Correlating Particulate Matter Mobile Source Emissions to Ambient Air Quality

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Introduction

This paper describes the work and results of the second phase of research sponsored by the Federal Highway Administration (FHWA) initiated to study the relationship between traffic activity and ambient $PM_{2.5}$ concentrations. The study, entitled "Estimating the Transportation Contribution to Particulate Matter Pollution", had the objective of performing a correlation analyses on particulate matter (PM) and traffic monitoring data collected in several metropolitan areas. This effort is a cooperative initiative between the FHWA, the Environmental Protection Agency (EPA), state Departments of Transportation (DOTs), and, in some cases, local transportation agencies. The study approach linked EPA monitoring initiatives with the traffic data collected by state and/or local transportation agencies to evaluate mobile source emission contributions to ambient PM concentrations.

Phase 1 served as the planning stage of the project. Specific tasks involved in Phase 1 included assessment of the ambient monitoring and traffic networks, evaluation of EPA monitoring initiatives, evaluation of the traffic counting requirements to conduct PM research, and recruitment of state departments of transportation to participate in traffic data collection.

The primary goal of Phase 2 is to determine whether correlations can be observed between traffic on highway facilities and ambient particulate matter (PM) concentrations. Specific tasks involved in Phase 2 include the collection of traffic and ambient air quality data and analysis of the data to examine the relationships that could be observed from the data. Key topics to be addressed in the study are the linkages between ambient PM concentrations and transportation sources including the spatial, temporal, and meteorological influences recognizing that ambient concentrations vary with time and location (time of day, day of week, season, geography, and vehicle fleet mix). This paper provides an update of the study.

Background

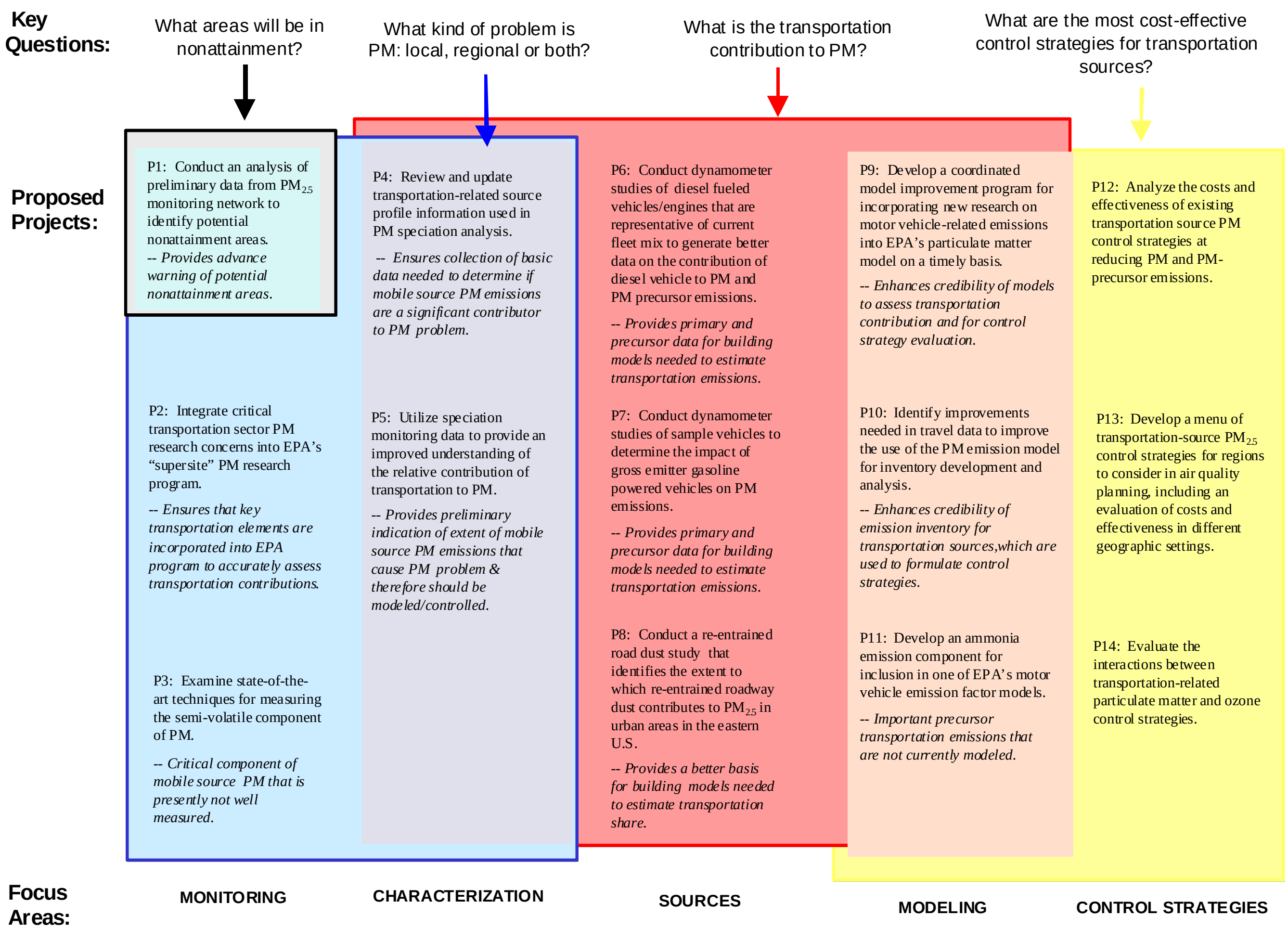
Research on the adverse health effects of high concentrations of ambient particulate matter led to regulations of PM dating back to the Clean Air Act (CAA) in 1971. Subsequent modifications to the CAA have been made and PM continues to be a regulated pollutant. On July 18, 1997, the EPA promulgated significant revisions to the existing national ambient air quality standards (NAAQS) for PM to include the new $PM_{2.5}$ standard. Two new standards were set: an annual standard of 15µg/m^3, and a 24-hour standard of 65µg/m^3. Previously, the PM standard only regulated PM_{10} (particulate matter with a nominal aerodynamic diameter less than or equal to 10 µm) – this standard was essentially retained, though slightly modified.

The revised NAAQS are expected to have a wide range of impacts on the transportation community, including an increase in the number of PM non-attainment areas. This increase will require the development of transportation emission inventories and transportation-related control strategies for inclusion in State Implementation Plans (SIPs) for PM. Requirements for transportation conformity analyses will likely follow. EPA is currently moving forward with implementation planning of the new PM standards and is expecting to make final non-attainment designations by December 2004.

In September 2000, FHWA adopted a Strategic Work Plan for Particulate Matter Research that identified five research focus areas. The areas and the projects targeted for future study are illustrated in Figure 1. The Work Plan recommends and describes PM-related research projects necessary to fill critical research gaps to the transportation community. The work performed in this study will contribute to two areas of interested noted in Figure 1, Monitoring and Characterization and in two specific projects identified in the Strategic Work Plan - Project P1 and Project P5.

Seven cities were selected and six cities participated in the PM Research Program based on the availability of both PM and traffic data. These cities included New York City (Queens), Baltimore, MD, Pittsburgh, PA, Atlanta, GA, Detroit, MI, and Los Angeles, CA. Five of the six locations are EPA Supersites which means that detailed PM and meteorological data are collected by EPA. Based on data available at the time of this paper, only five of these cities are presented. Los Angeles information has not been included. It will also be noted later that one city, Atlanta, includes some additional data included because it was the focus of a more detailed analysis effort.

Figure 1 Connection Between Transportation Issues and Research



Source: Strategic Workplan for Particulate Matter Research 2000 to 2004; ICF Consulting, Hagler Bailly, SAIC; September 2000. SAIC; September 2000.

Data Used in the Study

Traffic data collection systems are generally classified into three categories – ITS, Coverage Counts, and Supplemental Counts. ITS (Intelligent Transportation Systems) data are collected by roadway surveillance equipment that monitors traffic conditions. Volumes, speeds, and lane occupancies are the typical forms of data that are collected. The most prevalent form of technology for this system is loop detectors embedded in the roadway, although transportation agencies are increasingly turning to "non-intrusive" technologies such as radar and video image processing. Video image processing offers the potential of providing length-based vehicle classifications, but this capability is still emerging and no classification data of this type are included in any of the ITS data sets used in this study - only volumes, speeds, and occupancies.

Coverage counts are taken as part of routine traffic monitoring activities by state and local transportation agencies. They include data that are submitted to the Highway Performance Monitoring System (HPMS). Traffic volumes are the most common kind of data collected, with vehicle classifications taken at a limited number of locations. The vast majority of coverage counts are of short duration – typically 48-hour counts taken at the same location every year. The 48-hour volume counts are adjusted using day and seasonal factors to represent "average annual daily traffic." Due to the short sampling period for coverage counts (typically 48 hours), HPMS data have not been used in this study except as supplemental data for the more detailed Atlanta study.

Supplemental counts were collected specifically for this PM Research Project. They are either total volume or vehicle classification counts, collected using the same portable equipment used to take the short-duration coverage counts. They are focused on non-freeways in the immediate vicinity of the PM monitors. Though not collected continuously throughout the year, they are more intensive than the typical 48-hour counts taken for routine traffic planning purposes. The number of locations and the sampling periods vary by city, as described in Table 1. These counts would not have existed without the help of state and/or local transportation agencies, and in some cases, Supersite researchers, who have gone to considerable expense and effort to provide the data for the study.

Air quality data presented in this study have been obtained from three sources. These are the EPA AIRS AQS system, data obtained directly from the Supersite personnel, and data obtained from the NARSTO data archive site. The Air Quality System (AQS) is an EPA database of measurements of ambient concentrations of air pollutants and meteorological data from thousands of monitoring stations operated by US EPA and state, local, and tribal agencies throughout the United States. These monitors track the levels of criteria pollutants over time. The data in the system is well organized and controlled. Hence, the AQS an ideal source for the purposes of this research.

Table 1. Traffic Data Collected for the Traffic-Ambient Concentration Study.

City	Locations	Measurement	Parameter	Durations	Notes
New York	ITS	Volume, Speed, Occupancy	85 freeway miles covered (Long Island Expwy); 191 count locations	Continuously for CY2001-2002	
	Special Counts	Volume	Kissena Blvd., Jewel Ave., and Main St. (125 days)	7/2/01-8/9/01, 5/14/02-6/5/02, 8/11/02-9/10/02, 10/22/02-11/25/02	
Baltimore	Coverage Counts: AVCs	Vehicle Class	Toll Plazas at Baltimore Harbor Tunnel (I-895) and Ft. McHenry Tunnel (I-95)	Continuous data for all of CY2002	Paper copies scanned to datasets; 6 axle-based categories
	Special Counts	Volume	Ponca Street (116 days)	5/20/02-7/16/02, 7/27/02-8/5/02, 8/16/02-8/28/02, 10/6/01-12/1/02	
Pittsburgh	ITS	Volume, Speed, Occupancy	78 freeway miles covered; 58 count locations	Continuously for CY2001-2002	
			Schenley Avenue (117 days)	1/1/02-1/19/02, 1/23/02-1/31/02, 4/1/02-4/30/02, 6/24/02-7/31/02, 10/1/02-10/31/02	
Detroit	ITS	Volume, Speed, Occupancy	117 freeway miles covered; 58 count locations	Continuously for CY2001-2002	
	Special Counts	Vehicle Class	6-Mile Road (99 days)	9/27/01-10/30/01, 4/01/02-5/1/02, 10/2/02-11/06/02	13 length-based classes converted to FHWA classes
Atlanta	ITS	Volume, Speed, Occupancy	95 freeway miles covered; 240 count locations	Continuously for CY2001-2002	
	Special Counts	Vehicle Class	Jefferson St. (24 days)	8/16/02 – 9/9/02	

Another data collection source is to obtain the air quality data directly from the Supersite personnel. There are a range of pros and cons associated with this option. The personnel at the site are the people taking and validating the actual measurements. They know the area and the equipment in operation and can provide direct accounts and explanations for many situations. Furthermore, personnel at the sites will also be able to provide information and data from monitors that do not report to the AQS system. Inclusion of such information and input from these personnel is imperative.

The Supersite research teams are contractually responsible to archive their data through the North American Research Strategy for Tropospheric Ozone (NARSTO) data archive. Once uploaded to NARSTO and made publicly available, the data can be accessed through FTP links. NARSTO also hosts an on-line tracking system that can be used to monitor the status and the availability of the some of the parameters. This information is updated on a monthly basis and is used by the research team to monitor the availability of needed data. Preliminary data from Pittsburgh were downloaded from the NARSTO data archive. A summary of the air quality data used in the study is provided in Table 2.

Table 2. Air Quality Collected for the Traffic-Ambient Concentration Study.

					Year	
City	**Location**	**Measurement**	**Parameter**	**Duration**	**2001**	**2002**
New York	Queens College Site:					
		Air Quality	$PM_{2.5}$ Mass	1-hr	Jan-Dec	Jan-Sep
			EC, OC	24-hr	Apr-Dec	Jan-Aug
			CO, NO_X	1-hr	Jun-Dec	Jan-Aug
			NO_2, SO_2, O_3	1-hr	Jun-Dec	
			Trace Elements, Organics	1-hr, 24-hr	Jan-Dec	
		Meteorological	WD, WS, Temp, BP	1-hr	Jul-Dec	
Baltimore	Ponca Street Site:					
		Air Quality	$PM_{2.5}$ Mass, EC, OC	1-hr, 24-hr		Jan-Dec
			CO, NO_2, NO, NO_X, O_3	1-hr		Jan-Dec
			Trace Elements	24-hr		Jan-Dec
			NO_3^-, Na^+, NH_4^+, SO_4^-	24-hr		Jan-Dec
		Meteorological	WD, WS, Temp, Prec., BP	1-hr		Feb-Dec
Pittsburgh	Schenley Park Site:					
		Air Quality	$PM_{2.5}$ Mass	1-hr, 24-hr	Jul-Dec	Jan-Aug
			EC, OC	1-hr	Jan-Dec	Jan-Aug
			CO, NO, NO_X, O_3	1-hr, 24-hr	Jul-Dec	Jan-Aug
			NO_3^-, NH_4^+, SO_4^-	1-hr, 24-hr	Jul-Dec	Jan-Jul
			Cl^-, NO_2^-	1-hr, 24-hr	Jul-Sep	
		Meteorological	WD, WS, Temp, BP	1-hr	Jul-Dec	Jan-Jul
Detroit	Goddard Street Site:					
		Air Quality	PM_{10} Mass, EC, OC	24-hr	Jan-Dec	
			$PM_{2.5}$ Mass, CO	1-hr, 24-hr	Jan-Dec	
			O_3	1-hr	Apr-Sep	
			Trace Elements, Organics	24-hr	Jan-Dec	
			Na^+, NH_4^+, SO_4^-	24-hr	Jan-Dec	
		Meteorological	WD, WS, Temp, BP	1-hr	Jan-Dec	
Atlanta	Jefferson Street Site:					
		Air Quality	$PM_{2.5}$ Mass, EC, OC	24-hr		Aug-Sep
			NO_3^-, Trace Elements	24-hr		Aug-Sep

Data Analysis

The study was designed to answer a series of questions regarding the observed patterns of ambient pollutant concentrations, meteorology, and local/regional traffic activity. These questions involve the temporal (daily, monthly, seasonal) and spatial (local/hot spot, regional) patterns of $PM_{2.5}$ concentrations as related to traffic activity (local and regional). Influence of meteorology, background concentrations and contributions from other sources was to be considered as well as variations of $PM_{2.5}$ concentrations and traffic volumes in relation to other ambient pollutants.

Since much of the data analyzed consisted of hourly measurements, many of the plots developed represent the mean of several thousand measurements. Providing average results in this manner represents the long-term average trends in air quality and traffic activity and lessens the influence of any one meteorological event since meteorological conditions are averaged over the entire study. While this is useful, the reader should also be aware that meteorology greatly influences the observed patterns and pollutant concentration for individual sampling days and although the data is accurate for illustrating “trends”, individual air pollution “episodes” may not be characterized.

Diurnal patterns of ambient $PM_{2.5}$ concentrations, were examined using the traffic and air quality data noted earlier. The figures illustrating the relationships are based on average diurnal patterns of $PM_{2.5}$ concentration and traffic activity over the entire study period. Figure 2 through Figure 6 illustrate the patterns seen in Baltimore, Detroit, New York, Pittsburgh, and Atlanta for all days. For most cities, distinct differences are observed when comparing Weekday vs. Weekend traffic activities. Typical Weekday traffic volume plots show a “double hump” traffic volume pattern with maximums near 7:00 am and 6:00 pm. These peaks are due to morning and evening rush hours where traffic activity is greatest in urban US cities. In contrast, a typical Weekend and holiday traffic patterns exhibit a single hump traffic volume pattern with a peak early to mid afternoon. This traffic pattern was observed at all sites, with perhaps some shifting in the hours of maximum traffic volumes. Table 3 provides data illustrating the general pattern for Weekdays and Weekends.

Graphical Correlation Analysis

In general, Weekday $PM_{2.5}$ patterns tracked local ITS traffic volume and vehicle-hours well in the morning Weekday hours. In most cases $PM_{2.5}$ concentrations decreased after the morning rush hour maximum and do not increase as dramatically in most cities during the evening rush hour. In addition, $PM_{2.5}$ concentration maximums also vary by city and time of day, though most cities have maximum concentrations near 7:00 a.m.

The observed patterns for regional VMT are similar, but not identical, to the local ITS traffic volume patterns. The choice of local ITS traffic sites may not always be representative of the regional temporal traffic patterns. In addition, some areas may be more defined in the regional case and better match the morning $PM_{2.5}$ patterns than the local ITS traffic volumes.

Figure 2. PM2.5 Concentrations versus Traffic for Baltimore Maryland

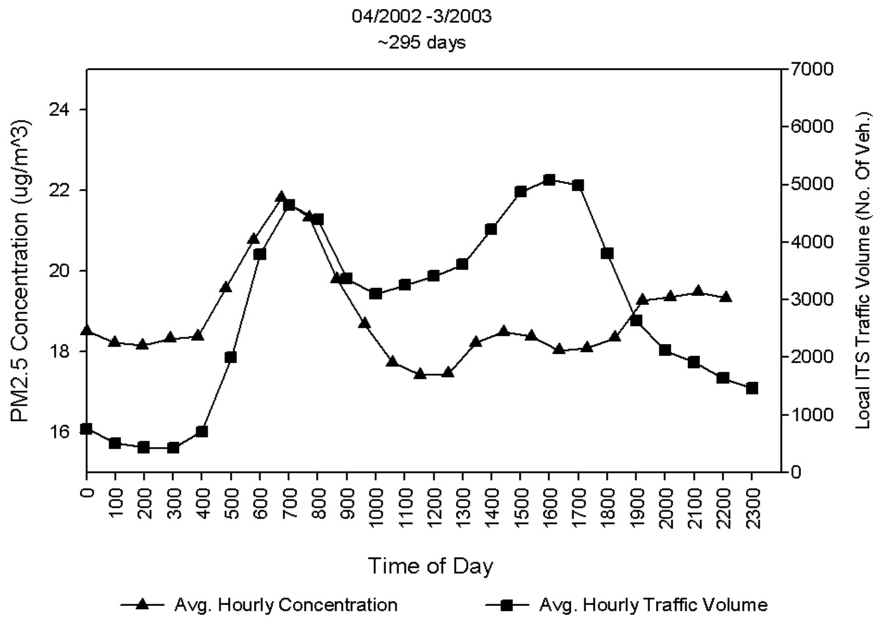


Figure 3. PM2.5 Concentrations versus Traffic for Detroit, Michigan

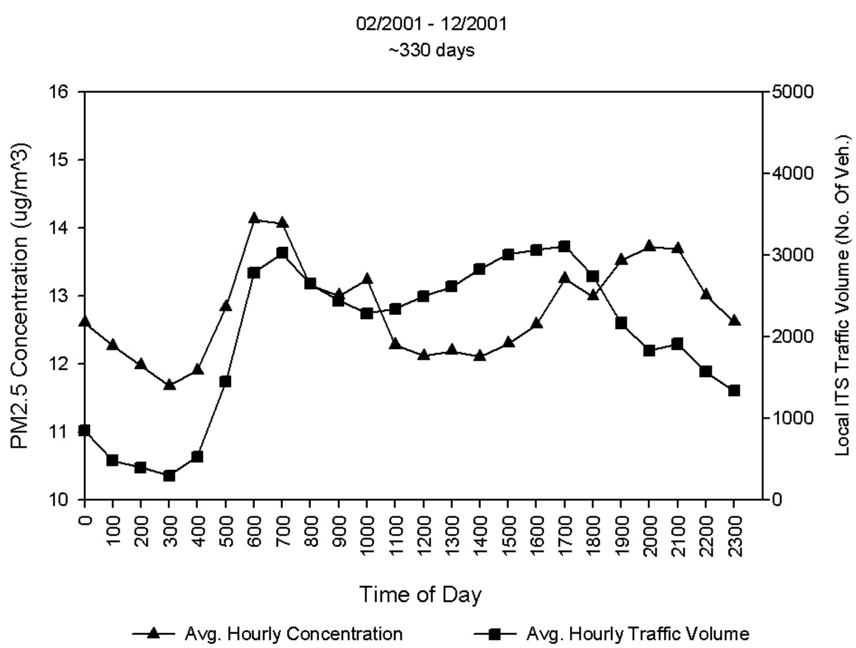


Figure 4. PM2.5 Concentrations versus Traffic for New York City, New York

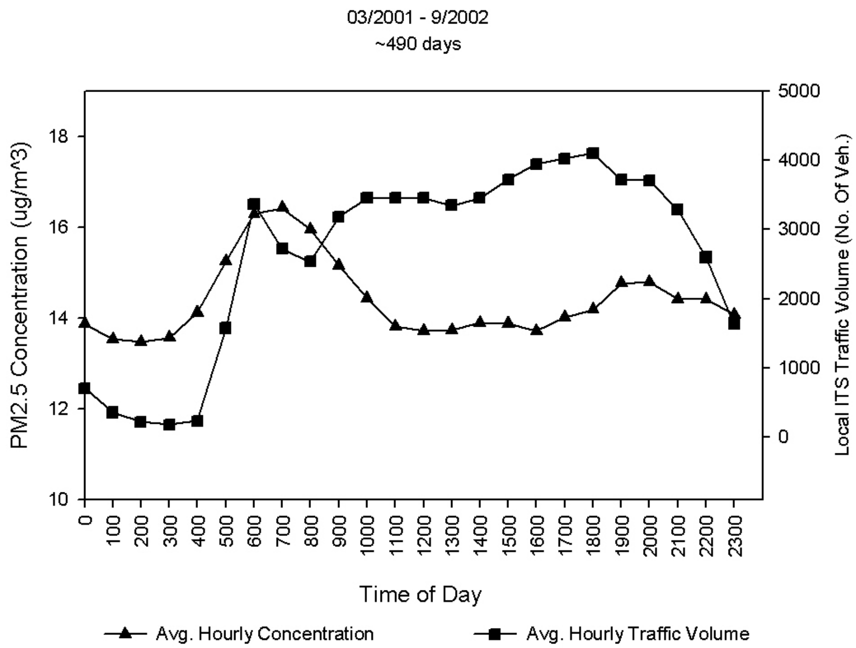


Figure 5. PM2.5 Concentrations versus Traffic for Pittsburgh, Pennsylvania

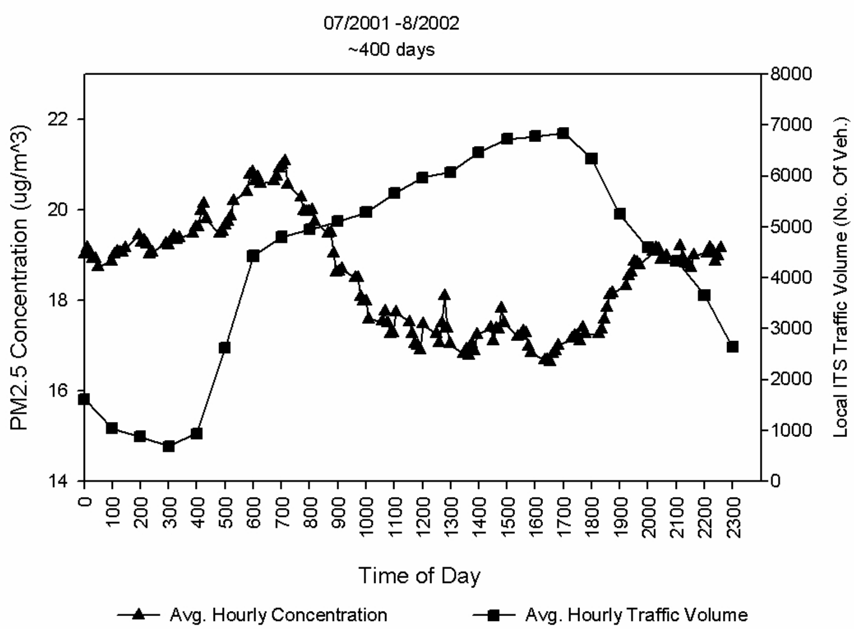


Figure 6. PM2.5 Concentrations versus Traffic for Atlanta Georgia

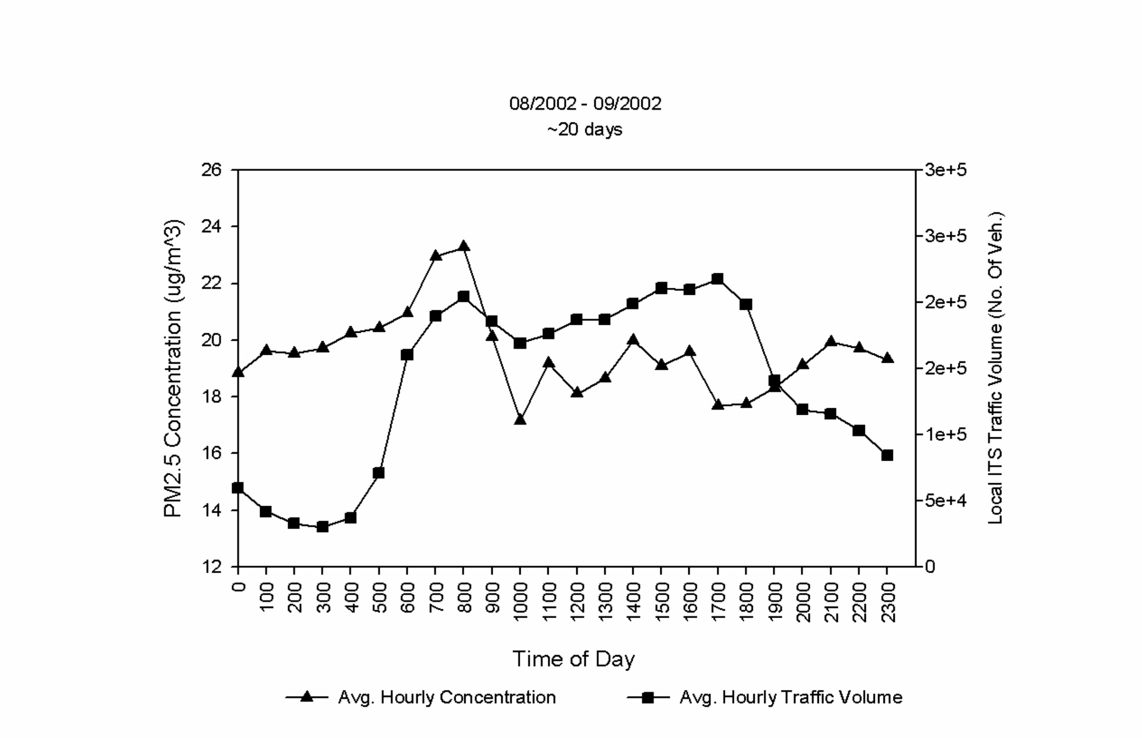


Table 3. Weekday vs. Weekend Regional ITS-Derived VMT and $PM_{2.5}$ Concentrations.

	Weekend		Weekday	
City	**Daily Avg. $PM_{2.5}$**	**Regional VMT (thousands)**	**Daily Avg. $PM_{2.5}$**	**Regional VMT (thousands)**
Baltimore	17.44	N/A	19.53	N/A
Detroit	11.36	10,884	13.45	15,755
New York	12.34	4,242	15.28	5,314
Pittsburgh	17.07	3,114	19.24	4,107

Some cities do, however, show a slight afternoon increase in $PM_{2.5}$ concentrations, but these changes are much smaller than the concentrations observed during morning rush hour. The lack of pattern tracking in the afternoon and evening hours is perhaps due more to meteorological effects than changes in mobile source emissions. One hypothesis as to why this pattern occurs is that when the sun rises, the lower atmosphere heats up and causes more vertical mixing of air pollution to occur. This causes a diluting effect of the atmospheric PM. During the morning hours when the atmospheric is relatively stable pollutant concentrations build up and are better correlated with emissions.

Meteorological effects have a clear impact on concentrations and can demonstrate this effect when the monitors are downwind from the transportation facility. Comparisons of other pollutants at the same time and location have been made in some cases and these analyses were part of the statistical analysis discussed in the next section.

Statistical Correlation Analysis

To determine if more direct relationships between ambient $PM_{2.5}$ concentrations could be identified, a series of statistical analyses were performed. The analysis consisted of a series of statistical procedures applied to the data in each city. These included Pearson Correlation Analysis (PCA), Analysis of Covariance (ANOCOVA) and Polynomial Regression on the hourly data, average hourly data across all days, and daily data. Pearson correlation coefficients (r) were calculated for the matrix of $PM_{2.5}$ concentrations and traffic activity variables. Three groupings were used - overall, by wind direction, and by time period. Time periods were identified based on whether traffic activity was monotonically increasing or decreasing which was done since the correlation analysis only reveals linear relationships.

The most highly correlated variables from the Pearson correlation analysis were included in an analysis of covariance with wind direction as the covariate. Separate analyses were performed for each time period, again to control for the linear dependencies. Polynomial regressions between $PM_{2.5}$ and the most correlated traffic variables from the PCA above were also attempted in a few cases. However, the resulting goodness-of-fit measures for the polynomial models were extremely poor and the results questioned the slight correlations that may be interpreted visually in the graphical analysis of the figures. Pearson Correlation Analysis for average hourly data across all days were aggregated. This eliminated much of the variation, but produced results consistent with the averaged time series plots. The daily average of the hourly $PM_{2.5}$ concentrations was correlated against the total traffic activity for the same day.

The result of these analyses were "r" values ranging from 0.16 to 0.57 for all cities, hourly and daily averages. This suggested that a poor correlation between the traffic volumes and the ambient PM concentrations could be found. The question that remains is whether the traffic proximity was close enough to the PM monitors to enable an accurate correlation. This leads to another goal of the study which was to determine if $PM_{2.5}$ could be a project level concern. This question was addressed in a more detailed study conducted at the Atlanta site on Jefferson Street which is described below.

Consideration of $PM_{2.5}$ as a Microscale Issue

Motor vehicles are a significant source of fine particulate matter, formed predominantly through combustion processes. Because PM emission rates are so uncertain, and because limited detailed PM profile data exist, it has been historically very difficult to apportion the particulate matter back to specific vehicle classes and stationary source categories. High-resolution traffic data are critical to conducting spatial/temporal statistical analyses designed to source-apportion ambient PM monitoring readings. A detailed study using modeling to derive statistical relationships between monitored $PM_{2.5}$ concentrations at the Jefferson Street site and monitored hourly traffic volumes on proximal facilities was undertaken to further investigate local influences.

Given that the study discussed above determined that the daily correlations between monitored $PM_{2.5}$ measurements and monitored proximal traffic volumes were poor, or at least inconclusive, the research team set out to develop a method that would support a more refined analysis of hourly correlations between monitored $PM_{2.5}$ and proximal traffic volumes. Traffic downwind of the Jefferson Street site would not be expected to impact monitored concentrations. Roadways that yield low pollutant mass flux due to low traffic volumes or emission rates, will also have limited impact on monitored PM values. Plus, given the dispersion mechanisms at work between the roadway pollutant source and the receptor, pollutant impacts at the site are affected by distance and meteorological parameters that affect pollutant mixing. Even when detailed analyses are performed between local and sub-regional traffic volumes and monitored PM concentrations, it should not be surprising if poor correlation results in such comparisons because the analyses do not take into account the relative importance of each roadway link in contributing to the measured $PM_{2.5}$ values as a function of wind direction and distance to the receptor.

The research team investigated a methodology that would account for dispersion impacts by developing a method to weight roadway traffic volumes based upon projected dispersion impacts upon mass emissions generated by each roadway segment (as a function of geographic and meteorological parameters). To undertake these analyses, the team relied upon the application of two modeling tools - MOBILE-Matrix and CALINE-Grid. MOBILE-Matrix is an iterative modeling approach used to generate a MOBILE output lookup table providing link-based emission rates directly from the MOBILE6.2 model. CALINE-Grid is an iterative modeling approach used to estimate the pollutant for a grid of receptors, given a large set of roadway links.

This analytical methodology allows for a more refined analysis of the correlation between monitored $PM_{2.5}$ and proximal traffic volumes. Statistical correlation between PM monitor readings and proximal traffic volumes must take into account the fact that relative contributions from each roadway link are a function of the link traffic volumes, vehicle mix, emission rates, wind direction, wind speed, and other meteorological parameters. These relationships are inter-dependent, and various parameters interact in a nonlinear fashion. A simple weighting approach, however, may not adequately account for all of these interactions.

The research team was not able to find statistically significant correlations between monitored and estimated traffic volumes and the monitored $PM_{2.5}$ readings at the Jefferson Street Station. Analysis of prediction residuals did not reveal any patterns to suggest that temporal or spatial bias may be affecting model results. Additional analyses are proposed but significant improvements in correlation are not expected. The distance of the site from major freeway sources, the potential presence of significant unquantified stationary and area source contributions near the monitor, and lack of available background data (which may vary significantly with time and wind direction) likely contributed to the findings of poor correlation. Additional near-roadway research at another site will be considered in which the monitored is located closer to the major transportation source contributions and in which research controls can be improved (quantification of hourly area and stationary source contributions and upwind background concentrations by wind direction).

Summary

The main conclusion from the analyses conducted so far is that only a weak correlation exists between $PM_{2.5}$ concentrations and traffic activity for several of the sites and this is mainly confined to weekday mornings (midnight to noon). This weak correlation was not found at all sites including the Atlanta, Pittsburgh, and New York sites which did not even correlate weakly with traffic activity.

In some cases, average hourly patterns for both $PM_{2.5}$ and traffic activity measurements appear to track well visually, during weekday morning rush hour periods. However, when formal quantitative relationships are explored on an hourly basis, a large amount of unexplained variation exists. That is, it is difficult to predict the level of $PM_{2.5}$ concentrations for an hour from the companion level of traffic activity. This is true even for the time periods when average trends track closely. These fluctuations in $PM_{2.5}$ concentrations are typical of urban atmospheres influenced by multiple $PM_{2.5}$ sources and meteorological conditions. Still, the existence of the general patterns indicate that some kind of link exists between $PM_{2.5}$ and traffic activity, but quantifying this relationship has proven to be difficult.

The data model explored in this work assumes that traffic sources are close enough to the ambient PM monitors to provide sufficiently strong source strengths to allow relationships between PM concentrations and traffic activity to be identified. It was postulated that by having both local and regional traffic activity data, this effect could be accounted for in the analysis. Based on the data reviewed thus far, it appears that the traffic sources may not be close enough to these monitors.

Another limitation to the current data model is that it assumes that vehicle activity (i.e., traffic volume and vehicle type) is a good surrogate for mobile source emissions. This assumption may also not always be true as several studies have suggested that a majority of mobile source emissions are due to a small percentage of the vehicles. Mobile source emission estimates were not evaluated in this study, except in Atlanta, and the results there showed no relationship exists between estimated mobile source emissions and ambient $PM_{2.5}$ concentrations. It should be noted that these results are probably directly related to the situational characteristics of the different $PM_{2.5}$ monitoring locations, a hypothesis that is worthy of additional investigation.

In addition, the analysis conducted so far is limited because details of the emission rates, contributions and, in some cases, the locations of non-traffic sources of PM and its precursors are not well known. The qualitative relationships between PM and traffic sources could perhaps be improved if accurate knowledge of the contributions of the other sources was better known, including a quantification of long-range transport of air pollution.

The main finding that only a vague relationship between ambient $PM_{2.5}$ concentrations and traffic activity can be established, and only at some locations, is related to several factors including distance and direction to major freeway facilities and the likelihood that the PM monitor will detect emissions from those freeways. It indicates that many more factors in addition to traffic activity influence ambient $PM_{2.5}$ concentrations. Factors such as non-mobile sources as well as atmospheric chemical reactions and mixing all influence what the monitors detect. While this fact is well established in the literature, this study did indeed verify the point. This case is especially true if the monitors are located in such a way as to not be influenced by any single source or group of sources.

The results from Phase 2 of the study, as reported here, are seen as the first stage of a more detailed analysis. Phase 3 offers the opportunity to explore the data in more depth such as was attempted in Atlanta. The main results discussed above indicate that more detailed investigation and analysis is required. In other words, we have uncovered very general trends that upon further examination could reveal more quantifiable relationships. Even if quantifiable relationships cannot be established, that in itself would be a valuable result for the air quality and transportation communities.

References

Estimating the Transportation Contribution to Particulate Matter Pollution: Phase 2 Draft Report, Federal Highway Administration, October 2003.

Strategic Workplan for Particulate Matter Research, Federal Highway Administration, September 2000.