PARTICULATE MATTER EMISSIONS FROM ROADS IN BIRMINGHAM

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16. Abstract

Air quality concerns continue to pose a challenge to the transportation industry. This project investigated the extent to which traffic flow impacted particulate emissions from roadways in Birmingham, Alabama. Through repeated measurements at five locations, it was determined that truck flow is a controlling influence on roadway particulate emissions. In particular, queuing of trucks greatly increases emissions. Therefore, emissions and planning models and activities must include a description of truck operational mode to accurately describe roadway contributions. If roadway particulate emissions are to be minimized, optimizing traffic flow on high truck (not necessarily high average daily traffic) routes needs to be considered.

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Executive Summary

Particulate emissions from roadways are of increasing concern in Birmingham, Alabama and throughout the country. As the Environmental Protection Agency continues to regulate particulate matter concentrations, the importance of quantifying the contributions of roadways to regional particulate matter inventories will increase. Therefore, there is a need in the transportation community for high quality, local data to describe particulate emissions from roadways. This research is a first step at determining the role of traffic flow and composition on air quality in Birmingham, AL. Using highly sensitive particle count data, it was determined that roadways significantly raise background particulate concentrations. It was also observed that the percentage of trucks and modal descriptions of flow are critical in determining the contributions of roadways to local particulate inventories. If roadway particulate emissions are to be minimized, optimizing traffic flow on high truck (not necessarily high average daily traffic routes needs to be taken into consideration.

Section 1
Introduction

In recent history, advancements in technology have led to a greater understanding of the impact of airborne particulate matter on human health and environmental quality. In 1997, the United States Environmental Protection Agency (EPA) revised the National Ambient Air Quality Standards (NAAQS) for particulate matter (PM) and adopted two new regulations for particulate matter with an aerodynamic diameter smaller than 2.5 microns in diameter ($PM_{2.5}$). The regulatory standard is assessed as the three-consecutive year arithmetic mean of annual averages and is set at 15 micrograms per cubic meter ($\mu g/m^3$); the short term regulatory standard is assessed as the 98th percentile of 24-hr concentrations averaged over three consecutive years and is set at $65 \mu g/m^3$ (Parkhurst, et al. 1999). The EPA is currently designating areas of non-attainment with these standards and Jefferson County, Alabama will certainly be faced with the challenge of reducing $PM_{2.5}$ levels to an allowable limit in order to maintain economic prosperity and governmental funding (Jefferson County Department of Health 2004). However, since PM standards were developed much knowledge has been gained about the interaction of ultrafine particulate matter ($D_p < .1 \mu m$) and the human body. As monitoring technologies improve, so will the ability to monitor and regulate the ultrafine size ranges.

Throughout the last twenty years various studies have indicated that airborne particulate matter can have detrimental health effects upon the human lung (Dockery, et al. 1993; Schwartz 1991). As of now, it is uncertain whether or not the number count or the mass concentration of particulates plays a larger role in causing these adverse health effects. In particular, there is still a large debate among researchers whether the chemical composition or the physical characteristics (e.g. number, size, shape, and aggregation properties) of particulate matter have a more harmful effect (Zhu, et al. 2004). However, recent toxicological studies have concluded that, at the same mass concentration, ultrafine particles are more toxic than larger particles with the same chemical composition (Donaldson, et al. 1998, 2001; Brown, et al. 2000).

Deposition of particles within the various regions of the human respiratory system is based primarily on size and shape, with the greatest fractional deposition of particles occurring in the deep lung between 5nm and 100nm (Hinds 1999). In the ultrafine size range, particle deposition increases greatly as the particle size decreases (Jaques and Kim 2000; Yeh, et al. 1997; Zhu, et al. 2004). If studies similar to the few mentioned above are continually released, governmental regulations will inevitably be forced to include a number concentration component because ultrafine particulates have a relatively insignificant mass. On a mass basis, ultrafine particulates are only a minor component of the atmospheric aerosol (~1% by weight) but on a number basis they are a major constituent (~86% by count) (Abraham, et al. 2002). Future efforts in air pollution prevention will be focused more in reducing the number concentrations, making it important to determine the ultrafine "hotspots" in urban environments.

In an urban environment the majority of particulate matter lies within the ultrafine size fraction (Buzorius, et al. 1999). Current emission inventories suggest that motor vehicles are the major source of ultrafine particulates to the atmosphere in urban environments (Hitchins, et al. 2000). The majority of vehicle exhausts are in the size range of 20-130nm for diesel engines (Morawska, et al. 1998a,b) and 20-60nm for gasoline engines (Ristovski, et al. 1998). Therefore, due to the insignificant mass of ultrafine particulates, to determine the contribution of vehicles to ultrafine particulate levels it is necessary to use an instrument that measures number concentrations, because a mass measurement will not be sensitive enough to see changes in concentrations due to traffic. As with other environmental problems in which transportation plays a role, the primary challenge for the transportation community is in obtaining data to accurately quantify the transportation contribution to urban particulate concentrations.

Project Objective

The objective of this report was to determine the number concentrations of particulates emitted from roadways in Birmingham and to assess the relative impact of traffic characteristics on these emissions. The goal was to begin a fine and ultrafine particulate emission inventory specific to the Birmingham area and to determine if there were any underlying correlations between ultrafine particulate concentrations and observed traffic flows that could be used to estimate emissions based on traffic data. Moreover, suggestions for the transportation community to become proactive in addressing emissions concerns based on collected data and reviewed literature are provided by this document. The following report sections will explain earlier particulate matter studies, experimental methodologies, data analysis techniques, and final results associated with this roadside study.

Section 2
Relevant Studies

A focused literature review of recent transportation-related air quality studies was performed to design the data collection for this UTCA-funded study. Specific items investigated included

- types of instrumentation;
- general strategies involved in particulate matter field studies;
- proper location of sampling equipment relative to the roadway;
- relevant meteorological parameters and their effects on roadside particulate concentrations.

The first objective of reviewing past articles was to determine an appropriate device to obtain ultrafine particulate concentration data. Secondly, general agreements across all studies that would need to be incorporated into this experiment were reviewed to develop an experimental methodology. Also, the results of these studies were used for comparison to the results of this UTCA study. Table 2-1 lists the studies that were reviewed and gives a description of the instrumentation and measurement methodologies used while Table 2-2 discusses the key findings of each project. These reported results are compared to those observed in this study in Section 5.1 of this report.

This review of literature indicated that the main meteorological parameters that influence concentrations are wind speed and direction. Other meteorological parameters are known to influence ultrafine concentrations; however, they are considered to be relatively constant over short periods of time. All roadside studies reviewed looked solely at downwind concentrations at varying distances from the roadway by using either a condensation particle counter or a scanning mobility particle sizer and corresponding meteorological data in order to observe traffic impacts on air quality. In conjunction with the real-time meteorological data, video tapes were used to determine traffic flow characteristics at discrete time intervals.

Table 2-1
Summary of key measurement and instrument knowledge from reviewed ultrafine particulate studies

Study	Instrumentation and Measurement Methodologies
Zhu, Y., Hinds, W.C., Kim, S., Shen, S., Sioutas, C. (2002). Study of Ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment*. **36** 4323-4335.	Measurements were taken at varying distances downwind of the roadway and one upwind concentration 200m from the roadway were recorded using a condensation particle counter and a scanning mobility particle sizer. The road selected had 25% heavy-duty vehicles. Randomly selected one minute-average wind data was used for analysis.
Nanzetta, M.K. and B.A. Holmén (2004). Roadside particle number distributions and relationships between number concentrations, meteorology, and traffic along a Northern California freeway. *Journal of the Air & Waste Management Association.* **54** 540-554.	Particle number distributions were measured simultaneously upwind and downwind of a freeway with 6330 vehicles/hr with 10% heavy-duty trucks. Traffic was video taped in both directions and randomly selected 2-minute averages were used for analysis of meteorological impacts.
Morawska, L., Jayaratne, E.R., Mengersen, K., Jamriska, M., Thomas, S. (2002). Differences in airborne particle and gaseous concentrations in urban air between weekdays and weekends. *Atmospheric Environment*. **36** 4375-4383.	Particle number concentrations were measured within the central business district of Brisbane, Australia and correlated with traffic flow rate to investigate the difference in weekday and weekend concentrations. A canning mobility particle sizer was used for data collection. The monitoring was performed over a five-year period. Mean traffic flow on the freeway was 142,000 and 96,000 vehicles per weekday and weekend day, respectively.
Zhu, Y., Hinds, W.C., Kim, S., Sioutas, C. (2002). Concentration and size distribution of ultrafine particles near a major highway. Journal of the Air and Waste Management Association. **52** 1032-1042.	Particle number concentration and size distribution in the size range from 6 to 220nm were measured by a condensation particle counter and a scanning mobility particle sizer. Measurements were taken at varying distances downwind of the roadway and a background concentration 300m from the roadway was recorded as well. Average flowed was 13,900 vehicles/hr with ~7% being heavy-duty trucks.

Table 2-2 Results and conclusions from reviewed ultrafine particulate studies

Study	Results
Zhu, Y., Hinds, W.C., Kim, S., Shen, S., Sioutas, C. (2002). Study of Ultrafine particles near a major highway with heavy-duty diesel traffic. *Atmospheric Environment*. **36** 4323-4335.	Total particle number concentration ranged from 180,000-350,000/cm^3. Concentrations decreased exponentially away from the roadway and at 300m downwind of the roadway concentrations were indistinguishable from upwind numbers. Atmospheric dispersion and coagulation were reported to be responsible for the rapid decrease in concentrations away from the roadway.
Nanzetta, M.K. and B.A. Holmén (2004). Roadside particle number distributions and relationships between number concentrations, meteorology, and traffic along a Northern California freeway. *Journal of the Air & Waste Management Association.* **54** 540-554.	Total downwind 6-237nm particle number concentrations ranged from 9,300 to 250,000/cm^3. Number distributions were bimodal with the primary mode at ~10-25nm, suggesting that newly formed particles were in fact being sampled.
Morawska, L., Jayaratne, E.R., Mengersen, K., Jamriska, M., Thomas, S. (2002). Differences in airborne particle and gaseous concentrations in urban air between weekdays and weekends. *Atmospheric Environment*. **36** 4375-4383.	Mean particle number concentration on weekdays was (8,800±100)/cm^3 and on weekends (5,900±200)/cm^3—a difference of 47%. Overall conclusion as to the effect of traffic on concentration levels near a roadways carrying traffic of the order of 100,000 vehicles per day, is that about a 50% increase in traffic flow rate results in about a 70% increase in particle number concentration.
Zhu, Y., Hinds, W.C., Kim, S., Sioutas, C. (2002). Concentration and size distribution of ultrafine particles near a major highway. Journal of the Air and Waste Management Association. **52** 1032-1042.	Total particle number and mass concentration ranged from 130,000-200,000/cm^3 and 30.2-64.6µg/m^3, respectively. Both wind direction and wind speed played an important role in determining the characteristics of ultrafine particles near the freeway.

From Table 2-2, it is observed that large variability exists in the ultrafine particulate concentrations across the four studies. Concentrations ranged from 5,900 to more than 350,000/cm^3. This large variability in roadside concentrations suggests that the roads are in fact a source of ultrafine particulates; however, changes in roadway characteristics (e.g. modal distribution of traffic, average daily traffic (ADT), number of heavy-duty trucks, etc.) significantly influence roadway emissions.

Section 3
Measurement Methodologies

3.1 Overview

As stated in Section 1 of this report, the primary objective of this project was to examine the relationship between traffic and roadway emissions of ultrafine particulate matter in Birmingham, AL. The instrumentation used for measurements is discussed in detail in Section 3.2. The instrument was placed near the roadside at specified locations that are discussed in Section 3.3. It was assumed that by placing the instrument as close as possible to the roadway, the instrument was within the mixing zone of the roadway and therefore the road contribution was measured at the source and wind did not substantially impact the measurement of the roadway contribution. This assumption is verified in Section 4.2. For site comparisons, only the roadway contribution was used. The roadway contribution for this study was defined as the concentration at any instant in time minus the average background concentration for that site. The average background concentration was taken at a location upwind of the roadway and subtracted from measured concentrations at the roadway so that regional contributions to ultrafine concentrations could be factored out.

3.2 Instrumentation

The TSI 3007 Condensation Particle Counter (CPC) was chosen due to sensitivity of the measurement to changes in traffic composition and flow patterns. This particular instrument measures the number of particles smaller than 1µm in diameter in real-time. The majority of particulate emissions from vehicles have been shown to be smaller than 0.1µm, therefore the ability to see the smaller size ranges of particulate matter is necessary to investigate traffic flow and composition effects on roadway particulate emissions. The CPC has this capability in real-time and is completely mobile which makes it ideal for experimentation. The CPC has the option of giving 1, 5, and 60 second average concentrations, and because the weather instrument that will be described later in this report gives 1-minute averages only, all concentrations are given as 1-minute averages. Figure 3-1 is a picture of the display screen from the CPC used in this study.

Figure 3-1 TSI 3007 condensation particle counter

The CPC has a maximum concentration reading of 500,000 particles per cubic centimeter (pp/cc); however, concentration readings above 100,000 are beyond calibration ranges. Diffusion screens are put at the inlet of the CPC until numbers under 100,000 are consistently achieved. Throughout the entirety of the experiment one diffusion screen was used to consistently produce numbers under 100,000. In doing this, the particle size range is modified from .01-1µm to approximately .016-1µm. This size range still provides sufficient sensitivity to observe changes in traffic composition on particle number emissions from roadways.

3.3 Site Selection and Description

When selecting sites for experimentation, the objective was to isolate various traffic parameters to best observe their effects. For example, sites having both high and low traffic levels were evaluated in order to see the impact of ADT on particulate concentrations. Without using sites from both extremes (high and low ADT) and attempting to hold all other factors relatively constant, the overall impact of ADT becomes difficult to evaluate.

Five sites within Birmingham were selected based on the ADT and percent trucks at each location. Figure 3-2 shows the exact locations in which experiments were performed. Each sampling location has unique parameters that influenced their selection for this study. Table 3-1 lists the five selected sites and reports an average value for the number of passenger vehicles per hour, number of trucks per hour, and percent trucks as counted in this study.

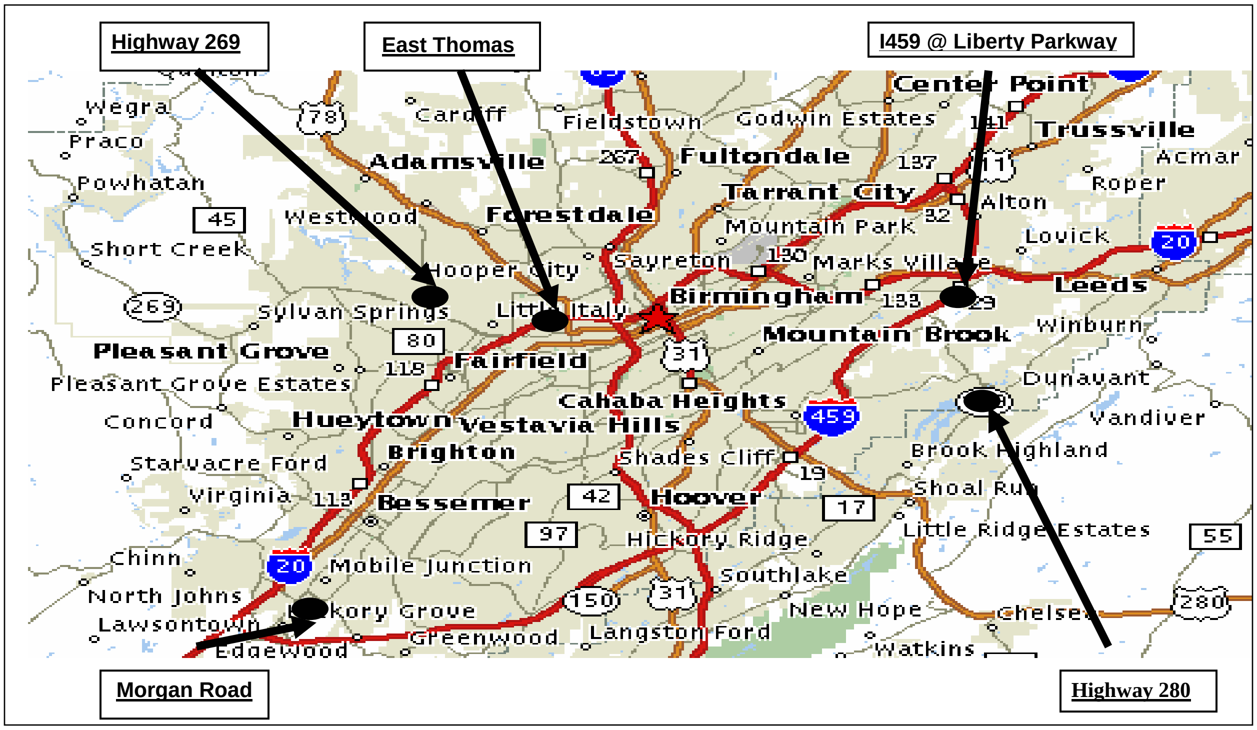

FIGURE 3-2 Site locations

TABLE 3-1 Selected sites and traffic descriptions

Site Name	Ave. Vehicles Per Hour	Average % Trucks	Average Trucks Per Hour	Description of Flow
East Thomas	2840	13.7	389	Varies due to red light; 40 mph speed limit
Highway 280	4530	2.8	126	Varies due to red light; 55 mph speed limit
Highway 269	1390	6.1	85	Varies due to red light, 55 mph speed limit
Morgan Road	1030	2.6	27	Free flow; 35 mph speed limit
Interstate 459	6170	8.3	515	Free flow; 65 mph speed limit

Listed below are detailed descriptions of each selected study site including traffic characteristics, a plan drawing of the surrounding area, and a photograph of the site. In addition, Table 3-2 summarizes the date, time, and traffic characteristics of all sampling events.

East Thomas

The East Thomas site was selected because of the large percentage of diesel trucks traveling the roadway. A large truck stop, which brings in a significant amount of diesel trucks, is located on the far side of the roadway from the normal sampling location (right-hand side of roadway). Sampling occurred at a three-way intersection with a traffic light causing a large amount of queuing. During periods of free flow, vehicle speed averaged approximately 45mph. The CPC was placed at two separate locations depending on the wind direction. If the predominant wind direction was to the east the right location was used and if the wind was to the west the left location was used. Approximately 80 percent of all sampling occurred from the right-hand location.

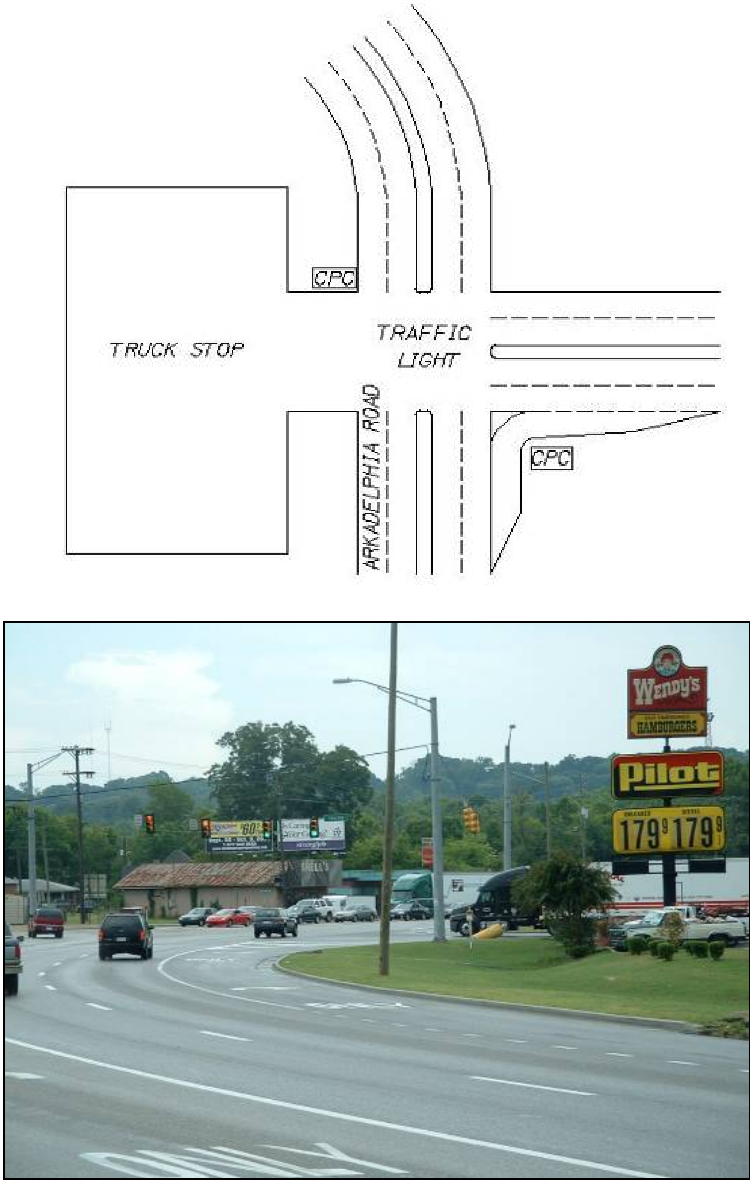

Figure 3-3 East Thomas
Note: Only one CPC was used for sampling. Depending on direction of wind, CPC was placed in one of the two specified locations

Highway 280

The Highway 280 site was selected due to the low percentage of heavy-duty trucks traveling the roadway with a relatively high flow of passenger vehicles. The intersection contained a traffic light which created a large amount of queuing. During free flow vehicle speed averaged approximately 50mph. Two gas stations were located at the intersection and their impact was taken into account in Section 4. The impact of the intersecting road (Highway 119) on measured emissions was taken into account as well in Section 4.3.

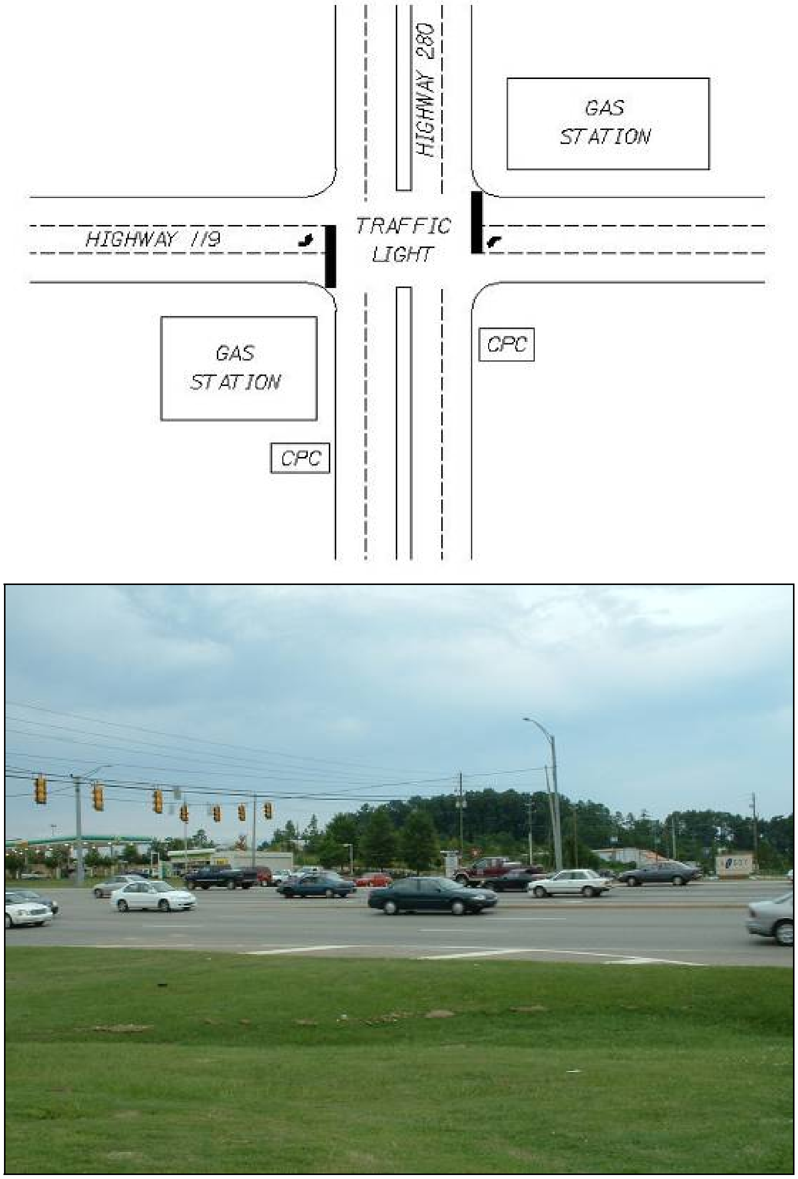

Figure 3-4 Highway 280
Note Only one CPC was used for sampling. Depending on direction of wind, CPC was placed in one of the two specified locations

Highway 269

The reason for the selection of Highway 269 was its relatively low traffic flow while still containing a moderate number of trucks. The site is located in northwest Birmingham in a location where diesel trucks are hauling loads to and from the local port and also servicing a local construction firm. The largest component of the diesel truck traffic traveling the roadway was dump trucks. Sampling was performed near a traffic light, which created a significant amount of queuing and the intersecting roadway was not considered important due to its extremely low traffic flow.

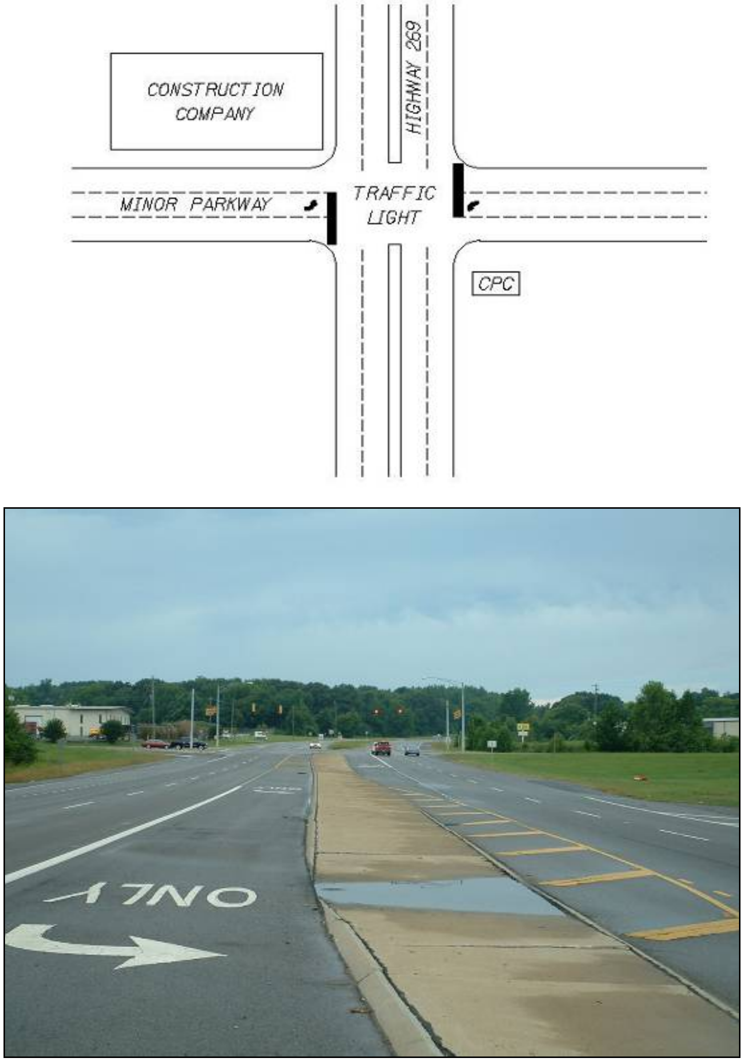

Figure 3-5 Highway 269

Morgan Road

Morgan Road was selected so that final comparisons could be made against a site that had a low traffic flow and low percentage of trucks. The site is located in western Birmingham and is not considered to be a heavily traveled roadway even during peak hours. This site was at an intersection; however, there was no traffic light, thus no queuing, and the traffic along the two side roads was negligible. The background concentration was much higher than that of any other site which was expected to be because of local industry within the area. In addition, evaluation at this site will be explained in Section 4.2.

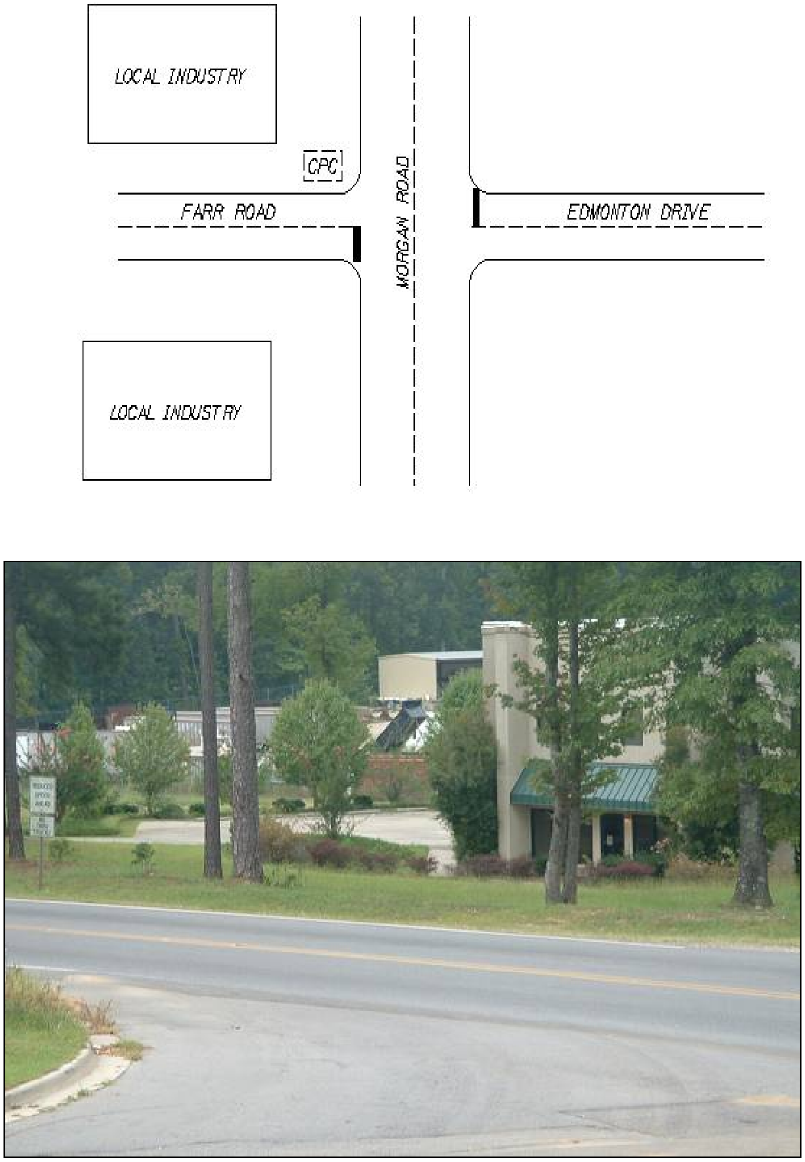

Figure 3-6 Morgan Road

Interstate 459

Interstate 459 was selected because of its large traffic flow while having a relatively large percentage of diesel trucks as well. The traffic was always at free flow and the interstate speed limit was 70mph. In Section 4.2, it can be seen from Figure 4-2 that Interstate 459 was the only site with a large amount of scatter in its background concentrations. This is believed to be because the instrument was placed too close to the mixing zone of the roadway, which was much larger when vehicles are traveling at higher speeds and also because the roadway is set in a valley that allowed mixing of particulate matter throughout the area including the "background" location. However, the data obtained for the background concentrations was used for analysis; therefore, contributions from Interstate 459 are probably underestimated.

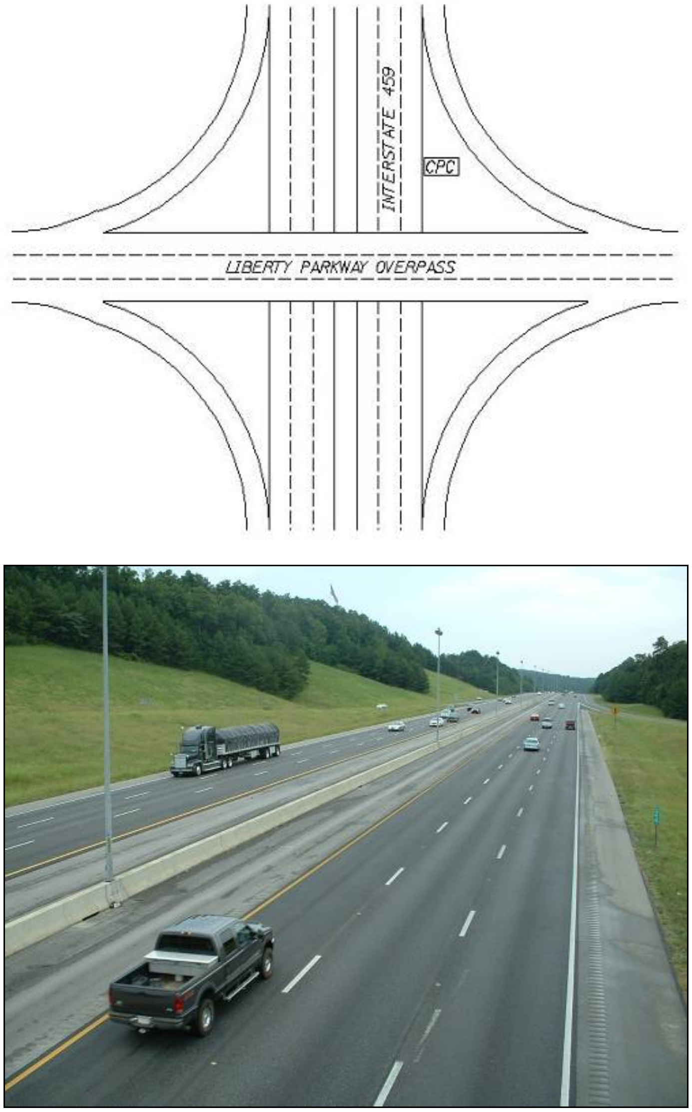

Figure 3-7 Interstate 459

Table 3-2 Sampling dates, times, and traffic characteristics

Site	Date	Time of Sampling	Number of Traffic Counts	Average Vehicles per Hour	Average Trucks per Hour	Average % Trucks
Highway 280	August 11, 2003	330-530	4	4329	171	4
	September 19, 2003	445-615	3	4732	76	1.6
Interstate 459	August 8, 2003	325-520	3	6444	444	6.9
	August 13, 2003	405-515	4	6294	528	8.4
	September 23, 2003	330-605	6	5572	536	9.6
	September 24, 2003	430-600	4	6384	540	8.5
East Thomas	August 28, 2003	150-315	3	2496	436	17.5
	September 11, 2003	200-515	6	2868	458	16
	September 12, 2003	335-515	3	3080	296	9.6
	September 29, 2003	320-630	N/A	N/A	N/A	N/A
Morgan Road	September 25, 2003	325-530	4	969	27	2.8
	September 30, 2003	445-605	4	1089	27	2.5
Highway 269	October 9, 2003	340-550	4	1320	108	8.2
	October 21, 2003	300-445	3	1368	76	5.6
	October 28, 2003	335-500	4	1458	90	6.2
	October 31, 2003	335-505	3	1408	64	4.5

3.4 Traffic Data Collection

Traffic composition was based on visual counts of video-taped traffic and qualitatively classified either as heavy-duty or passenger vehicles. Five minute average traffic counts were taken three times an hour during sampling and plotted versus their corresponding five minute average concentration in Figure 4-4 and Figure 4-5.

3.5 Meteorology

At times, roadside ultrafine concentrations can be influenced more by meteorological parameters than by traffic parameters. Wind speed and direction, temperature, humidity, UV radiation, precipitation, etc., all play a significant role in the formation, transportation, and dispersion of particulate matter (Jung, et al. 2004). In an ideal environment all meteorological parameters remain constant throughout all measurements so that changes in traffic would be the only factor influencing concentrations. As mentioned in Section 3.1, all meteorological parameters were assumed to remain constant except for wind speed and direction due to the short period of time in which samples were recorded. Also, experiments were all performed at random times during late summer/early fall therefore seasonal changes did not have a significant role.

Also in Section 4.1, it is mentioned that only the *Downwind* data was compared to *All* the data from a particular site to check the assumption that the instrument was within the mixing zone. The *Downwind* data consisted of data points that were observed when wind direction was no more than ±15° from 90° downwind of the roadway. If similar numbers were seen between only the *Downwind* data and the *All* data set, the assumption that the instrument does lie within the roadside mixing zone was acceptable, as demonstrated in Section 4.1.

Section 4
Results and Discussion

4.1 Particulate Matter Emissions

The intent of this research was to evaluate several different sites based on their roadway contribution and traffic characteristics as part of early exploratory research to help determine the extent of the roadway contribution to the particulate emissions inventory in Birmingham. The first step was to validate the assumption of using *All* data instead of only using *Downwind* data because of the roadway mixing zone assumption (as introduced in Section 3.1 Overview). The assumption that both data sets are equivalent was checked by comparing *All* data to solely the *Downwind* data and seeing if there was in fact a difference. If there were to be a large difference in the two data sets, either a local source was contributing to concentrations or the wind is diluting the source contributions from the roadway, and therefore, only the *Downwind* data should be used when comparing roadway contributions. Figure 4-1 compares the two data sets and shows that at all sites except for Highway 280 and Morgan Road, there were no statistical differences**.** The circles within the figure indicate the mean concentration and the “whiskers” indicate the 95 percent confidence interval. The difference between the *All* and *Downwind* data sets was due to the local industry at Morgan Road and the gas stations at Highway 280, which increase the roadway contributions when *All* data is used. Although there is disagreement between the Highway 280 and Morgan Road *Downwind vs. All* data sets, *All* data was used for analysis which will be further discussed in Section 4.3. By using All data, local sources are contributing to concentrations along with the roadway which will result in an overestimation of the roadway contribution at these two sites. Also, an early comparison between sites to determine the difference in particulate matter contributions from different roadways can be made here. From Figure 4-1 it can be seen that Highway 280 has the lowest average concentration while East Thomas has the highest. Also, there is a large amount of scatter at Morgan Road which again can be attributed to local industry.

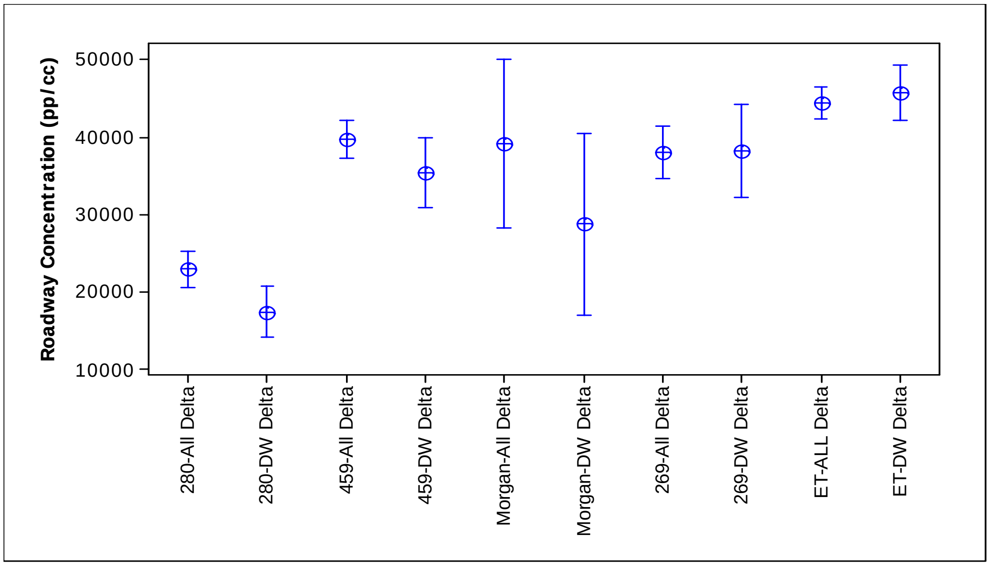

Figure 4-1 Interval plot of downwind data vs. all data

4.2 Evaluation of Background Concentration

Background concentrations were examined for two reasons: (1) to insure that an appropriate baseline was used to develop the roadway PM contribution estimate, and (2) to quantify how background concentrations change within an urban area and how these changes influence estimates of roadway emissions. In order to verify that the background concentrations taken each day had no local contributions effecting concentrations, boxplots of the background concentrations were analyzed to see whether or not the concentrations had any variation. A true background concentration should remain relatively constant between sampling events. Any site having variation in its background concentration is seeing some other kind of influence on measured particle number concentrations and therefore on estimated roadway emissions.

Figure 4-2 shows the boxplot of the background concentrations at all five sites. The box represents the inner quartiles (25th-75th) while the centerline indicates the median concentration. Interstate 459 is the only site that carries a great deal of variation; therefore, it is assumed that the instrument was not completely out of the mixing zone when background samples were taken, which could make roadway contributions look lower than they actually were. Of the five sites, Interstate 459 carried traffic at the highest rate of speed, which in turn created a larger mixing zone. Also the sampling location was set in a roadway canyon, allowing particulates to thoroughly mix. Because of the larger mixing zone and the urban canyon effect, the background concentration at Interstate 459 was influenced by local sources, which caused the high degree of variability in the background concentration. Since this background concentration is already accounting for a fraction of the roadway emissions, emissions reported here are considered to be minimum estimates of the true roadside emissions. In future inventory data collection activities, selection of sampling sites will have to include an assessment of background concentrations and of placement to avoid mixing of background and roadside contributions.

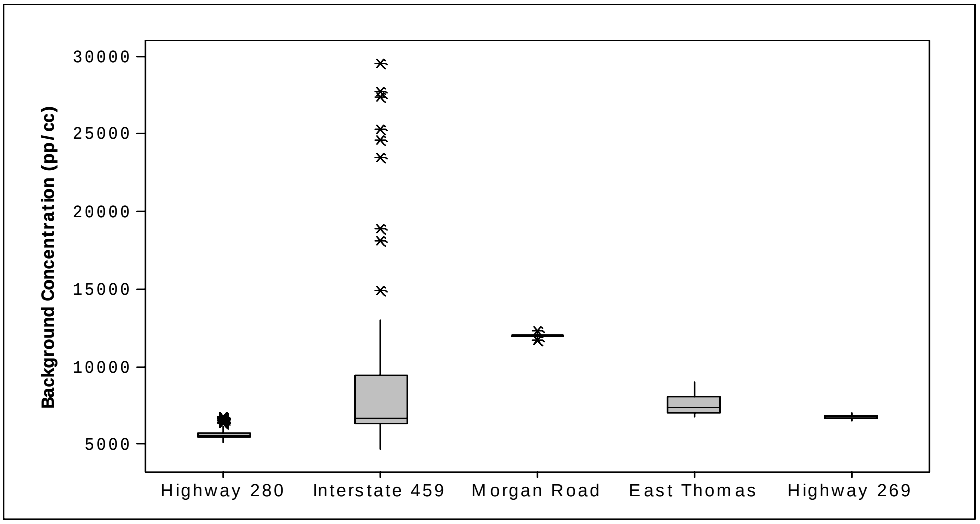

Figure 4-2 Boxplot of background concentrations

In addition to visual inspection of background concentrations, the Kruskal-Wallis (KW) nonparametric statistical analysis was performed to determine if the background concentrations differed significantly from site to site. The data was analyzed and no known distributions gave a good fit therefore a nonparametric analysis was used. The KW test has the hypothesis that a number of unpaired samples originate from the same population and for the hypothesis to be rejected the "P" value must be less than .05. Table 4-1 shows the output of the KW test performed.

Table 4-1 Kruskal-Wallis test on background concentrations

Site	N	Median	Ave Rank	Z
Highway 280	171	5557	98.7	17.81
Interstate 459	61	6656	319.6	1.46
Morgan Road	87	12001	526.0	14.27
East Thomas	18	7357	445.0	3.99
Highway 269	242	6771	321.3	3.82
Overall	579		290.0	

Test Statistics
H = 422.50 DF = 4 P = 0.000
H = 422.51 DF = 4 P = 0.000 (adjusted for ties)

From Table 4-1, a resulting "P" value of 0.000 indicates that at least one site is statistically different from the other four. The "Z" ranking given in Table 4-1 indicates that the background number concentrations are the same at East Thomas, Highway 280 and Highway 269, but Morgan Road and Highway 280 have significantly different background concentrations from these three sites. Highway 280 has a statistically lower background concentration, which can be explained by the fact that the background sampling was performed in a location with little urbanization. At Highway 280 the background measurement was taken in an undeveloped field with a large wooded track providing a "buffering" effecting from regional particulate pollution. The KW test also showed that Morgan Road had the highest background concentration, which is due to the local industrial influence. The other three sites had statistically similar background concentrations.

4.3 Roadway Contribution

The objective of this study was to observe whether or the not Birmingham roadways made any difference to ultrafine particulate number concentrations. *All* (not just downwind data) were used to account for variability in wind directions at the sites, as the CPC was located close enough to the roadway to be in the source regardless of wind direction. In doing this, the reported roadway contributions from Morgan Road and Highway 280 are expected to be slightly higher than they actually are because the *All* concentrations from these two sites were higher than *Downwind* concentrations (but can only change the roadside contribution at most 15%). In Figure 4-1 this difference can be seen at Morgan Road and Highway 280; however, the other three sites are not statistically different. While variability in Interstate 459 emissions concentrations was large, the true roadside contribution is underestimated as the background measurements were "contaminated" by the roadside emissions (as discussed in Section 4.2.

Background concentrations were compared to the roadway contributions (CPC average minus background average) to see if the roadway did in fact contribute to ultrafine concentrations. Figure 4-3 shows a stacked bar chart of average background concentrations and the corresponding averaged roadway contribution from each site. The darker and lighter bars represent the roadway and background concentrations averaged at each site, respectively. From the bar chart it can be seen that the roadway does have an influence on concentrations since concentrations were much higher at the roadway compared to the background concentration. The objective now is to quantify exactly how much each site contributes.

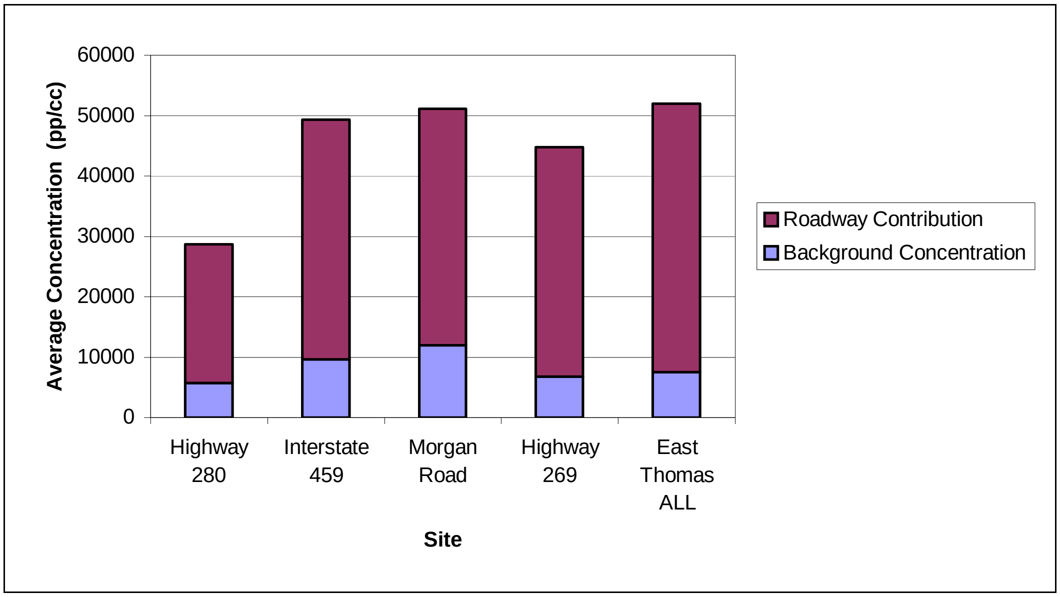

Figure 4-3 Roadway contribution vs. background concentration

As noted in Table 3-2, five-minute traffic counts were recorded during sampling and compared to the corresponding five-minute roadway contribution estimates to determine if any correlations exist between traffic characteristics and concentrations.

Figure 4-4 is a plot of the total number of passenger vehicles traveling each road versus the ultrafine PM concentration. There does not appear to be a consistent mathematical correlation between passenger vehicles and ultrafine concentrations. However, careful examination of Figure 4-4, along with the data reported in Table 3-2 Characteristics and Figure 4-3, reveals that some patterns do exist in the collected emissions data. At most sites there is a relatively large range in concentrations over a relatively small range of passenger vehicle flow suggesting that passenger vehicle flow does not control the range of particulate emissions from roadways. At times, the largest passenger vehicle flows are yielding the lowest concentrations and some of the lowest flows are yielding the highest concentrations. This suggests that passenger vehicles are probably not a large contributor to ultrafine particulate concentrations; however, some other factor (i.e. diesel trucks, queuing, etc.) is definitely influencing concentrations to produce this high level of variability.

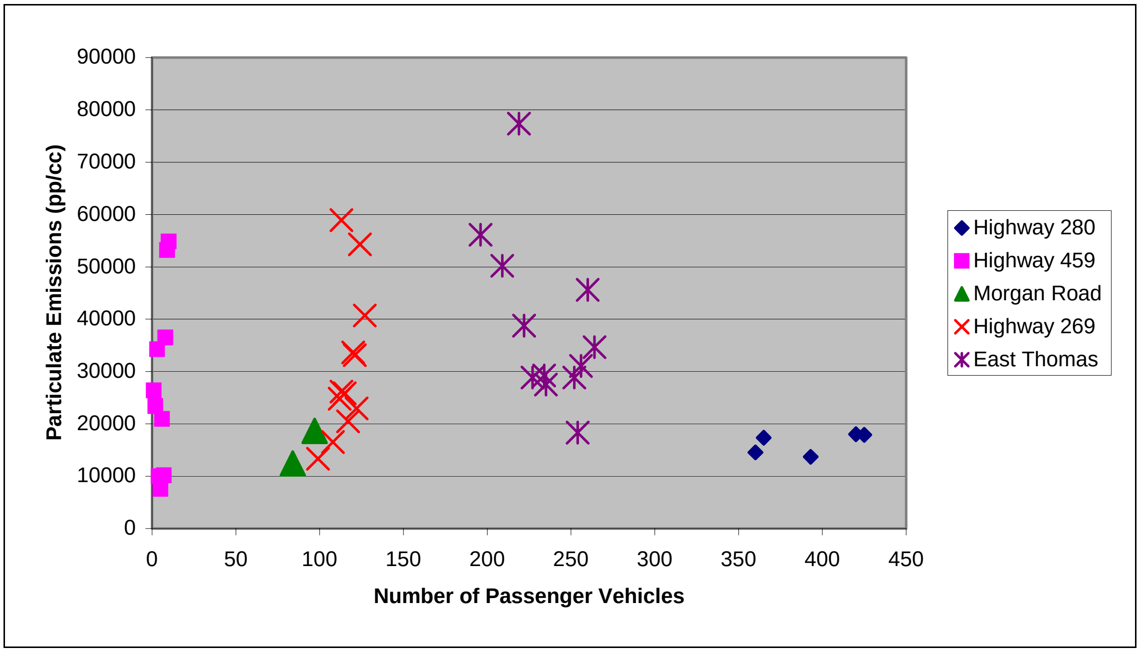

Figure 4-4 Number of vehicles vs. ultrafine particulate emissions

Figure 4-5 does not show consistent, mathematical correlation between the number of diesel trucks and the roadway contribution; however, there are several qualitative observations that can be drawn from the graph. First, the two sites with the lowest number of trucks, Morgan Road and Highway 280, have the lowest roadway contributions and the two sites with the highest number of heavy-duty diesel trucks, Interstate 459 and East Thomas, have the highest roadway contributions. This observation suggests that diesel trucks are the main contributor to roadway emissions of ultrafine particulates in urban locations. Secondly, the three sites that have the highest number of trucks have the largest range of particulate concentrations. This second observation suggests that truck flow and queuing of trucks is very important in inventory estimation and that the energy associated with truck travel produces different roadside turbulent mixing regimes that impact roadway emissions. Also, it is important to note that Highway 280, which has the second highest total number of vehicles, has the lowest roadway contribution. This again suggests that passenger vehicles are not a large factor in roadway contributions.

The relatively large range of concentrations occurring at Highway 269 and East Thomas, while maintaining a steady number of trucks, is probably due to queuing from the traffic light located at the intersection of these two sites. However, Highway 280 also had a traffic light but it concentrations were the lowest of the five sites. This implies that queuing of diesel trucks may be a significant factor to consider in the design of an inventory model; however, the queuing of passenger vehicles is far less significant in terms of controlling ultrafine particulate emissions from roadways.

Another interesting note from Figure 4-5 is that at times Interstate 459, which contains some of the largest numbers of diesel trucks, had some of the lowest concentrations. Two possibilities exist for the observed behavior. The first is that without queuing (start and stop of large engines), the emissions of diesel trucks drops to much lower levels. Additionally, the low roadway contribution from Interstate 459 may be partially explained by the more turbulent mixing zone created by the increase in diesel trucks traveling at high speeds which could possibly dilute the roadway contribution or raise the background concentrations which would in turn reduce the estimated roadway contribution.

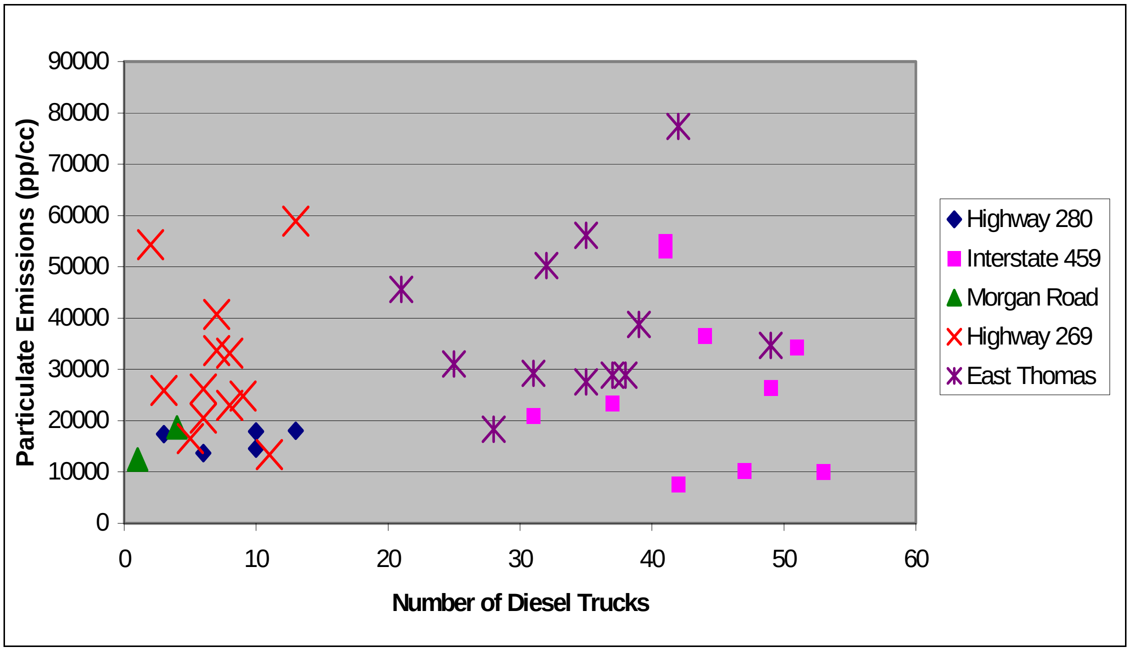

Figure 4-5 Number of diesel trucks vs. ultrafine particulate emissions

Table 4-2 shows that there are statistical differences between the sites. Again the null hypothesis that the five sites are equal is rejected due to a "P" value less than .05. Therefore, changes in traffic characteristics have a statistically significant influence on ultrafine particulate concentrations (with 95% confidence). Highway 280 and Morgan Road, which may have high estimations for the roadway contribution due to local contributions (as previously discussed in Section 4.1 Overview), have the lowest roadway emissions. Conversely, East Thomas and Interstate 459 have the highest number of trucks and the highest ultrafine particulate concentrations.

Table 4-2 Kruskal-Wallis test on roadway contributions

Site	N	Median	Ave Rank	Z
Highway 280	116	20738	337.0	-9.00
Interstate 459	335	36599	635.7	0.76
Morgan Road	44	28843	550.8	-1.36
Highway 269	290	30667	565.9	-3.09
East Thomas	460	39357	728.8	7.95
Overall	1245		623.0	

Test Statistics:
H = 122.75 DF = 4 P = 0.000
H = 122.75 DF = 4 P = 0.000 (adjusted for ties)

Section 5
Conclusions

5.1 Research Findings

The objectives of this research were to determine whether there were any underlying correlations in traffic characteristics and ultrafine roadway concentrations, and to determine the major control parameters for ultrafine particulates. The random nature of traffic, weather, and ultrafine particulates themselves disguise these correlations, however, it has been shown that the major "hotspots" for ultrafine particulates are going to occur at locations with a significant amount of diesel trucks and queuing of the traffic flow as well. The main observations obtained from this research are that roadways do make a significant contribution to ultrafine particulate concentrations, diesel trucks are the largest traffic parameters involved in constructing ultrafine inventories, and that queuing of diesel trucks can cause large variability in concentrations due to the start and stop of the diesel engine.

Roadside concentrations were similar to those in the literature (see Section 2); however, concentrations in this study were at the low end of the concentration range from those four studies. This was due in large to the fact that measurements were performed with one diffusion screen at the inlet of the CPC which cut out a large amount of the ultrafine concentration (everything smaller than .016µm). Therefore, the results from this study are generally in agreement with the trends reported in similar research.

5.2 Recommendations

It was shown in Section 4-3 that retiming traffic signals for air quality purposes should include consideration of the impact of queuing large numbers of diesel trucks. This implies that the mode and traffic flow are important when creating roadside inventories; however, as of now, most roadside models do not account for modal distribution of traffic. Also, from the observations it can be concluded that when coordinating traffic signalization for air quality purposes, only intersections carrying a large number of diesel trucks are a significant enough contributor to ultrafine particulate concentrations to be considered for modifications. It is apparent that a much larger database of concentrations and traffic flows needs to be developed to unmask the disguised correlations due to the randomness of traffic and meteorology. This is the beginning of a database that should be expanded throughout the Birmingham area showing the number concentrations, mass concentrations, and size distributions of fine and ultrafine particulate matter and its variability throughout the city.

5.3 Engineering Significance

This data is the beginning of an inventory that will be useful as governmental regulations evolve and state implementation plans (SIPs) are initiated. It is important to recognize that modal distribution of traffic flow has a strong influence on ultrafine particulate concentrations and should be taken into account in future particulate inventories. Moreover, the queuing of diesel trucks has been shown to create an urban “hotspot” and should be considered when air quality planning is initiated. Also, it is equally important to recognize that passenger vehicles do not contribute a significant amount to ultrafine particulate concentrations; therefore, the focus of air quality planning should not be towards roadways solely servicing passenger vehicles. In addition, addressing congestion on truck routes will improve safety and reduce car/truck collisions through enhanced signalization and increased roadway efficiency.

Section 6
References

Abraham, J.L., Siwinski, G., Hunt, A. (2002). Ultrafine particulate exposures in indoor, outdoor, personal and mobile environments effects of diesel, traffic, pottery kiln, cooking and HEPA filtration on micro-environmental particle number concentration. *Ann Occup Hyg*. 46 (Suppl. 1) 406-411, 2002.

Brown, D.M., Stone, V., Findlay, P., Macnee, W., Donaldson, K. (2000). Increased inflammation and intracellular calcium caused by ultrafine carbon black is independent of transition metals or other soluble components. *Occupational and Environmental Medicine*. 57(10) 685-691.

Buzorius, G., Hämeri, K., Pekkanen, J., Kumala, M. (1999). Spatial variation of Aerosol Number Concentration in Helsinky City. *Atmospheric Environment*. 33 553-565.

Dockery, D.W., Pope, A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., and Speizer, F.E. (1993). An Association Between Air Pollution and Mortality in Six U.S. Cities. *New England Journal of Medicine*. 329 1753-1759.

Donaldson, K., Li, X.Y., MacNee, W. (1998). Ultrafine (nanometer) particle mediated lung injury. *Journal of Aerosol Science*. 29 553-560.

Donaldson, K., Stone, V., Clouter, A., Renwick, L., MacNee, W. (2001). Ultrafine particles. *Occupational and Environmental Medicine*. 58(3) 211-216.

Hinds, W. C. (1999). *Aerosol Technology Properties, Behavior, and Measurement of Airborne Particles*. 2nd ed. Wiley, New York.

Hitchins, J., Morawska, L., Wolff, R., Gilbert, D. (2000). Concentrations of submicrometer particles from vehicle emissions near a major road. *Atmospheric Environment*. 34 51-59.

Jaques, P.A., Kim, C.S. (2000). Measurement of total lung deposition of inhaled ultrafine particles in healthy men and women. *Inhalation Toxicology* 12 715-731.

Jefferson County Department of Health. 2004. Air Pollution Control. July 29, 2004. http//www.jcdh.org/default.asp?ID=79.

Jung, I., Kumar, S., John, K. (2004). Impact of meteorology on the fine particulate matter distribution in central and southeastern Ohio. 12th Joint Conference on the Applications of Air Pollution Meteorology with the Air and Waste Management Association. July 29th, 2004. http//ams.confex.com/ams/AFMAPUE/12AirPoll/abstracts/38553.htm

Morawska, L, Bofinger, N.D., Kocis, L., Nwankwoala, A. (1998a). Submicrometer and super micrometer particles from diesel vehicle emissions. *Environmental Science and Technology*. 32 2033-2042.

Morawska, L., Thomas, S. Bofinger, N.D., Wainwright, D., Neale, D. (1998b). Comprehensive characterization of aerosols in a subtropical urban atmosphere particle size distribution and correlation with gaseous pollutants. *Atmospheric Environment.* 32 2461-2478.

Parkhurst, W.J., Tanner, R.L., Weatherford, F.P., Valente, R.J., Meagher, J.F. (1999). Historic PM2.5/PM10 concentrations in the Southeastern United States—Potential implications of the revised particulate matter standard. *Air & Waste Management Association*. 49 1060-1067.

Ristovski, Z.D., Morawska, L., Bofinger, N.D., Hitchins, J. (1998) Submicrometer and super micrometer particles from spark ignition vehicles. *Environmental Science and Technology.* 32 3845-3852.

Savonis, M. “Strategic Plan for Transportation and Air Quality Research, 2000-2010.” *Transportation in the New Millennium*. Transportation Research Board, National Academy of Sciences, Washington, D.C., January 2000.

Schwartz, J. (1991). *Air Pollution and Daily Mortality in Philadelphia*. Presented at the 1991 Meeting of the American Lung Association. Anaheim, CA.

Yeh, H.C., Muggenburg, B.A., Harkema, J.R. (1997). In vivo deposition of inhaled ultrafine particles in the respiratory tract of rhesus monkeys. Aerosol Science and Technology. 27 465-470.

Zhu, Y., Hinds, W.C., Shen, S., Sioutas, C. (2004). Seasonal Trends of Concentration and Size Distribution of Ultrafine Particles Near Major Highways in Los Angeles. *Aerosol Science and Technology*. 38(S1) 5-13.

Section 7
Glossary of Terms

- PM_{10} – particulate matter with an aerodynamic diameter less than 10µm
- $PM_{2.5}$ – particulate matter with an aerodynamic diameter less than 2.5µm; also referred to as “fine” particulate matter
- Ultrafine – particulate matter with an aerodynamic diameter less than .1µm
- µm – one millionth of a meter (1×10^{-6}m)