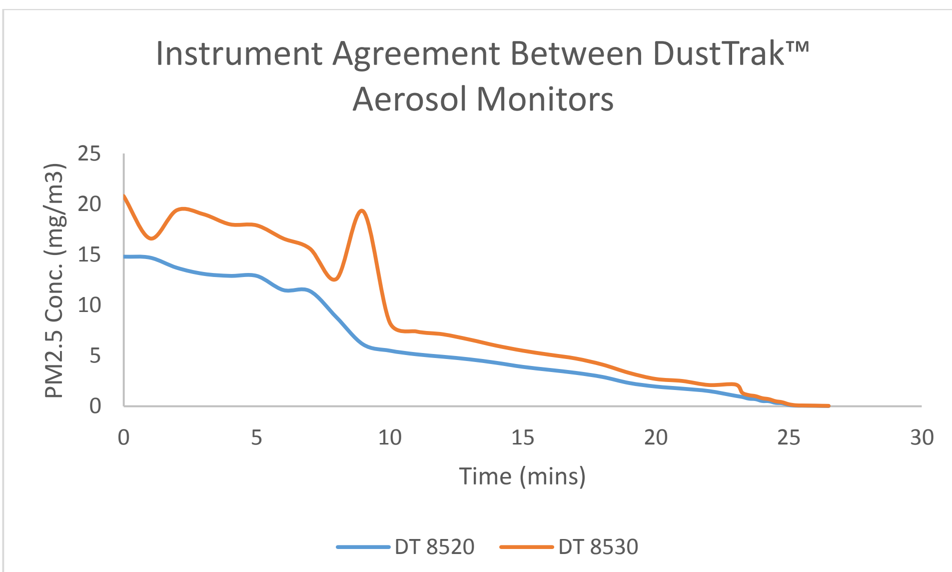


Figure 12. Comparison of time versus $PM_{2.5}$ concentration for the 2 aerosol monitors over 25 minutes of sampling.

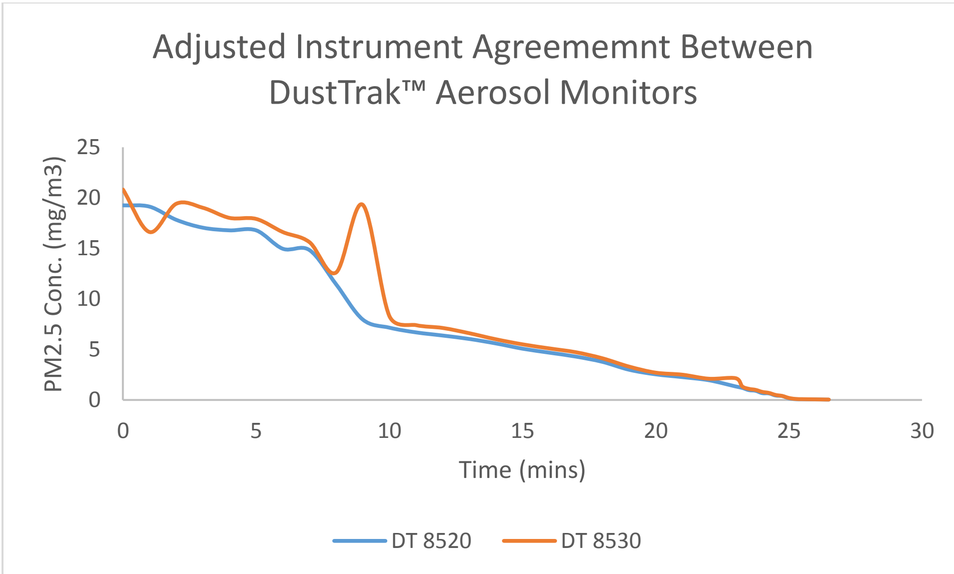


Figure 13. Comparison of time versus $PM_{2.5}$ concentration for the 2 aerosol monitors after using a 1.3 correction factor to adjust the DustTrak™ model 8520 graph.

Pre and post sampling Calibration of SKC personal pumps

Figure 14. Calibration of the SKC AirChek® XR5000 personal sampling pump using a Bios® DryCal DC-Lite primary air flow calibrator.

Determination of the Truck Air Changes per Hour (ACH)

Selection of tracer gas:

Carbon dioxide was used as the tracer gas because of its relatively high PEL (5,000 ppm), inexpensive, easy to obtain and measure (AIHA, 2004).

Method

Carbon dioxide was injected into the sealed truck cab for 1 minute at 50KPa with the engine idling and the blower set to the second position. The heat was turned on to simulate the cab climate on a cold night. The Concentration Decay Test was utilized to measure the decay rate of carbon dioxide over time to calculate the air exchange rate (figure 16).

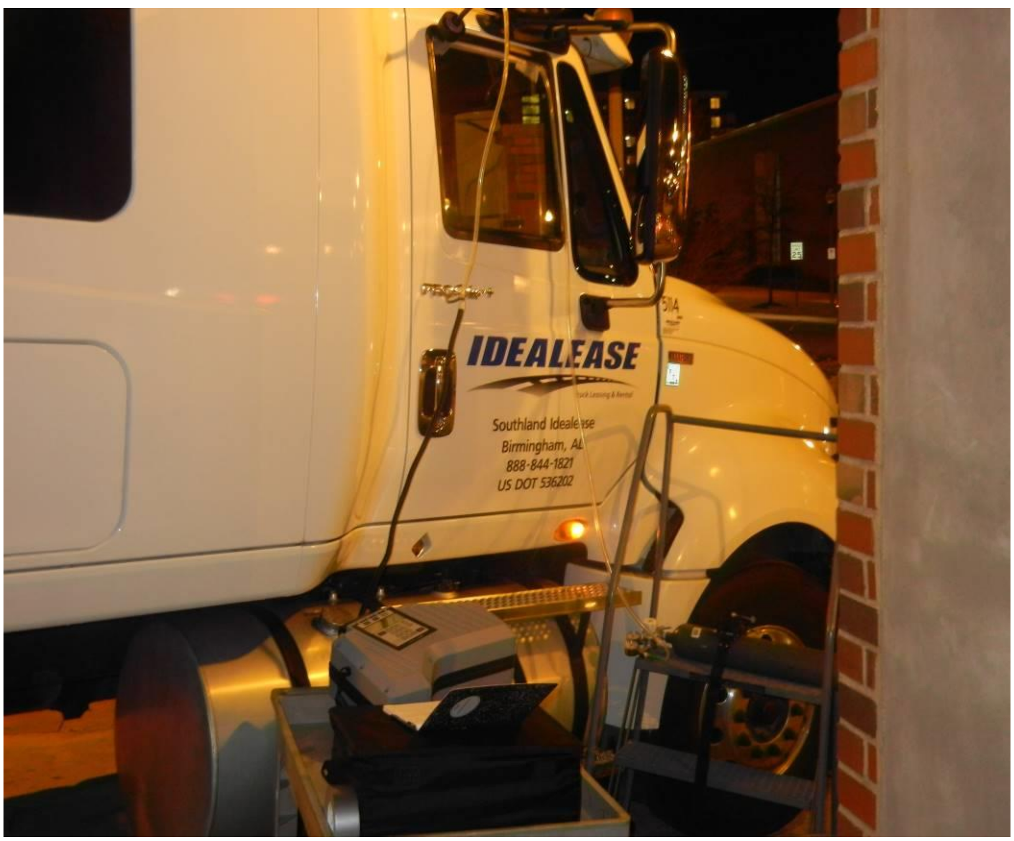


Figure 15. Experimental set-up to determine the truck air exchange rate.

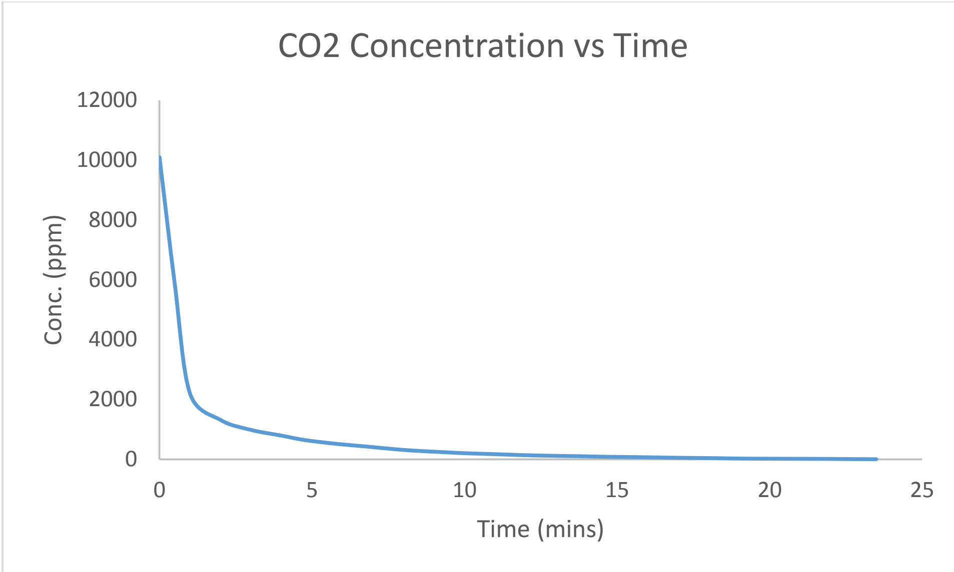


Figure 16. CO2 concentration decay curve used to calculate the air changes per hour.

Post Sampling

Post sampling calibration of pumps was performed immediately after each sampling session. The cassettes with collected DPM were detached from the flexible tubing, capped and stored in a zip-lock bag away from moisture, sunlight and heat. The storage conditions were applied as a precautionary measure. Diesel particulate samples from occupational settings generally do not require refrigerated shipment unless there is potential for exposure to elevated temperatures (NMAM, 2003). Samples were packed securely and shipped weekly via UPS parcel carrier to Bureau Veritas Laboratory, accredited by the American Industrial Hygiene Association-Laboratory Accreditation Program, LLC (AIHA-LAP, LLC). The shipping schedule was chosen based on cost and logistics. The laboratory analyzed the samples for EC, OC and TC using the NIOSH 5040method.In this method Thermal-Optical analysis is used to detect and quantify the different types of carbon. (NMAM, 2003).The estimated limit of detection in the laboratory for either elemental or organic carbon per filter is 2 µg. Assuming a pump flow rate of 2.4l/min for a 10 hour sampling period, this translates to approximately 1.4 $\mu g/m^3$.

$PM_{2.5}$ levels outside the truck cab gave a general indication of prevailing meteorological conditions and corroborate results from gravimetric analysis of DPM collected via active sampling. Historical weather data from the closest for weather station was archived from an online source (Weather Underground, Inc., AnnArbor, Mich.).

Data Analysis

Graphical and empirical methods were used to assess normality of EC, OC, TC and $PM_{2.5}$ concentration data. SAS V9.3 PROC Univariate and JMP were used to analyze the results. Statistical summaries of concentration data were presented including mean (standard deviation), median, range (minimum, maximum) and geometric mean (95% confidence intervals). GM values were calculated by the following equation

(2)

$$GM = \exp\left(\frac{\sum_{i=1}^{n} \ln x_i}{n}\right)$$

Where: x_i = untransformed EC or OC concentration.

The obtained concentration data failed normality tests as such a non-parametric test (Wilcoxon-Mann-Whitney) was used to determine differences between inside and outside concentrations Linear regression and scatter plots were used to assess associations between inside and outside EC, OC, TC and $PM_{2.5}$ concentrations. R-squared, p-values and MSE will be used to present model fit and strength of association. Observed concentration values below the limit of detection (LOD) were replaced with 1.4 $\mu g/m^3$. For samples reported as below the laboratory limit of detection (LOD), the LOD of the method was used to calculate the EC or OC level (Liukonen, 2002).

RESULTS

Of the 21 samples taken inside of the truck, 3 (14%) were below the LOD for elemental carbon (EC). While 8 out of 21 (38%) of samples from outside of the truck were below the LOD for EC. For values below the LOD (2 µg or 1.4 µg/m^3), the LOD mass or concentration (1.4 µg/m^3) was used for statistical analysis. The concentration of OC was detectable in all samples collected. Mean concentrations taken from inside the truck are significantly higher than from those sampled outside (EC 6.8 µg/m^3 vs 2.1; OC 34.9 µg/m^3 vs. 18.0 µg/m^3; TC 41.6 µg/m^3 vs. 19.8 µg/m^3) p-values = 0.002, 0.0002 and 0.0002 respectively. Box plots in figures 17 – 20 represent the overall comparison of inside versus outside concentrations for EC, OC, TC and $PM_{2.5}$.

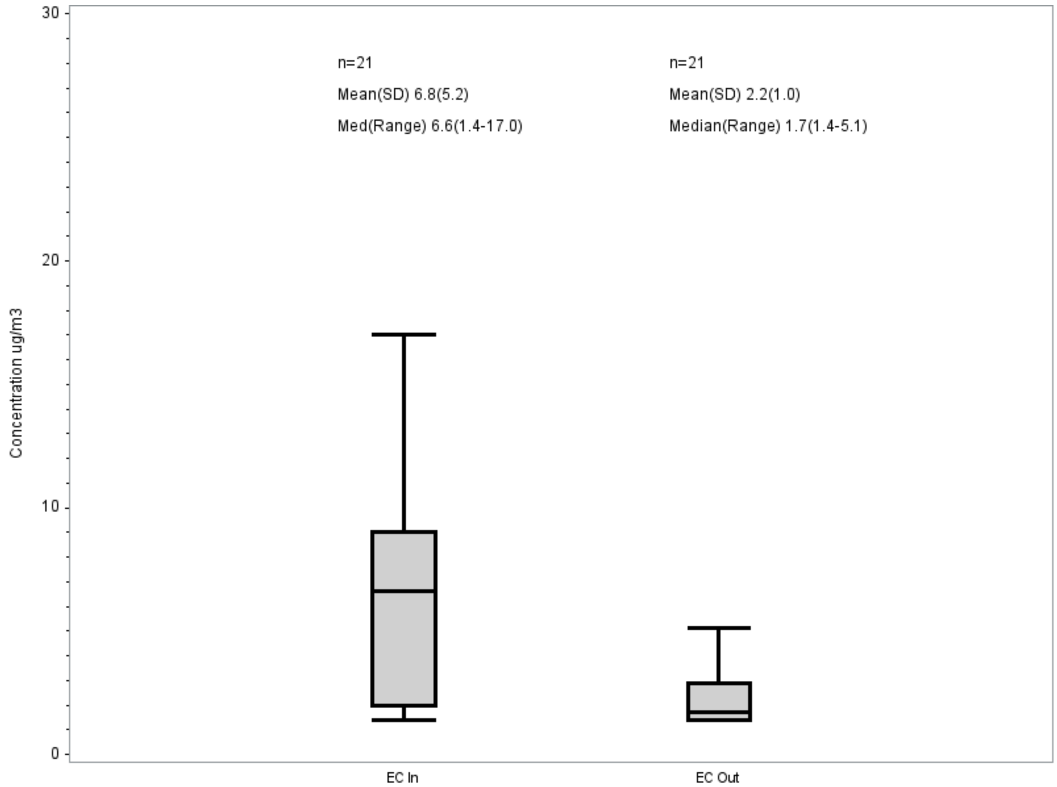


Figure 17. Overall Comparison of Inside versus Outside Concentrations for EC.

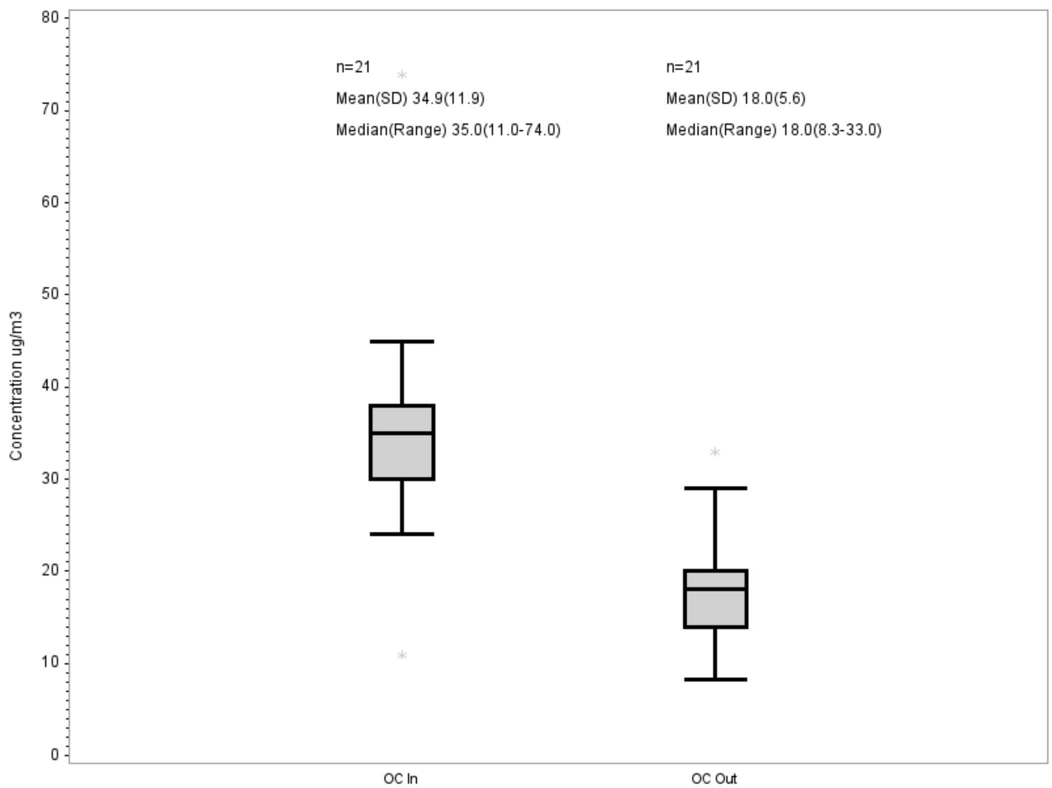


Figure 18. Overall Comparison of Inside versus Outside Concentrations for OC.

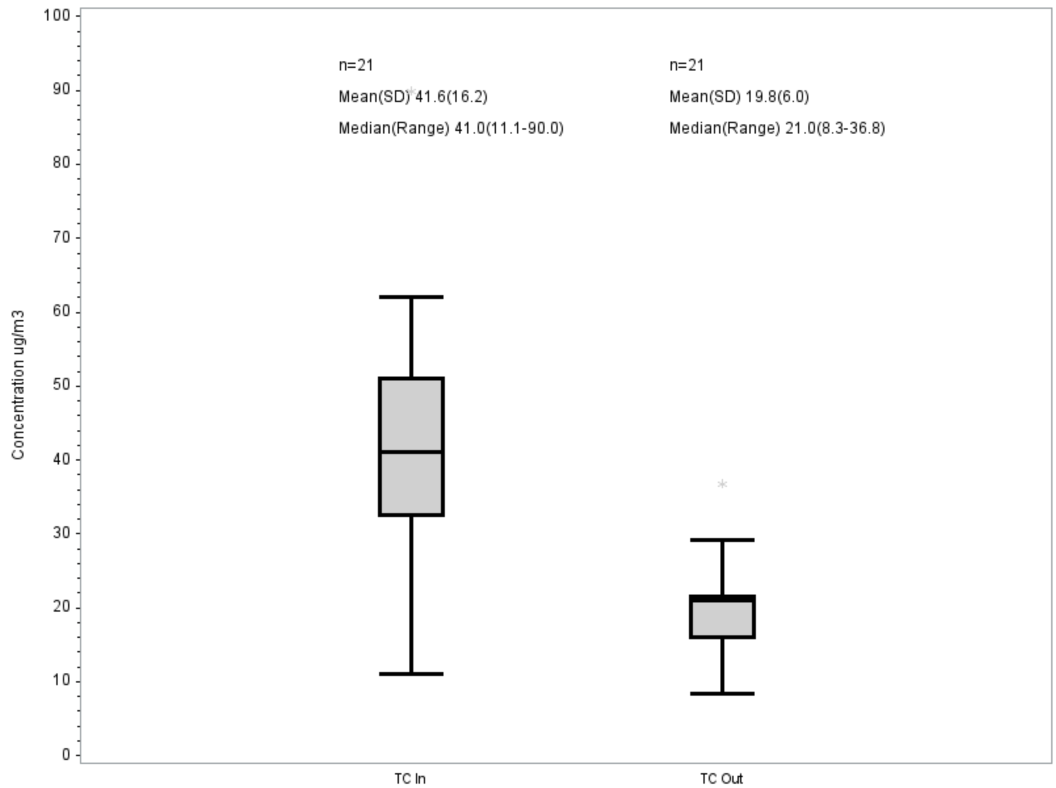


Figure 19. Overall Comparison of Inside versus Outside Concentrations for TC.

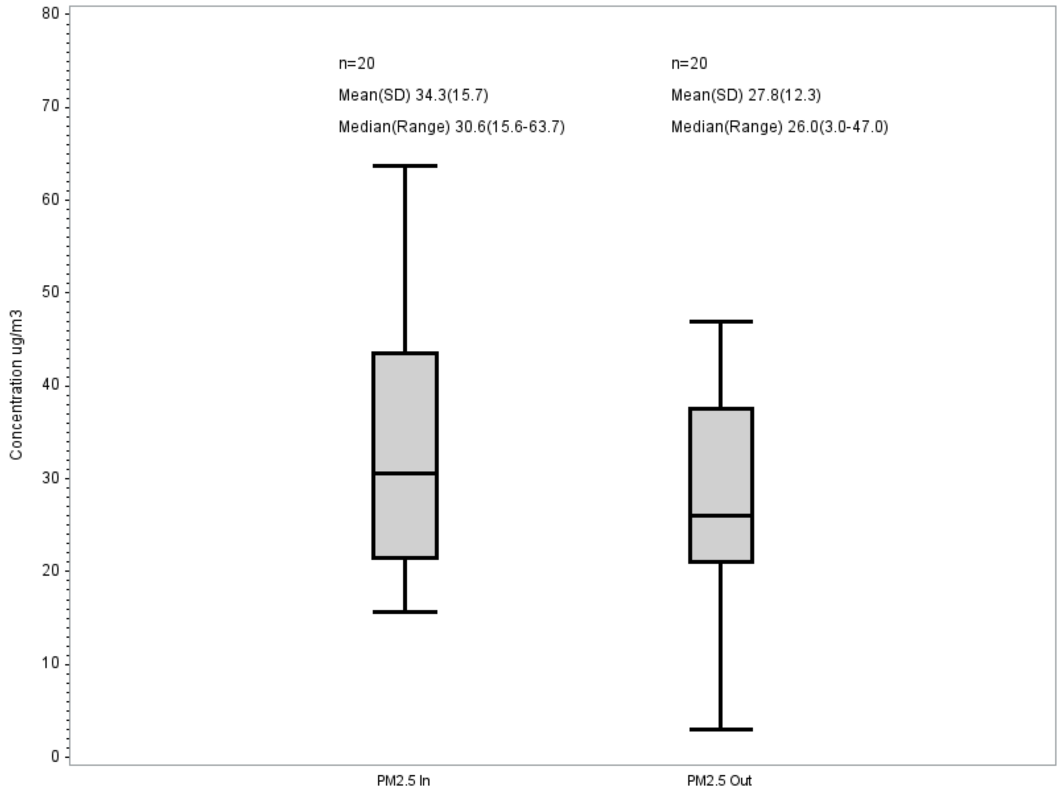


Figure 20. Overall Comparison of Inside versus Outside Concentrations for $PM_{2.5}$.

Overall mean concentrations differ significantly when comparing inside and outside concentrations for EC, OC, and TC ($p = 0.002$, $p = 0.0002$ and $p = 0.0002$ respectively). Overall $PM_{2.5}$ concentrations outside the truck are positively associated with $PM_{2.5}$ inside concentrations ($p = 0.005$, $r = 0.60$). Figures 25-28 represent scatter plots of inside versus outside concentrations with the corresponding correlations and p-values.

Lower concentrations of EC, OC, TC and PM2.5 were observed in samples taken from truck 1 (n = 9). Samples from truck 2 (n = 12) had relatively higher concetrations for the same analytes. Although truck 1 and truck 2 had similar engines and cab configurations, truck 1 probably had cleaner emissions, a more patent exhaust system and or better weather seals minimizing the infiltration of DE into the truck cab. As stated in the methods section, this study used EC as the proxy for DE.The overall geometric mean EC concentration inside the truck was 5.0 $\mu g/m^3$. The overall geometric mean for EC concentration from filters outside of the truck was 2.0 $\mu g/m^3$. Overall the mean EC concentration inside of the truck was significantly greater than the concetration outside of the truck ($p = 0.001$).

Similar trends can be observed in OC and TC concentrations (figures 18 &19). Again concentrations inside of the truck are significantly higher than outside concenrtations (p- < 0.0001). As with EC, OC and TC concentrations, $PM_{2.5}$ concentrations inside the truck are higher than outside concentrations. However the difference is not statically significant ($p = 0.337$).Tables in Appendix N represents the geometric means and 95% confidence intervals for the 21 samples collected.

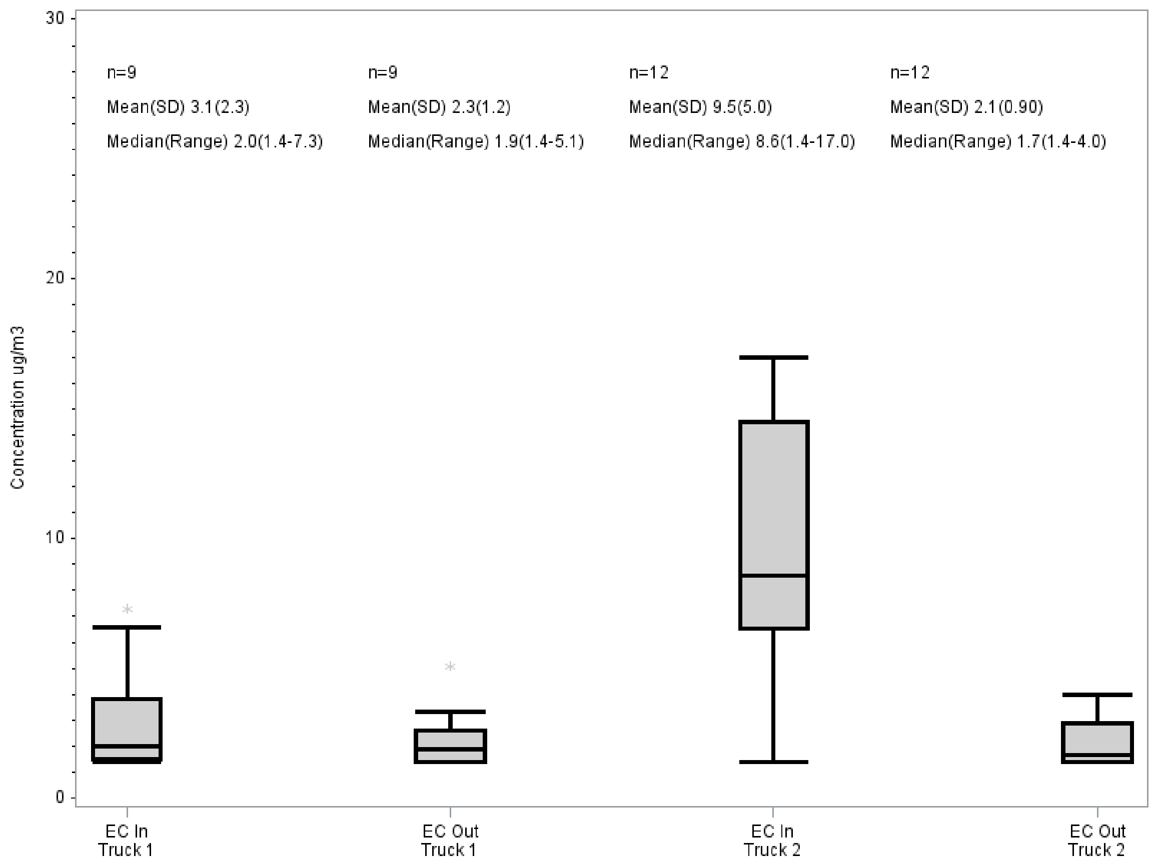


Figure 21. Comparison of elemental carbon concentration inside versus outside by truck.

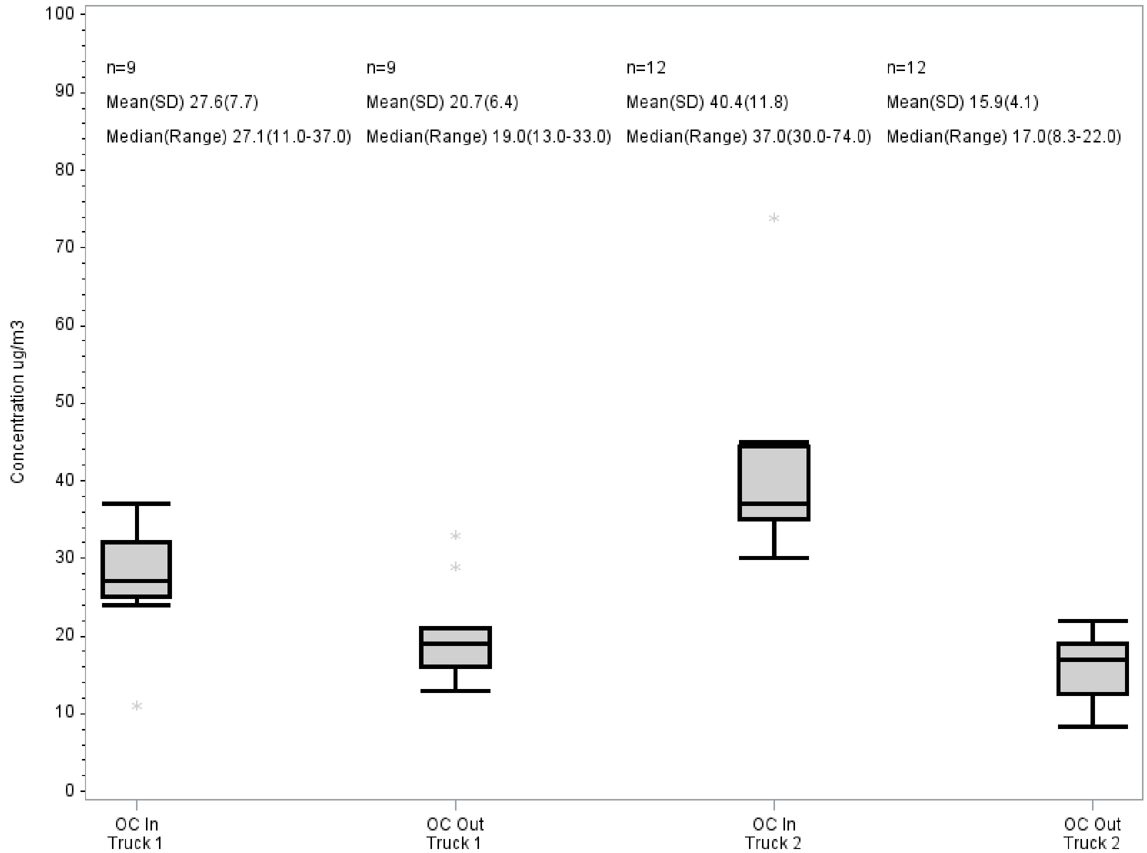


Figure 22. Comparison of organic carbon concentration inside versus outside by truck.

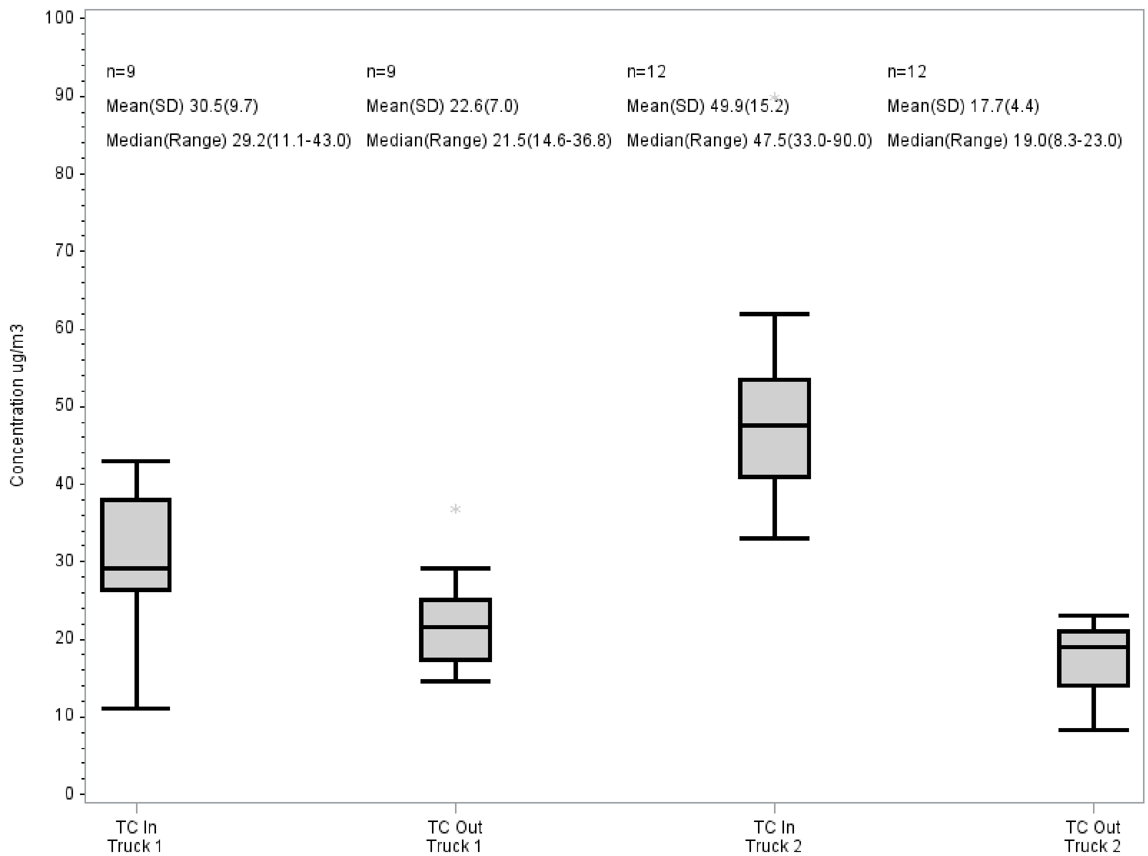


Figure 23. Comparison of total carbon concentration inside versus outside by truck.

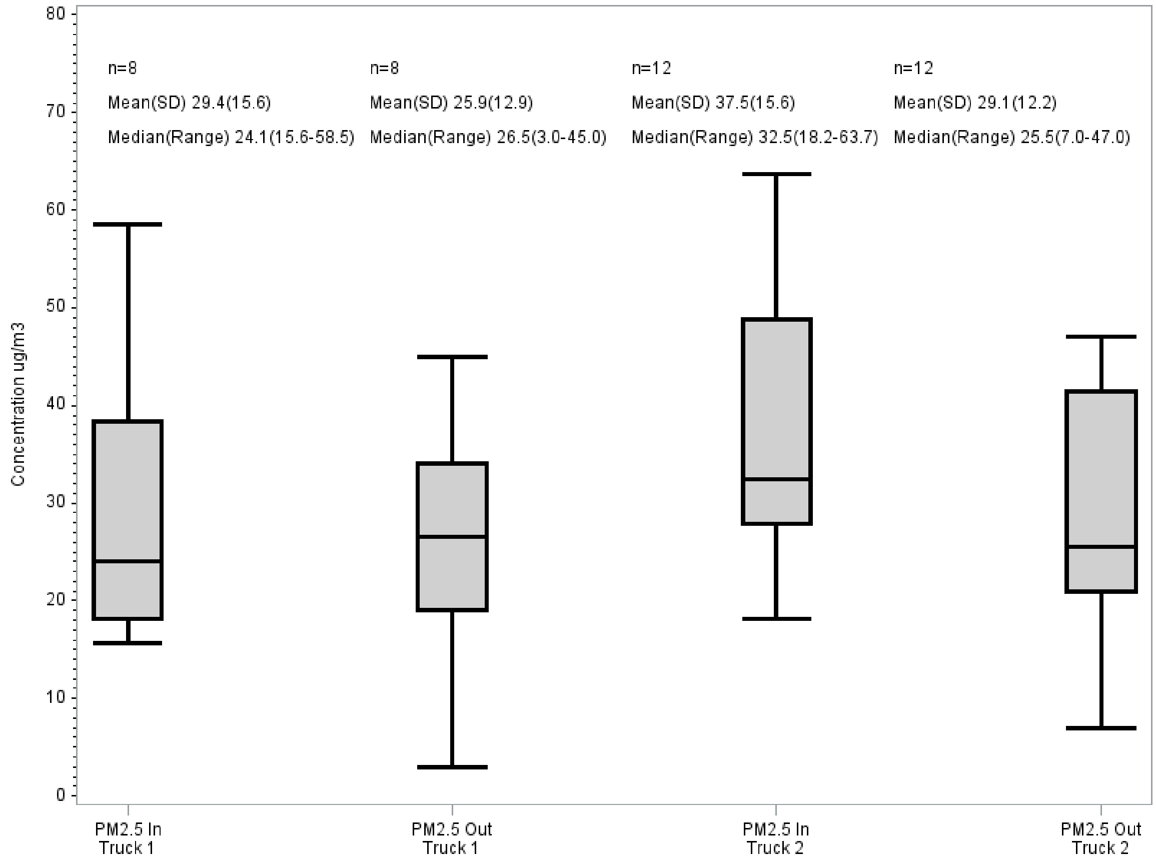


Figure 24. Comparison of $PM_{2.5}$ concentration inside versus outside by truck.

Table 4

Overall Comparison of Inside and Outside Concentrations for EC, OC, TC, and PM2.5

		Inside		Outside	
Analyte	**N**	**Geometric Mean μg/m^3 (95% C.I.)**	**N**	**Geometric Mean μg/m^3 (95% C.I.)**	**p-value**
EC Conc. (μg/m^3)	21	4.87 (3.25- 7.31)	21	1.99 (1.65- 2.4)	0.0014
OC Conc. (μg/m^3)	21	33.03 (28.12- 38.81)	21	17.18 (14.94- 19.77)	<.0001
TC Conc. (μg/m^3)	21	38.55 (31.86- 46.64)	21	18.92 (16.42- 21.79)	<.0001
PM2.5 Conc. (μg/m^3)	20	31.15 (25.3- 38.36)	20	23.93 (17.53- 32.67)	0.337

Table 5

***Summary** Statistics of Analytes by Truck*

		Both Trucks			Truck 1			Truck 2		
Analyte	**Filter Location**	**N**	**Median (Min, Max)**	**Mean (Std.)**	**N**	**Median (Min, Max)**	**Mean (Std.)**	**N**	**Median (Min, Max)**	**Mean (Std.)**
EC Conc. (µg/m3)	Inside	21	6.6 (1.4, 17)	6.8 (5.2)	9	2.0 (1.4, 7.3)	3.1 (2.3)	12	8.6 (1.4, 17.0)	9.5 (5.0)
EC Conc. (µg/m3)	Outside	21	1.7 (1.4, 5.1)	2.1 (1.0)	9	1.9 (1.4,5.1)	2.3 (1.2)	12	1.7 (1.4,4.0)	2.1 (0.9)
OC Conc. (µg/m3)	Inside	21	35.0 (11.0, 74.0)	34.9 (11.9)	9	27.1 (11.0, 37.0)	27.6 (7.7)	12	37.0 (30.0,74.0)	40.4 (11.8)
OC Conc. (µg/m3)	Outside	21	18.0 (33.0, 8.3)	17.9 (5.6)	9	19.0 (13.0, 33.0)	20.7 (6.4)	12	17 (8.3, 22.0)	15.9 (4.1)
TC Conc. (µg/m3)	Inside	21	41.0 (11.1, 90.0)	41.6 (16.2)	9	29.2 (11.1, 43.0)	30.5 (9.7)	12	47.5 (33.0,90.0)	49.9 (15.2)

Table 6

Summary Statistics of $PM_{2.5}$ Concentration by Truck

	Both Trucks			Truck 1			Truck 2		
Filter Location	**N**	**Median (Min, Max)**	**Mean (Std.)**	**N**	**Median (Min, Max)**	**Mean (Std.)**	**N**	**Median (Min, Max)**	**Mean (Std.)**
Inside	20	30.6 (15.6, 63.7)	34.3 (15.7)	8	24.0 (15.6,58.5)	29.4 (15.6)	12	32.5 (18.2,63.7)	37.5 (15.6)
Outside	20	26 (3.0, 47.0)	27.8 (12.3)	8	26.5 (3.0,45.0)	25.9 (12.9)	12	25.5 (7.0,47.0)	29.1 (12.3)

Table 7

Spearman Correlations (p-value) for Concentrations and Meteorological Parameters

Variable	Humidity %	Temperature ^{0}F	Wind mph
EC Outside	-0.68 (0.001)	0.16 (0.488)	0.12 (0.604)
OC Outside	0.16 (0.488)	0.048 (0.838)	0.26 (0.264)
TC Outside	-0.09 (0.706)	0.22 (0.344)	0.28 (0.225)
PM2.5 Outside	-0.20 (0.389)	0.17 (0.488)	-0.10 (0.689)

Table 8

Spearman Correlations (p-value) for Inside and Outside Concentrations

Variable	EC Outside	OC Outside	TC Outside	PM2.5 Outside
EC Inside	0.39	-0.20	-0.08	0.40
	(0.081)	(0.394)	(0.716)	(0.077)
OC Inside	0.06	-0.297	-0.25	0.48
	(0.807)	(0.191)	(0.278)	(0.03)
TC Inside	0.19	-0.31	-0.23	0.45
	(0.413)	(0.174)	(0.312)	(0.047)
PM2.5 Inside	0.27	-0.23	-0.14	0.60
	(0.243)	(0.331)	(0.558)	(0.005)

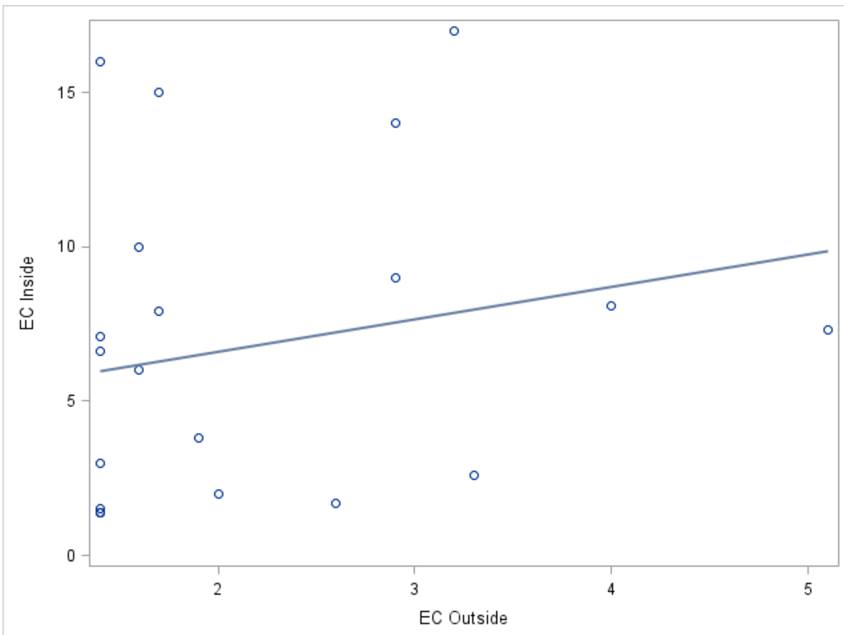


Figure 25. EC concentration regression plot. r = 0.39, p = 0.081

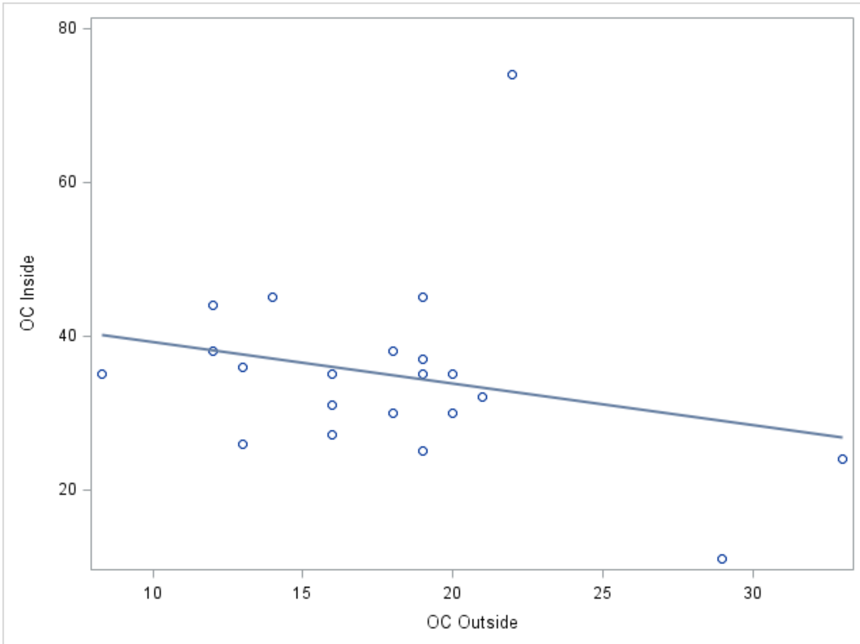


Figure 26. OC concentration regression plot: r = -0.3, p = 0.191

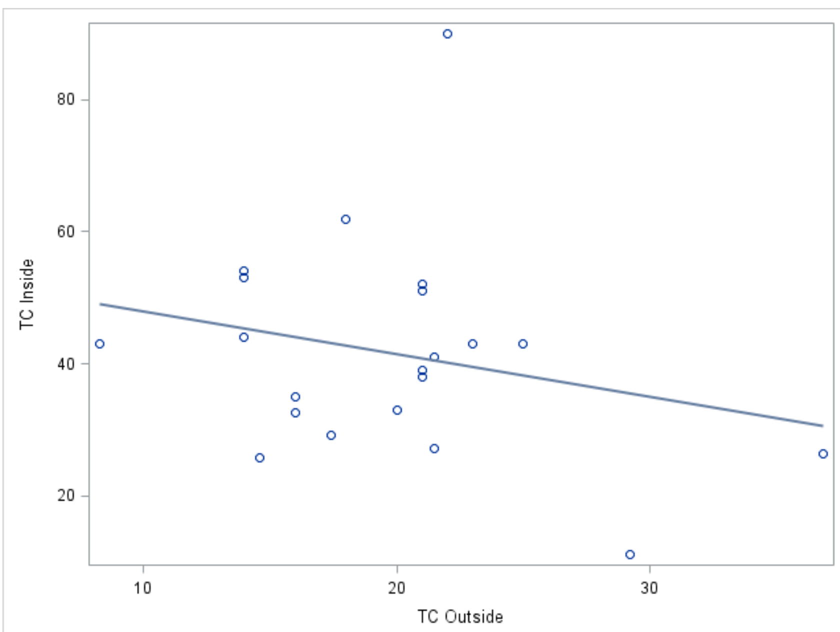


Figure 27. TC concentration regression plot: r = -0.2, p = 0.312

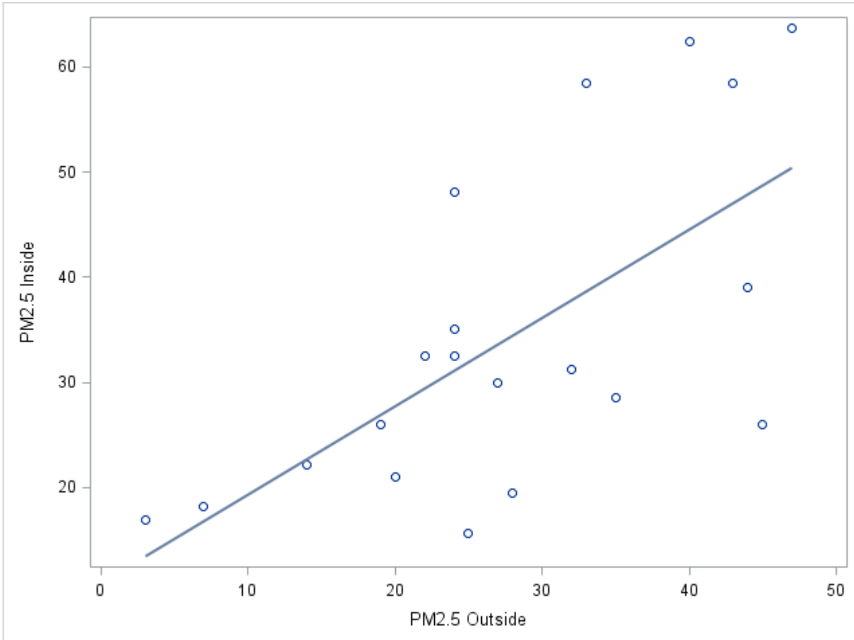


Figure 28. $PM_{2.5}$ concentration regression plot: $r = 0.6$, $p = 0.005$

DISCUSSION

All the measured pollutant concentrations (EC, CO, TC, $PM_{2.5}$) were generally higher inside than outside of the truck cab. However, with the exception of $PM_{2.5}$ concentrations, there was no significant association between concentrations of analytes measured inside the truck and concentrations outside of the truck. Overall $PM_{2.5}$ concentrations outside the truck are positively associated with $PM_{2.5}$ inside concentrations ($p=0.005$, $r=0.60$). Table 8. represents the Spearman Correlations for inside and outside concentrations. Figures 22-25 represent scatter plots of inside versus outside concentrations with corresponding correlations and p-values. No significant clustering pattern can be observed in figures 22, 23 and 24 resenting EC, OC and TC concentrations respectively. A clearer pattern can be seen in figure 28 where there is a significant, positive relationship between inside and outside concentrations for $PM_{2.5}$. Using EC or TC as per MSHA protocol as the surrogates for DE, correlation values ($r = 0.4$, $p = 0.081$ or $r =0.2$, $p = 0.413$ respectively) seem to indicate that there is no significant association between DE concentrations inside and outside of the truck idle parking at a truck stop.

The most plausible explanation for higher DE concentration inside of the truck than outside is self-pollution. This view is supported by conclusions drawn from a similar study by Davis, W. et al. It was discovered that extended periods of parked idling increased concentrations of CO, NOx and $PM_{2.5}$ inside of the truck cab. It was concluded that the elevated level of pollutants inside the truck cab was largely due to self-pollution from the truck itself (Davis, 2007). In a different study on DE exposure in truck drivers, investigators suggested that exposure within truck cabs under road conditions originated partly from the engine's own emissions. Engine exhaust entered the truck cab through holes in the truck cab floor where the pedals and gear shifter were located (Steenland, 1998). Although trucks used for our study were in a fairly good mechanical condition, the possibility of DE leaks into the cab through deteriorated seals cannot be ruled out. In other reviewed literature it was concluded that levels of fine particulates inside the cabins of operating trucks and school buses are usually higher than background levels. (Borak and Sirianni, 2007). Other investigators suggested that infiltration of DE into a truck cab worsens with the truck's age. Deteriorated rubber seals behind the instrument panel allow exhaust from the engine compartment to enter the cab (NRDC, 2007). In yet another study on DE exposure inside of school buses, investigators concluded that self-pollution in school buses can result in higher in-cabin concentrations (Lee, 2015).

Reviewed literature supports the plausibility of self-pollution from the truck's own DE as the cause for higher EC concentration inside the truck cab. Although the most plausible explanation to findings from this study is self-pollution by the truck itself, infiltration of DE from the immediate outside environment cannot be disregarded. In this present study, although there is no association between EC concentration (the surrogate for DE) inside and outside of the truck (r =0.4, p = 0.081), a moderate, positive association exists between inside and outside concentrations of $PM_{2.5}$ (r =0.6, p = 0.005). This supports the suggestion that a portion of the pollutants inside the truck originates from the truck stop environment. However in this setting where over one hundred other trucks are idling, source attribution is challenging because of the presence of DE emissions from other vehicles. Due to limitations in the study design, the proportion of

EC or DE inside the truck originating from the truck's own engine could not be ascertained. Other studies mentioned in the Literature Review section have employed an intentional marker to quantify entry of DE into school bus cabins. To some extent, these studies were able to estimate the concentration of DE inside the bus originating from the vehicle's own exhaust (Borak, 2007; Behrentz et al. 2004; Ireson, 2011).

A strong smell of tobacco in truck 2 used in the current study, led to the assumption that the previous occupant or driver smoked in the vehicle. From this position, it is reasonable to suggest that higher levels of TC concentration inside of truck 2 resulted from remnants of tobacco smoke. One study showed that third hand smoke (THS) accumulates in smokers' homes and persists when smokers move out even after homes remain vacant for 2 months and are cleaned and prepared for new residents (Matt, 2011). In a study on particulate exposures in the US trucking industry, investigators concluded that cigarette smoking significantly increased driver's $PM_{2.5}$ and OC levels. Both were nearly two fold higher in smokers compared to nonsmokers (Smith, 2006). In this study $PM_{2.5}$ and OC concentration were 28% and 46 % higher respectively in truck 2 than truck 1 (tables 7 & 8). A different study suggests that OC interferences should be suspected if the EC: TC ratio is <0.35 (Sirianni, 2003). Results from EC: TC ratios in this study were all below 0.27. This finding may lead one to consider THS as a significant contributor to the elevated EC and OC concentrations inside the truck. Appendix O is a photograph of sampling media from inside trucks 1 and 2. Filters from truck 2 are visibly darker than filters from truck 1. However cigarette smoke and carbonates ordinarily do not interfere in the EC determination. Less than 1% of the carbon in cigarette smoke is elemental. (NMAM, 2003).

Box plots presented in figures 18-21 show higher inside concentrations for EC, OC, TC and $PM_{2.5}$ irrespective of the truck from which samples came. In addition, the same figures show that truck 2 had higher inside concentrations for all the measured parameters. EC concentration inside the truck remained higher than outside concentrations regardless of the truck's presumed smoking status. This suggests that self-pollution was still the main source of pollutants inside the trucks used for this study. The use of a second truck (truck 2) and presumed smoking status are artifacts of the study. As stated in the methods and materials section, inclusion of these variables in the study was beyond the investigator's control. That being said, the contribution of THS to TC levels inside the truck warrant further investigation beyond the scope of this study.

The role of meteorology in influencing levels of DE inside and outside of the truck cab was also considered. The main meteorological parameters of influencing outside pollution levels are temperature, wind speed and relative humidity. Studies point to an inverse relation between wind speed and particulate concentrations (Sivaramasundaram and Muthusubramanian, 2009). In the current study, humidity is used as a surrogate for rain/precipitation in order to obtain more data points from the small sample (n = 21). Only 2 rain events occurred during the 21 days of sampling. Other studies have demonstrated the scavenging of particulates from the atmosphere due to precipitation (Maria and Russell, 2005). In this study concentrations of all the measured pollutants (EC, OC, TC, and $PM_{2.5}$) outside of the truck appeared lower on rainy days in comparison to non-rainy days. Research has shown that differing weather patterns cause day-to-day variability of outside concentrations of pollutants. In a study on diesel exhaust pollution inside of school buses, researchers saw a statistically significant association between PM_{10} concentrations and average daily temperature as well as humidity (Borak and Sirianni, 2007). Outside concentrations for $PM_{2.5}$ ranged from 3.0 to 47.0 µg/m^3. This wide range in $PM_{2.5}$ concentration may be explained by variability in weather conditions at the truck stop which experienced 2 rainy days and 3 days with wind speeds up to 26 mph. Varying weather conditions may also explain disparities in outside OC concentrations which ranged from 14 to 73 µg/m^3. Although variability in outside concentrations for OC and $PM_{2.5}$ could be attributed to prevailing meteorological conditions, Spearman correlations for concentrations and meteorological parameters do not show significant associations (Table 7.).The exception is outside EC concentration and humidity which appear to have a modest and inverse relationship ($r = -0.7$, $p = 0.001$). A possible explanation for the association is below cloud scavenging on the rainy days (Maria, 2005). The small number of data points in this current study ($n = 21$), limits the discussion on the role of weather in influencing concentrations of pollutants. Having found no significant association between the concentration of DE outside and inside of the truck ($r = 0.4$, $p = 0.08$), it follows that meteorological conditions would not be expected to influence the DE concentration inside the truck.

An EPA estimation of DPM concentration in different metropolitan area across the U.S. showed an overall mean value of background concentration for the entire country of 0.61 µg/m^3, a median of 0.54 µg/m^3 90th percentile at 1.07 µg/m^3, and 10th percentile of 0.21 µg/m^3 (EPA, 1993). In this study the mean EC concentration measured just outside of the truck was 2.4 µg/m^3.

During the 4 week sampling period between January 26 and February 19, 2015 the average PM2.5 concentration for the Birmingham AL area ranged from 1.0 µg/m^3 to

12.1 µg/m^3 (AIRNow, 2015). In the same period, $PM_{2.5}$ levels at the truck stop (measured just outside of the truck) ranged from 3.0- 47.0 µg/m^3 with an average concentration of 27.8 µg/m^3.Although current ambient DPM data for the Birmingham, AL area could not be obtained, inference from $PM_{2.5}$ levels show that the truck stop environment is a potential "hot spot" for both $PM_{2.5}$ and DE pollution. It is against this background that concerns for elevated risk of exposure to DE in LHTDs resting at trucks stops arise. In one study, exposure of truck drivers to elemental carbon in submicron particulate matter generally ranged from 1 to 10 µg/m^3 (Pronk, 2009).In another study, the average exposure to EC, OC and $PM_{2.5}$ concentrations for LHTDs was 1.4, 21.6 and 52.6 µg/m^3 respectively (Davis, 2007). By comparison, EC and OC concentrations of 4.4 and 33.0 µg/m^3 (measured inside the truck) in this current study are considerably higher.

Overall, exposure to DE inside and outside the truck at this truck stop was far below the MSHA PEL of 160 µg/m^3 (measured as TC) and the ACGIH recommended limit of 20 µg/m^3. The geometric mean of EC inside and outside of the truck was 4.9 µg/m^3 and 2.0 µg/m^3 respectively. $PM_{2.5}$ concentration inside of the truck had a geometric mean of 31.2 µg/m^3 which is close to the EPA daily limit [EPA 24-hour National Ambient Air Quality Standard (NAAQS) is 35µg/m^3 and 12 µg/m^3 for the annual limit] (EPA).

A recent survey showed that the mean number of years for employment as a long haul truck driver is 16.4 years (NIOSH, 2014). Studies show that lifetime exposures to DE concentrations of 2-6 µg/m^3 can result in a 50 percent increase in risk of lung cancer for people affected (CA, ARB, 1998). The EPA recommends a daily exposure limit of 5 µg/m^3 for diesel particulate matter. It goes to say there is still reason to be concerned about potential health implications for career truck drivers chronically exposed to the relatively low levels of DE that were observed in the current study.

Minimizing exposure to diesel exhaust is an occupational as well as a public health goal that depends on controlling diesel emissions.Long haul truck drivers who rest at truck stops have little control over the pollution that occurs in that environment neither do they have many alternatives in findings locations where the air is healthier. However drivers are responsible maintaining their trucks in a good mechanical condition as prescribed by the vehicle manufacturer. This can reduce DE emissions and exposure when drivers need to idle their trucks for extended periods. Ensuring integrity of all cab seals and weather-stripping around doors and windows can substantially reduce exposure to DE inside the truck cab regardless of the source. A study demonstrated that HEPA cabin filters are effective in reducing concentrations of particulates including DPM inside of school buses (Lee, 2015).The same could be done in trucks, potentially reducing the driver's exposure to DE by a significant amount. Argonne National Laboratory estimates that more than 650,000 long-haul heavy-duty trucks idle during required overnight rest stops every day (DOE, 2015). Educating truck drivers about hazards posed by DE and encouraging them to minimize idling their engines when taking rest breaks at truck stops is an administrative step that can go a long way in reducing DE exposure. Limiting engine idling can reduce emissions and fuel consumption both which are good for occupational and environmental health. The same can be said for the financial health of the trucking company. According to the EPA, it is estimated that trucks consume up to one gallon of diesel fuel for each hour at idle, using as much as 2,400 gallons of fuel every year per truck. This totals 1.2 billion gallons of diesel fuel consumed every year from idling, costing $1.8 billion (at $1.50 gallon/diesel). On average, each idling truck produces about 21 tons of carbon dioxide (C02) and 0.3 tons of nitrogen oxides (NOx) annually totaling over 11 million tons and 150,000 tons, respectively (EPA). Idle reduction technologies such as Electrified Parking Spaces (EPS) / Truck Stop Electrification (TSE), Auxiliary Power Units and Generator Sets (APU/GS), Battery Air Conditioning Systems (BAC) and Automatic Shut-down/ Start-up Systems are available to provide HVAC without operating the main engine (EPA, 2013). Implementing a combination of administrative and engineering controls suggested above can go a long way in reducing potential DE exposure in LHTDs resting at truck stops.

Study Limitations

- Small sample size.
- The investigation takes repeated measures on a single driver as such, results are not generalizable to the greater population of long haul truck drivers.
- Background air pollutant levels, varied within and between studies. Sampling in the 2 trucks was not done concurrently but rather consecutively. As such samples were taken under different meteorological conditions at the truck stop.
- Only one truck model was used in this research therefore, conclusions from this study cannot be generalized to the wide variety truck models found at truck stops.
- The contribution to higher OC concentration inside the vehicles from other sources such as tobacco smoke was not determined.
- It was not determined what proportion of the DE inside the truck was due to self-pollution.

- It was not established how much the air exchange rate or truck ventilation settings affected the concentration of pollutants inside of the truck.

Further Studies

In addition to analyzing correlations among concentrations from a larger sample size, the in-vehicle EC and $PM_{2.5}$ concentration can be estimated as a linear function of ambient DE and $PM_{2.5}$ concentration using equation 2.

$$C_{iv,vt} = k_{vt}\ C_{amb} + b_{vt} + \varepsilon_{vt} \qquad \text{(Equation 2.)}$$

Where,

b_{vt} = in-vehicle non-ambient EC or $PM_{2.5}$ concentration for vehicle type vt ($\mu g/m^3$)

$C_{iv,\ vt}$ = in-vehicle EC or $PM_{2.5}$ concentration for vehicle type vt ($\mu g/m^3$)

C_{amb} = ambient EC or $PM_{2.5}$ concentration ($\mu g/m^3$)

k_{vt} = in-vehicle/ambient ratio EC or $PM_{2.5}$ concentration for vehicle type vt, constant

vt = vehicle types: car, bus, truck, train, and other vehicles

ε = error term for residual variability in in-vehicle EC or $PM_{2.5}$ concentration, where $\varepsilon \sim N(0, \sigma\varepsilon)$ and σε is the standard deviation ($\mu g/m^3$)

The ratio of in-vehicle to ambient EC or PM2.5 concentrations, kvt, for vehicle type vt is determined by comparing in-vehicle measurement data with ambient data. The parameter bvt is non-zero only when there are in-vehicle sources of $PM_{2.5}$, such as smoking (Liu, 2009).The ratio of in-vehicle EC or $PM_{2.5}$ concentration to ambient EC or $PM_{2.5}$ concentration kvt is the key input to Equation (2). Studies have shown that the in-vehicle to fixed monitoring station (FMS) ambient ratio has a wide range of variability, depending on factors such as traffic counts or number of trucks idling at the truck stop during the sampling period in the case of the current study. Furthermore, several investigators conclude that there is not a strong correlation between ambient $PM_{2.5}$ concentration and in-vehicle concentration (Liu, 2009)

CONCLUSIONS

The purpose of this study was to determine whether there was an association between the concentration of DE inside a truck parked at a truck stop and the concentration of DE in the immediate environment outside the truck.Results from experiments conducted prior to this study appear to show an appreciable and significant association between the concentration of $PM_{2.5}$ inside and outside of the truck. It was also observed that the outside $PM_{2.5}$ concentration was generally higher than the inside concentration. Varying weather conditions may also explain disparities in outside OC concentrations which ranged from 14 to 73 µg/m3. Although variability in outside concentrations for OC and PM2.5 could be attributed to prevailing meteorological conditions, Spearman correlations for concentrations and meteorological parameters do not show significant associations (Table 9.).The exception is outside EC concentration and humidity which appear to have a modest and inverse relationship (r = -0.7, p = 0.001). A possible explanation for the association is below cloud scavenging on the rainy days (Maria, 2005). The small number of data points in this current study (n = 21), limits the discussion on the role of weather in influencing concentrations of pollutants.

Having found no significant association between the concentration of DE outside and inside of the truck (r =0.4, p = 0.08), it follows that meteorological conditions would not be expected to influence the DE concentration inside the truck.As in the preliminary study, a moderate, positive association between inside and outside levels of $PM_{2.5}$ was observed in the present study. However when inside versus outside concentrations were considered, a different picture emerged from the current study.In this experiment, the concentration of EC, OC, TC and $PM_{2.5}$ was higher inside compared to outside the truck for all 21 days of sampling. An insufficient number of samples (n = 2) for EC, OC and TC analysis were collected in the preliminary study to show any strength of association between inside and outside concentrations. Analysis of results from a relatively larger sample size (n = 21) used for the final study show that there was no significant association between the concentration of EC inside the truck and the concentration of EC outside of the truck. A significant difference was found between the two trucks used in this study when inside concentration for EC, OC and TC were compared. Air samples from the second truck had higher concentrations for all 3 analytes. However inside concentrations were considerably higher regardless of the truck from which samples were obtained. Analysis of data from both trucks show that there is no association between DE concentrations inside and outside of the truck. Diesel exhaust pollution in the truck stop environment is not the prime source of the driver's exposure to diesel particulates inside the truck. Self-pollution by the truck appears to contribute a greater proportion of the diesel particulate concentration inside of the truck. These conclusions are made with the acknowledgement of limitations of this study which restricts generalization to the greater body of LHTDs. A more extensive study with a larger sample size is needed to evaluate the risk for DE exposure in LHTDs who take their rest breaks at truck stops.

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The Deep South Center for Occupational Health and Safety

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APPENDICES

APPENDIX

A INSTITUTIONAL REVIEW BOARD APPROVAL

B TRUCK CAB INSIDE LAYOUT

C LOCATION OF CABIN FILTERS

D EXHAUST PIPE CONFIGURATION

E TRUCK STOP AT NIGHT

F DISTANCE BETWEEN TRUCKS

G SAMPLE DRIVER’S DAILY LOG SHEET

H MULTI-PARAMETER VENTILATION METER

I CALIBRATION OF INSTRUMENTS

J SAMPLING SET-UP

K DETERMINING INSTRUMENT AGREEMENT

L DETERMINATION OF THE ACH

M SUMMARY OF PRELIMINARY DATA

N GEOMETRIC MEAN OF ANALYTES

O SAMPLE FILTERS

APPENDIX A

INSTITUTIONAL REVIEW BOARD APROVAL

THE UNIVERSITY OF ALABAMA AT BIRMINGHAM
Institutional Review Board for Human Use

DATE: 1/12/15

MEMORANDUM

TO: Gumindenga F. Mabvuta
Principal Investigator

FROM: Cari Oliver, CIP
Assistant Director
Institutional Review Board for Human Use (IRB)

RE: Request for Determination—Human Subjects Research
IRB Protocol #N150112001 – Assessing Diesel Exposure in Truckers Resting at Truck Stops

A member of the Office of the IRB has reviewed your Application for Not Human Subjects Research Designation for above referenced proposal.

The reviewer has determined that this proposal is **not** subject to FDA regulations and is **not** Human Subjects Research. Note that any changes to the project should be resubmitted to the Office of the IRB for determination.

470 Administration Building
701 20th Street South
205.934.3789
Fax 205.934.1301
irb@uab.edu

The University of Alabama at Birmingham
Mailing Address:
AB 470
1720 2ND AVE S
BIRMINGHAM AL 35294-0104

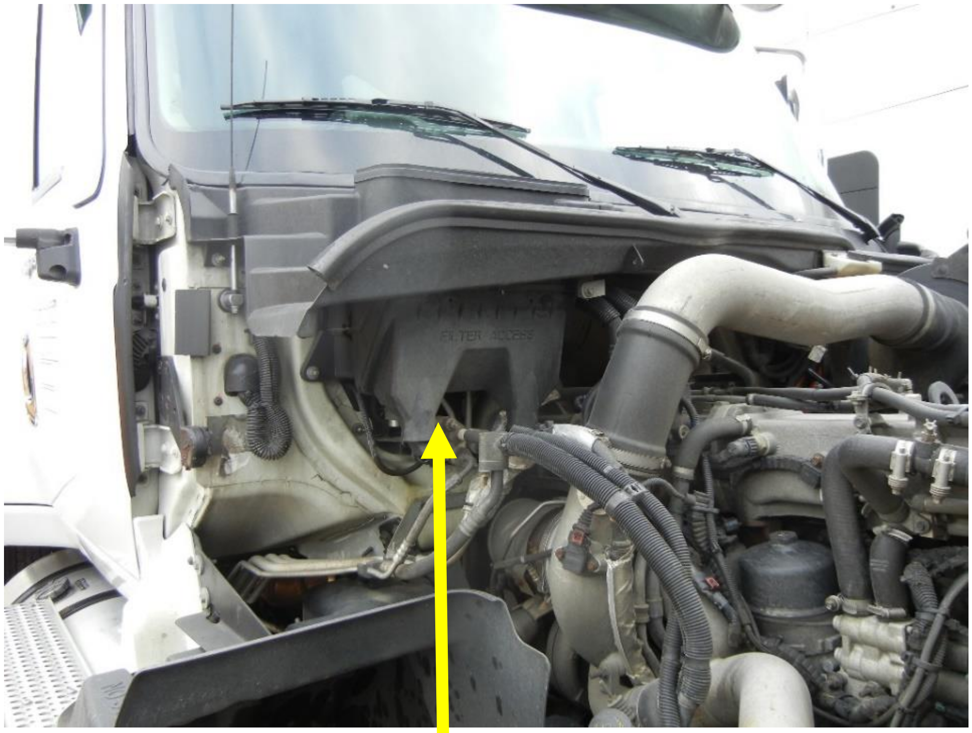
APPENDIX B

TRUCK CAB INSIDE LAYOUT

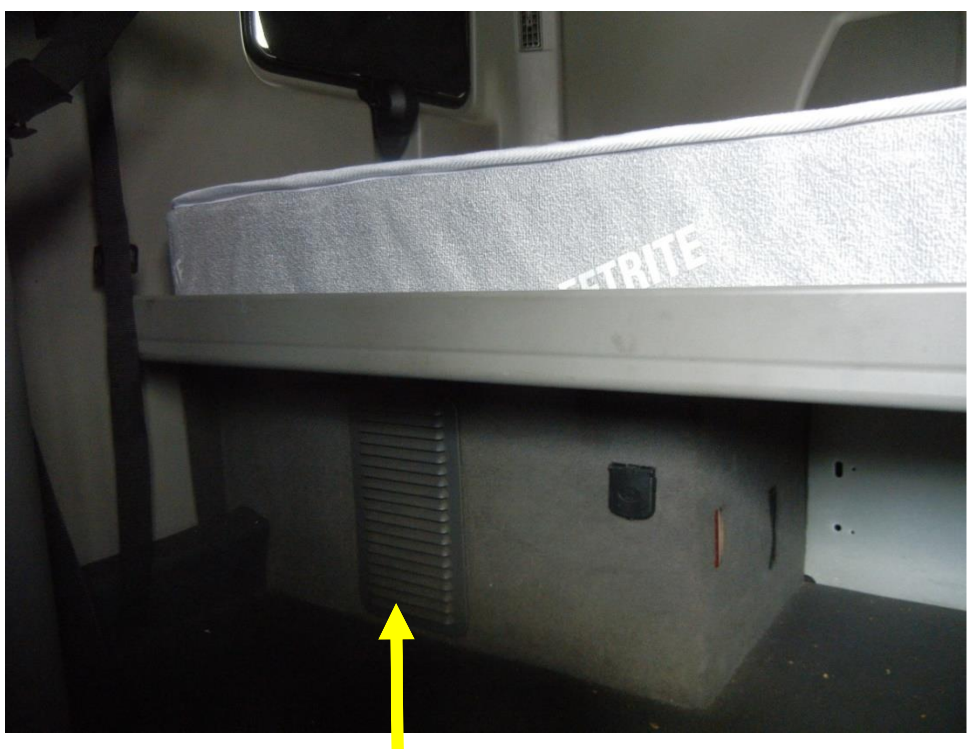
Truck cab, inside layout

APPENDIX C

LOCATION OF CABIN FILTERS



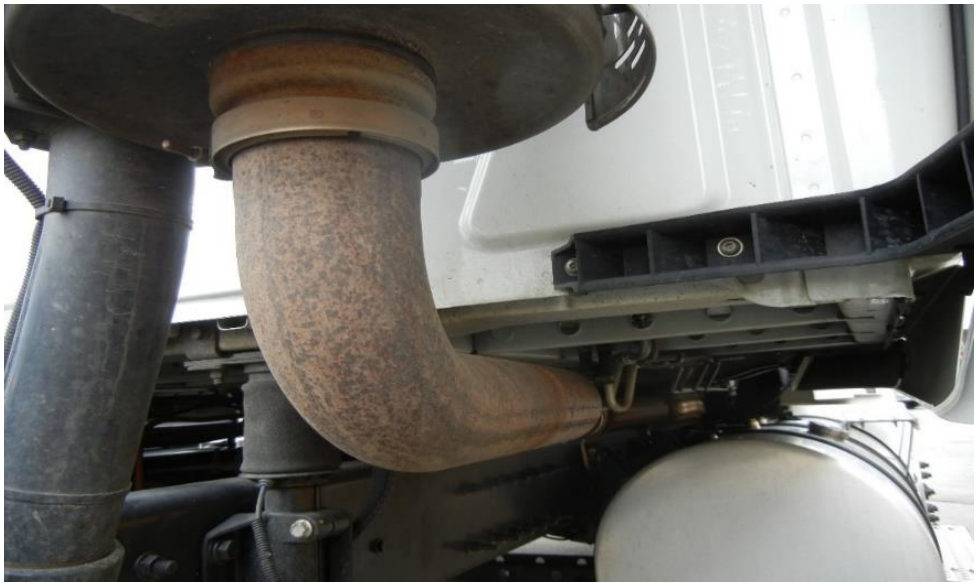
Location of Cabin Filter in the Engine Compartment



Location of Cabin Filter under the Sleeper Bunk Bed

APPENDIX D

EXHAUST PIPE CONFIGURATION


Exhaust Pipe Configuration under the Truck Cab


Exhaust Pipe Configuration behind the Truck Cab

APPENDIX E

TRUCK STOP AT NIGHT

Truck Stop filled to Capacity at Night (157 parking spots)

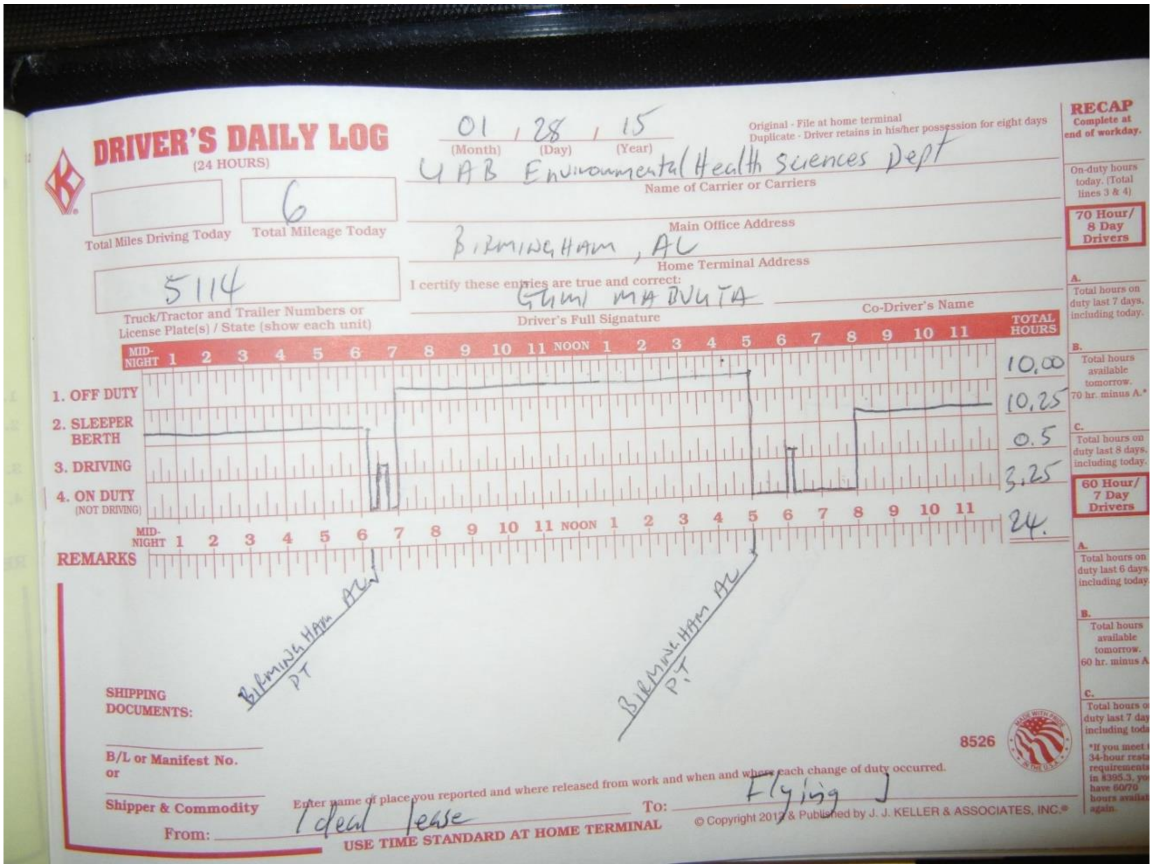
APPENDIX F

DISTANCE BETWEEN TRUCKS

Distance between research truck and neighboring trucks was approximately 5ft

APPENDIX G

SAMPLE DRIVER'S DAILY LOG SHEET


DRIVER'S DAILY LOG
(24 HOURS)

01 / 28 / 15
(Month) (Day) (Year)

Original - File at home terminal
Duplicate - Driver retains in his/her possession for eight days

6
Total Miles Driving Today
Total Mileage Today

UAB Environmental Health Sciences Dept
Name of Carrier or Carriers

Main Office Address

BIRMINGHAM, AL
Home Terminal Address

5114
Truck/Tractor and Trailer Numbers or License Plate(s) / State (show each unit)

I certify these entries are true and correct:
Driver's Full Signature
Co-Driver's Name

	TOTAL HOURS
1. OFF DUTY	10.00
2. SLEEPER BERTH	10.25
3. DRIVING	0.5
4. ON DUTY (NOT DRIVING)	3.25
	24.

REMARKS

BIRMINGHAM, AL PT

BIRMINGHAM, AL PT

SHIPPING DOCUMENTS:

B/L or Manifest No. or

Shipper & Commodity

Enter name of place you reported and where released from work and when and where each change of duty occurred.

From: Ideal lease To: Flying J

USE TIME STANDARD AT HOME TERMINAL

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8526

RECAP
Complete at end of workday.
On-duty hours today. (Total lines 3 & 4)

70 Hour/ 8 Day Drivers
A. Total hours on duty last 7 days, including today.
B. Total hours available tomorrow. 70 hr. minus A.*
C. Total hours on duty last 8 days, including today.

60 Hour/ 7 Day Drivers
A. Total hours on duty last 6 days, including today.
B. Total hours available tomorrow. 60 hr. minus A.*
C. Total hours on duty last 7 days, including today.

Sample of the Driver's/ Investigator's DOT Daily Log Sheet

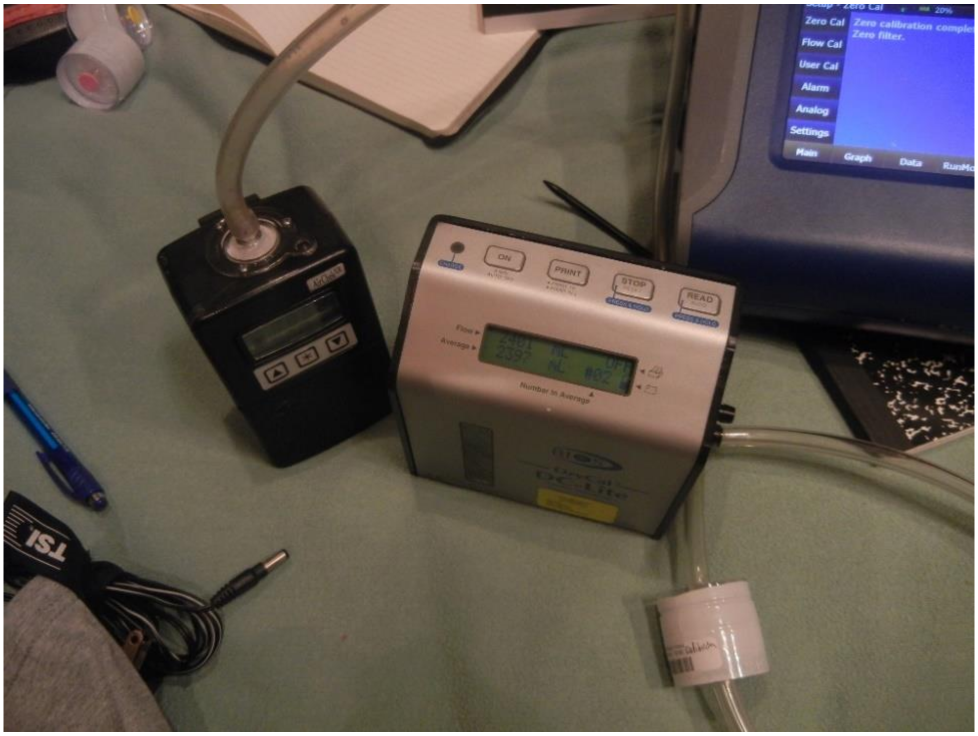
APPENDIX H

MULTI-PARAMETER VENTILATION METER

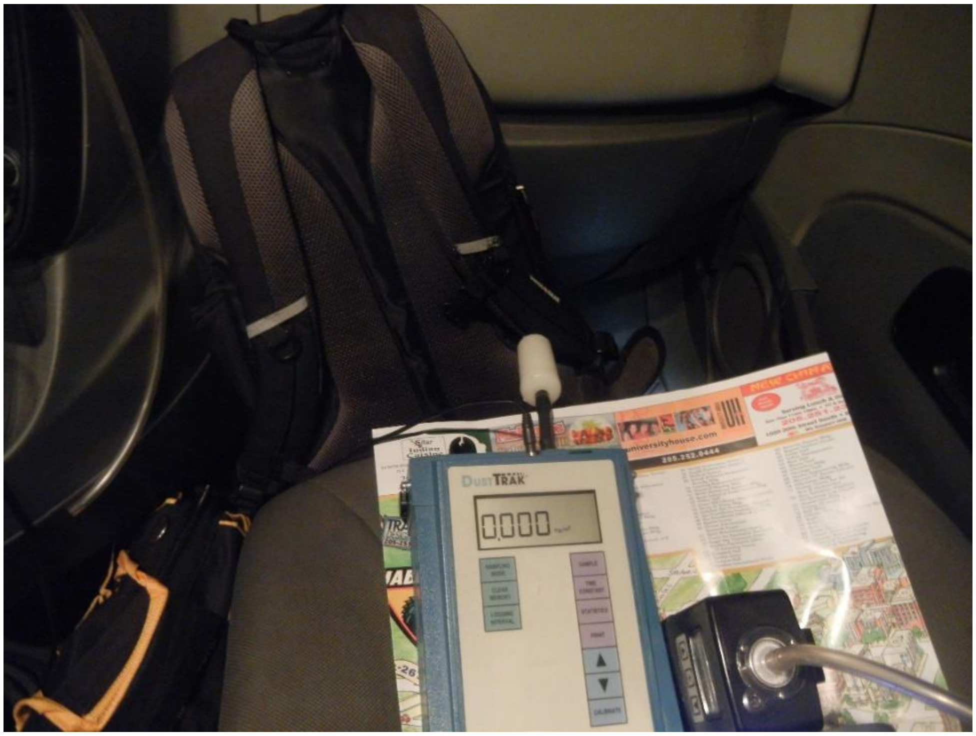
TSI Model 8360A VelociCalc® Plus multi-parameter ventilation meter

APPENDIX I

CALIBRATION OF INSTRUMENTS



Calibration of Instruments

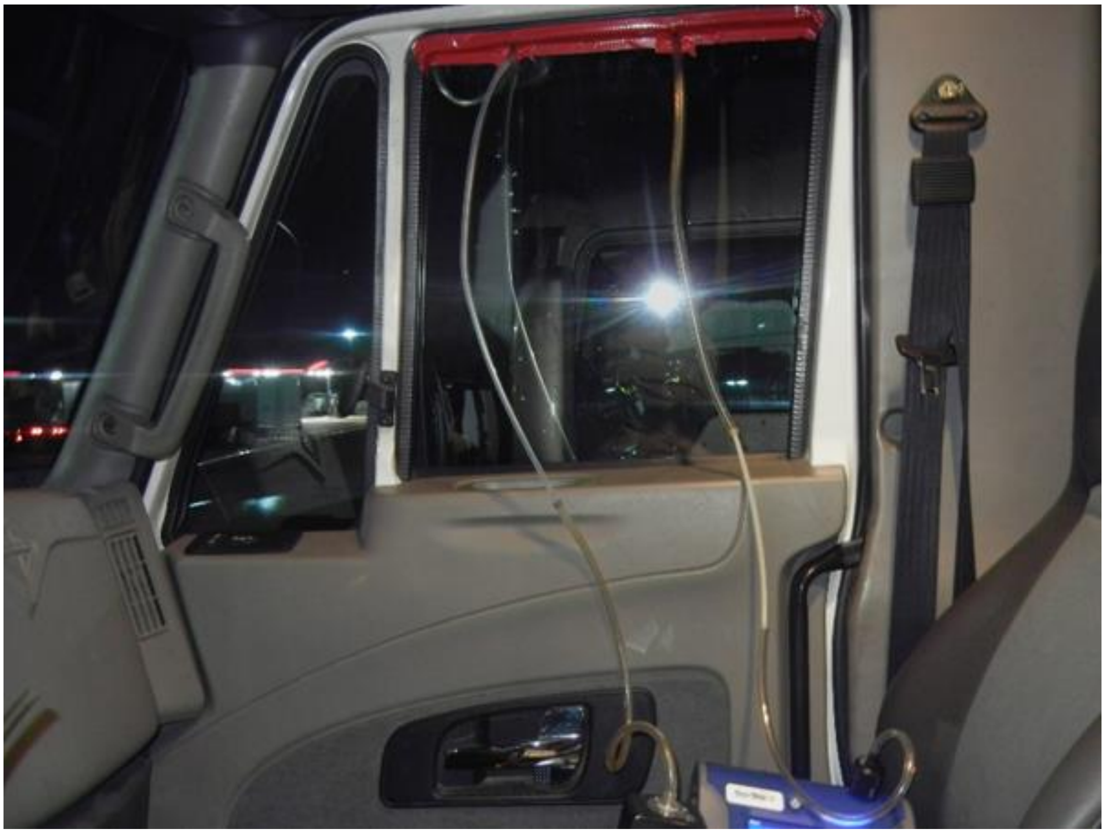


Zeroing the 8520 DustTrak aerosol monitor with a HEPA filter

APPENDIX J

SAMPLING SET-UP

Sampling Set-up on the Truck's Passenger Seat



Gap on top of the window sealed using duct tape.

APPENDIX K

DETERMINING INSTRUMENT AGREEMENT

Determining instrument agreement between the two DustTrak aerosol monitors used for the project.

Discrepancy in recording $PM_{2.5}$ concentration between the 8530 and 8520 DustTrak aerosol monitors (the 8530 model is on the left).

APPENDIX L

DETERMINATION OF THE ACH

Determining the ACH using the MIRAN SapphIRE to measure CO2 concentration over time inside the truck cab.

APPENDIX M

SUMMARY OF PRELIMINARY DATA

DustTrak $PM_{2.5}$ In-Cabin and Background Concentrations at Different Locations

Date	Location	Time of Day	In-Cabin Conc. (µg/m³)	Outside Conc. (µg/m³)
06/28/14	Marion, IL	13:30	12.0	18.0
06/29/14	Wood River, NE	02:30	13.0	5.0
06/29/14	Little America, WY	13:30	<1.0	<1.0
06/30/14	Rawlings, WY	07:30	<1.0	<1.0
07/01/14	Marston, MO	06:35	50.0	50.0
07/02/14	Tallulah, LA	06:30	22..0	81.0
07/02/14	Coppell, TX	21:00	8.0	5.0
08/16/14	Jacksonville, FL	15:45	17.0	41.0
09/05/14	Baldwin, FL	14:30	7.0	15.0
11/04/14	Knoxville, TN	03:00	15.0	25.0

In- Cabin Levels of Diesel Particulate Matter (EC, OC, TC) at Different Locations

Date	Filter #	Location	Mass (µg)			Conc. (µg/m³)		
			EC	OC	TC	EC	OC	TC
04/19/14	12560	Fruit Cove, FL	13.0	52.0	65.0	13.0	52.0	67.0
04/28/14	12557	Baldwin, FL	<2.0	40.0	40.0	<1.5	30.0	30.0
07/02/14	12768	Tallulah, LA	<2.0	22.0	22.0	<2.2	25.0	25.0
07/03/14	12790	Coppell, TX	<2.0	27.0	27.0	<1.9	25.0	25.0
08/16/14	12561	Orlando, FL	4.5	28.0	32.0	5.1	31.0	36.0
08/16/14	12558	Jacksonville, FL	<2.0	32.0	32.0	<2.7	44.0	44.0
09/05//14	12778	Baldwin, FL	<2.0	25.0	25.0	<2.0	25.0	25.0

APPENDIX N

GEOMETRIC MEAN OF ANALYTES

Geometric Mean of Analytes (µg/m3) (95% Confidence Interval)

Analyte Conc. (µg/m^3)	Filter Location	N	GMT (95% C.I.)
EC	Inside	21	4.72 (3.06-7.27)
EC	Outside	21	1.95 (1.46-2.62)
OC	Inside	21	33.03 (28.12-38.81)
OC	Outside	21	18.92 (15.93-22.48)
TC	Inside	21	38.55 (31.86-46.64)
TC	Outside	21	20.98 (17.67-24.92)

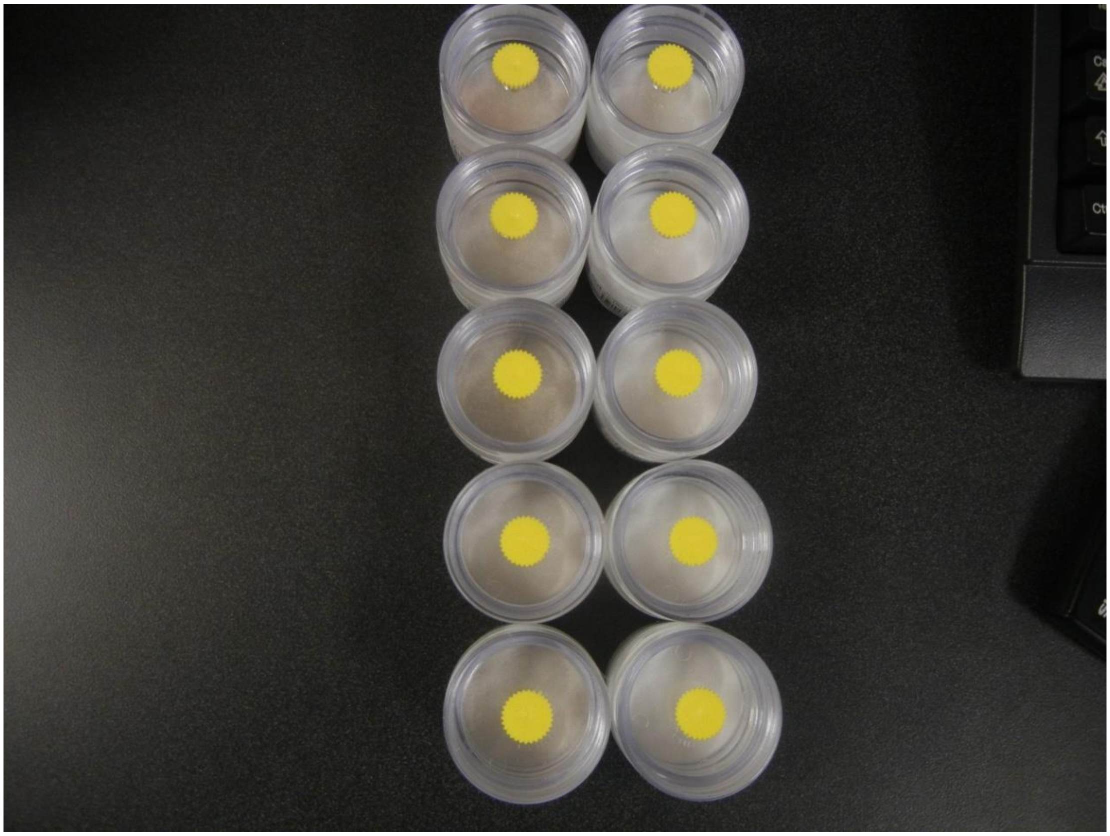
EC=Elemental Carbon, OC=Organic Carbon, TC=Total Carbon
Values < LOD were replaces with 1.4 µg/m^3

Geometric Mean of PM2.5 (µg/m^3) (95% Confidence Interval)

Filter Location	N	GMT (95% C.I.)
Inside	20	23.93 (17.53-32.67)
Outside	20	31.15 (25.30-38.36)

APPENDIX O

SAMPLE FILTERS



Filters from active sampling inside the truck. Visibly darker filters on the left are from truck 2.