Comparison of modeled traffic exposure zones using on-road air pollution measurements

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ABSTRACT

Modeled traffic data were used to develop traffic exposure zones (TEZs) such as traffic delay, high volume, and transit routes in the Research Triangle area of North Carolina (USA). On-road air pollution measurements of nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), black carbon (BC), coarse ($PM_{2.5-10}$), fine ($PM_{2.5}$) particulate matter and ultrafine particles (UFPs) were made on routes that encountered these TEZs. Results indicated overall greater traffic pollutant levels in high volume and delay road sections than bus routes or areas of higher signal light density. The combination of delineating roadways into TEZs with highly time resolved on-road measurements demonstrated how pollutant levels can vary within roadways.

Keywords: Air pollution, Geographic information system (GIS), Mobile monitor, Traffic

1. Introduction

Traffic emissions are a major contributor to urban air pollution, especially near busy highways. Traffic pollutants from gasoline and diesel vehicles include nitrogen dioxide (NO_2), carbon monoxide (CO), carbon dioxide (CO_2), black carbon (BC), coarse ($PM_{2.5-10}$), fine ($PM_{2.5}$) particulate matter and ultrafine particles (UFPs), and air toxics. These pollutants come from traffic and other combustion sources (HEI, 2010).

Epidemiologic studies have shown association of specific adverse respiratory, cardiovascular, and birth outcomes with traffic pollution (Wilhelm and Ritz, 2003; McConnell et al., 2006; McCreanor et al., 2007; Chang et al., 2009; van den Hooven et al., 2009). In addition to limited air monitoring, many of these health studies have used exposure metrics from geographic information system (GIS)-based proximity and related spatial models or dispersion models to assess inter-urban as well as roadway gradients of traffic pollution (Jerrett et al., 2005). Limited studies have also used direct exposure measures of PM and UFPs while walking or bicycling in traffic areas to assess health effects (Vinzents et al., 2005; McCreanor et al., 2007).

Spatial gradients of traffic pollutant levels vary inversely with roadway distance and traffic volume. Depending on the pollutant measured, downwind concentrations of roadways generally drop to background levels within 100 to 500 m (Zhou and Levy, 2007; Karner et al., 2010; HEI, 2010). Measurements of traffic pollutant spatial gradients have typically involved stationary air samplers at varying distances from select roadways with meteorology, traffic count and roadway classification (Baldauf et al., 2008; Vette et al., 2013; Zhu et al., 2002). Traffic pollutants downwind of roads are generally used to assess near road gradients, although trajectory models have shown that other urban and background sources near monitored roads can contribute to measured roadside concentrations (Henry et al., 2011). As a result of the variability of spatial gradients for different traffic pollutants, it has been recommended that high-resolution monitoring near traffic sources be conducted to adequately assess impacts from traffic exposure zones (Zhou and Levy, 2007).

An increasing number of studies have used mobile air monitoring near and on roadways to assess traffic pollution from different roadway classifications. Real-time mobile air monitoring has been demonstrated to have an advantage of identifying spatial and temporal differences of on-road traffic pollutants from different road types, traffic intensities, and road features, such as roadway barriers, that can affect pollutant dispersion. These studies have also revealed that differing background levels should be considered when assessing on-road traffic pollutants (Hagler et al., 2010; Van Poppel et al., 2013). However, access to real-time mobile air monitoring technology is limited because of the requirement for fine time-scale, advanced air monitoring instruments. Therefore, it is of interest to understand whether existing available data such as traffic volume and signal light density, combined with traffic demand models could discriminate between areas differentially influenced by traffic conditions.

This study seeks to address this knowledge gap by delineating and comparing traffic exposure zones (TEZs) using very fine scale on-road ambient air monitoring. Using detailed information on traffic conditions combined with GIS capabilities, roadways were partitioned into TEZs. The TEZs were: traffic delay, high traffic volume, transit routes, signal light density, urban areas, and remainder of the study area. On-road measurements of NO_2, CO, CO_2, BC, $PM_{2.5-10}$, $PM_{2.5}$, PM_{10}, and UFPs were made on the 12 selected routes using a real-time mobile air monitoring vehicle. Traffic-dominated TEZs were compared to assess spatial variability of these traffic pollutants across and within TEZs. Evaluation of these TEZs is being used to assess cardiopulmonary association with traffic pollution for the study area (Ward-Caviness et al., 2014a, b).

2. Methods

2.1 Establishment of TEZs

Traffic and census data were acquired for the North Carolina counties of Wake, Durham, and Orange which encompass the Raleigh-Durham-Chapel Hill metro area (Fig. 1). The Institute for Transportation Research and Education at North Carolina State University supplied estimates from a 2005 traffic demand model which incorporated traffic volume, signal light, and transit route information (TRMSB, 2009). The supplied data represent a typical workday (Monday through Thursday) in the spring and fall. Urbanized areas were based on U.S. Census 2000 urbanized areas (US Census, 2002). Spatial processing primarily used ArcGIS Desktop 10 (ESRI, 2011).

Six, mutually-exclusive TEZs were formed based on traffic variables, transit routes, county, and urbanization data. Fig. 1 shows their locations in the study area. TEZs were categorized from lowest to highest expected traffic exposure. The first three TEZs were based on areas: the three county study area (TEZ 1), Census urbanized area (TEZ 2), and areas with high signal light density (TEZ 3). An additional three TEZs with higher expected traffic exposure were based on road segments defining areas near roadways with transit authority bus routes (TEZ 4), roadways with high traffic volume (TEZ 5), and roadways with large traffic delays (TEZ 6). The supporting material provides further detail on TEZ definitions.

For the analysis conducted here, a hierarchical approach was used to overlay TEZs with higher numbered, traffic dominated TEZs taking priority in the overlay. For example, if TEZ 6 overlapped TEZ 5, the higher priority TEZ 6 remained intact and overlapping portions of TEZ 5 were clipped. This was true for all layers, so TEZ 6 took precedence, followed by TEZ 5, and so on. An exclusion zone was created by applying a 1 km buffer to the Raleigh-Durham International Airport (RDU) boundaries (Fig. 1). An examination of EPA's National Emissions Inventory and Toxics Release Inventory for the study area showed that RDU was the only major point source for these pollutants, especially fine particulate matter. TEZs falling in the RDU zone were not considered in the study to avoid air traffic and related influences as a potential interference.

2.2 Mobile monitoring

Potential routes were visually examined both directly and via Google Earth® to assure the viability of the route. Twelve driving routes within the three-county study area were selected (Fig. 1) to emphasize sampling in TEZs 4 – 6 since previous research indicated proximity to certain roadway classifications such as stop-and-go bus and truck traffic volumes and diesel-only traffic could be associated with adverse respiratory health effects (Ryan et al. 2005; McCreanor et al., 2007). Note that all routes included multiple TEZs. This selection process was biased toward what were anticipated to be more highly impacted TEZs and therefore the data collected from TEZs 1 and 2 were not necessarily representative over the three-county area.

Due to limitations in battery life of the electric vehicle, the routes ranged from 5.2 – 18.1 km. This permitted multiple circuits on each route. Monitoring took place during morning rush hours on weekdays between August 16 and October 11, 2012 with each route being sampled on two days. Sampling on each day is referenced below as a run. Total sampling time on the routes ranged between 2.80 and 4.15 hours.

The mobile air monitoring and data processing components of this study are detailed elsewhere (Brantley et al., 2013). In brief, an instrumented electric car with a global positioning system (GPS) was used to measure in-traffic pollutant levels at one second intervals utilizing the following on-board sampling instrumentation: 1) cavity attenuated phase shift (CAPS) monitor (Aerodyne Research, Inc., Billerica, MA, USA) for NO_2 measured in ppb; 2) dual quantum cascade laser (Aerodyne Research, Inc.) for CO in ppb; 3) non-dispersive infrared (NDIR) analyzer (Li-COR 820, LiCOR Biosciences, Lincoln, NE, USA) for CO_2 in ppm; 4) portable aethalometer (AE42, Magee Scientific, Berkeley, CA, USA) for BC in µg m^{-3}; 5) Aerodynamic Particle Sizer (Model 3321, TSI) for size-resolved particle counts for PM_{10}, $PM_{2.5}$ and $PM_{2.5-10}$ (PM_{coarse}) all in µg m^{-3}; and 6) Engine Exhaust Particle Sizer (Model 3090, TSI, Shoreview, MN, USA) for size-resolved particle counts that include UFPs <100 nm). All measurements were adjusted to account for extraneous near road influences (Brantley et al., 2013) prior to TEZ analyses.

2.3 Statistical analysis

Overall sampling capture was good for each pollutant, ranging between 81% (for UFP) and 91% (for NO_2). Some additional data were removed from the analysis because definitive assignments of TEZs could not be made for some sections of roadway. Generally this occurred where TEZs abutted, particularly in conjunction with bends in the roadways. No attempt was made to impute a TEZ in such cases, resulting in the removal of about 1.86% of the data. In addition, prior to the statistical analysis, data from any TEZ that constituted less than two minutes of sampling on any run were eliminated from the analysis to ensure TEZs had adequate data to represent the local air quality. Overall, this reduced the available data by 0.6%, and most of these short sampling periods occurred in TEZ 2. Notwithstanding these data losses, the amount of overall (all routes and runs) sampling time spent in the TEZs ranged between 6.05% (TEZ 2) and 37.40% (TEZ 4); see Table 1.

Given the second-by-second nature of the monitoring, extremely high autocorrelation of the measurements was observed. In addition, multiple occurrences of the same TEZ category happened on individual routes, and each route was driven twice. To ensure that independent observations were used to compare the TEZs, the following procedure was employed: for each pollutant within each run, data were first summarized by determining the median of the measured levels within each TEZ encountered on the individual routes. These median values were then averaged across the two runs for each route.

This resulted in 9, 11, 8, and 9 estimates of pollutant levels for TEZs 3, 4, 5, and 6, respectively. TEZ levels 1 and 2 were excluded from the subsequent analysis because: 1) they were each only encountered on 4 separate routes; 2) the time spent sampling in them accounted for less than 10% each of overall sampling time; and 3) these two TEZs were inherently of less interest for the health analyses (Ward-Caviness et al., 2014a, b). Of course, as noted above, these reasons were also reflected in the selection of the routes to be driven.

Comparisons were made between TEZs 3, 4, 5, and 6 using the Wilcoxon rank sum test with exact p-values estimated via Monte Carlo sampling in SAS procedure NPAR1WAY. No adjustment was made for the fact that multiple comparisons were being conducted. The magnitudes of the differences between TEZs were provided by Hodges-Lehmann estimates (Hollander and Wolfe, 1999).

3. Results

Table 2 provides summary statistics for the averaged medians by TEZ for each pollutant. As stated in the methods section, these values represent adjusted, not absolute, concentrations.

Though the table summarizes average medians, the ranges of these summary statistics could be quite wide. Generally, CO and CO_2 showed broader ranges than the other pollutants with a factor of roughly 10 in TEZ 3 and two orders of magnitude in TEZ 5. (Note that the latter is driven by the very low minima observed.) However, note that the observed values for these two pollutants was much higher than the other pollutants. If one looks on a relative basis at, say, the ratio of the median to the range, the differences among the pollutants are much less. UFP also exhibits a very broad range in TEZ 5, but this is engendered by the large maximum there. For the other pollutants the minima and maxima are generally separated by a factor of less than 10 within TEZs, and more commonly factors between 3 and 6 are observed.

Aside from CO_2, the monitored pollutants showed differences between the TEZs (Table 3). As noted above, comparisons were restricted to TEZs 3, 4, 5, and 6. Note that Table 3 reports the actual p-values; in this paragraph, 10% is used as the significance level. BC was found to be higher in TEZ 5 (high volume) vs. TEZ 4 (bus route), but this was the only significant difference found for this pollutant. NO_2 was found to be higher in TEZ 6 (delay) than in TEZs 3 (high signal light density) and 4, but not TEZ 5. CO was significantly higher in TEZ 5 than in any of the other three TEZs. TEZ 5 was also higher than the other three TEZs for each particulate matter pollutant (except for PM_{coarse} and UFP levels relative to TEZ 6). Similarly, TEZ 6 was higher in the particulate pollutants than either TEZ 3 or 4, except for PM_{coarse}. TEZs 3 and 4 did not significantly differ with regard to any of the pollutants.

4. Discussion and Conclusion

Modeled traffic counts with on-road measurements of traffic pollutants were used to characterize traffic delay, high traffic volume, transit routes, signal light density, urban areas, and remainder of the Research Triangle study area. High traffic volume routes categorized as TEZ 5 showed significantly higher levels for most particulate pollutants, ultrafine particulates (except PM_{coarse} and UFP versus TEZ 6) and CO than the other traffic zones. Areas with large traffic delays categorized as TEZ 6 showed significantly higher impact for particulate pollutants, ultrafine particulates and NO_2 than in bus routes or high signal light density areas. Higher levels of particulate pollutants in high volume and traffic delay zones may suggest greater impact from resuspended road dust and tire/brake wear versus other zones. These preliminary findings indicate a greater traffic pollutant impact in high volume and delay road sections than bus routes or areas of higher signal light density for the Research Triangle study area. In related health analyses, TEZs 5 and 6 have been found to be associated with high-density lipoprotein cholesterol, and TEZ 6 with peripheral vascular disease, both of which are known risk factors for cardiovascular disease (Ward-Caviness et al, 2014a, b).

Due to logistic constraints, traffic characterization and comparisons in this pilot study were limited to relatively few routes and two sampling runs on each route. In future research, a larger number of routes would be desirable to better characterize all the TEZs including TEZs 1 and 2. In addition to allowing more complete comparisons between TEZs, a larger number of routes might offer the possibility of comparing overlapping and non-overlapping TEZs (for example a road section with TEZs 4, 5, and 6 versus TEZ 5 only). Finally, it would be desirable to monitor routes in different seasons to see if the relationships found here are also observed.

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Supporting Material Available

Traffic exposure zone (TEZ) descriptions provided. This information is available free of charge via Internet at http://www.atmospolres.com.

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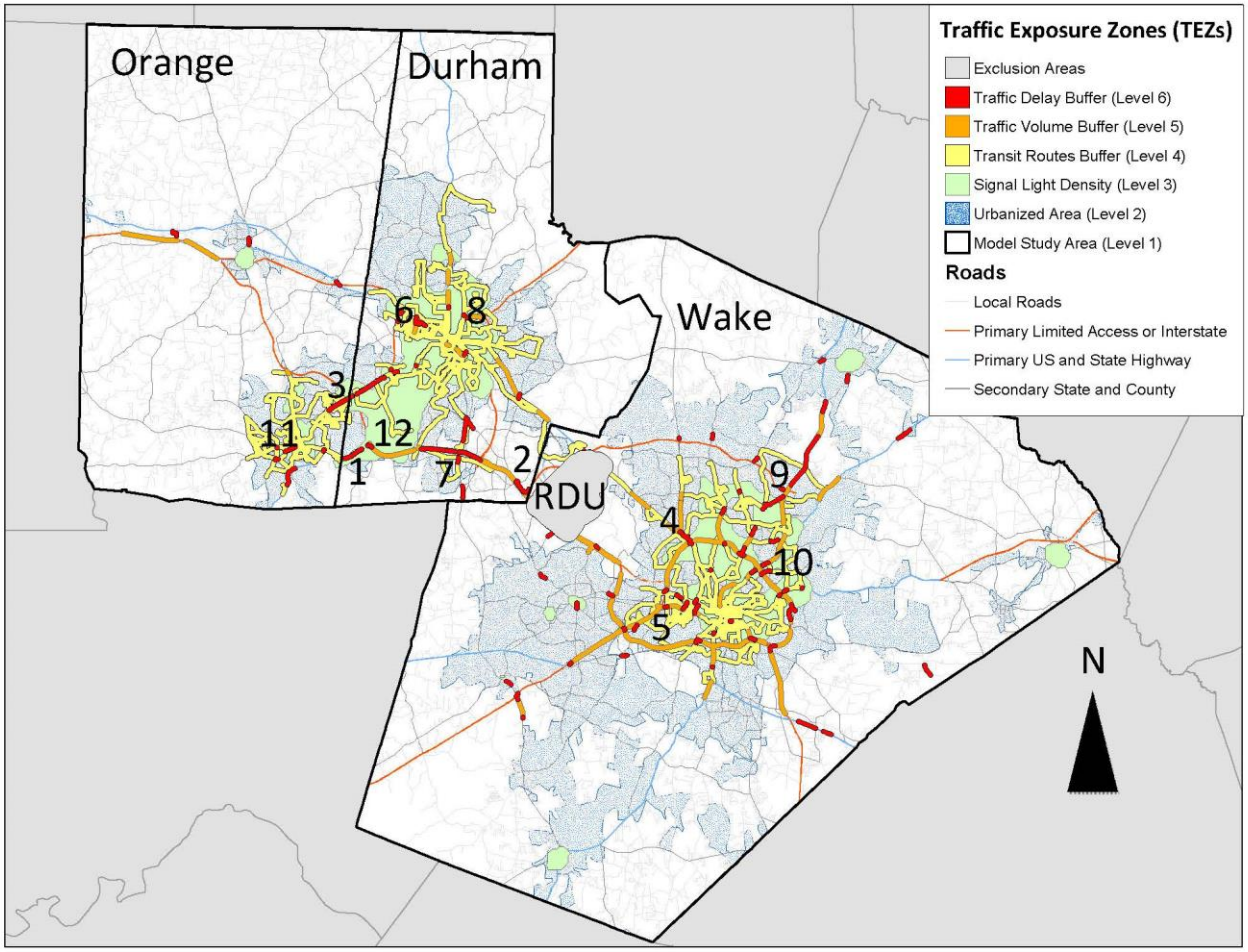

Figure 1. *Three-county study area in North Carolina with TEZs [a]; approximate location of mobile monitoring routes as numbers, and RDU exclusion area labelled.*

[a] A 200 m buffer around road segments is used to display TEZs 4 to 6

Table 1. *Percentage of total sampling time (all routes, all runs) spent in each TEZ*

TEZ	Total sampling time (%)
Uncategorized	1.86
1	9.75
2	6.46
3	19.71
4	37.40
5	13.26
6	11.56

Table 2. *Pollutant summary statistics for averaged medians by TEZ*

	BC (μg m-3)	CO (ppb)	CO_2 (ppm)	NO_2 (ppb)	PM_{10} (μg m^{-3})	$PM_{2.5}$ (μg m^{-3})	PM_{coarse} (μg m^{-3})	UFP (cm^{-3})
TEZ 6 (n=9)								
Median	1.69	211	55	8.30	4.33	2.04	2.77	6 477
Mean	1.78	248	74	7.78	4.41	2.12	2.90	7 398
Minimum	0.75	130	39	3.13	3.50	1.65	2.40	3 882
Maximum	3.02	441	176	9.65	5.57	2.68	3.64	12 773
TEZ 5 (n=8)								
Median	2.77	436	79	8.40	5.48	2.89	3.27	12 011
Mean	2.61	416	67	7.76	5.13	2.70	3.17	12 783
Minimum	0.00	1.23	0.52	1.22	1.84	1.01	1.34	1 013
Maximum	5.55	707	95	12.47	6.55	3.42	3.98	34 606
TEZ 4 (n=11)								
Median	1.34	197	41	6.13	3.84	1.75	2.66	4 160
Mean	1.36	210	58	5.50	3.80	1.80	2.59	5 016
Minimum	0.84	75	22	2.62	2.77	1.27	2.09	2 429
Maximum	2.13	353	119	8.49	4.54	2.57	3.20	8 908
TEZ 3 (n=9; n=8 for UFP)								
Median	1.25	172	30	6.68	3.36	1.64	2.42	4 697
Mean	1.56	238	50	6.17	3.58	1.78	2.51	4 908
Minimum	0.55	88	12	3.51	1.78	0.94	1.59	3 202
Maximum	4.08	849	131	8.88	6.41	3.99	3.37	8 212
TEZ 2 (n=4)								
Median	1.68	338	69	5.61	4.69	2.33	2.83	6 160
Mean	1.79	313	70	6.27	4.47	2.35	2.75	9 638
Minimum	0.47	97	51	1.93	3.20	1.99	2.24	3 170
Maximum	3.33	478	92	11.91	5.29	2.76	3.10	23 064
TEZ 1 (n=4)								
Median	1.13	77	21	3.08	2.39	1.31	1.77	3 438
Mean	1.03	92	21	3.47	2.41	1.26	1.78	3 453
Minimum	0.38	64	11	1.76	2.08	1.00	1.53	2 134
Maximum	1.49	149	31	5.96	2.81	1.43	2.06	4 804

Table 3. *Results of TEZ comparisons*

Pollutant	3 vs. 4			3 vs. 5			3 vs. 6			4 vs. 5			4 vs. 6			5 vs. 6		
	p-value	> TEZ [a]	Est. diff. [b]	p-value	> TEZ	Est. diff.	p-value	> TEZ	Est. diff.	p-value	> TEZ	Est. diff.	p-value	> TEZ	Est. diff.	p-value	> TEZ	Est. diff.
BC	1.00	4	0.01	0.138	5	1.21	0.260	6	0.35	0.063 [c]	5	1.31	0.128	6	0.36	0.325	5	0.83
CO	0.552	4	28.8	0.074 [c]	5	223	0.187	6	11.2	0.011 [d]	5	231	0.506	6	15.4	0.060 [c]	5	174
CO_2	0.196	4	13.2	0.329	5	28	0.110	6	29.8	0.602	5	12.8	0.209	6	14.0	0.813	5	2.51
NO_2	0.551	3	0.55	0.230	5	1.72	0.100 [c]	6	2.07	0.111	5	2.23	0.024 [d]	6	2.30	0.963	5	0.10
PM_{10}	0.332	4	0.43	0.028 [d]	5	1.96	0.031 [d]	6	0.97	0.007 [d]	5	1.65	0.027 [d]	6	0.52	0.061 [c]	5	1.00
$PM_{2.5}$	0.329	4	0.16	0.044 [d]	5	1.28	0.019 [d]	6	0.51	0.006 [d]	5	1.10	0.055 [c]	6	0.33	0.023 [d]	5	0.76
PM_{coarse}	0.944	4	0.03	0.049 [d]	5	0.72	0.222	6	0.34	0.017 [d]	5	0.72	0.113	6	0.28	0.118	5	0.43
UFP	0.842	3	181	0.082 [c]	5	3 312	0.088 [c]	6	1 800	0.062 [c]	5	6 555	0.057 [c]	6	1 979	0.277	5	4 064

[a] > TEZ indicates which of the pair is larger.

[b] Est. diff. indicates Hodges-Lehmann estimated difference; pollutant units same as in Table 2.

[c] Significant at the 10% level.

[d] Significant at the 5% level.

SUPPORTING MATERIAL

Comparison of modeled traffic exposure zones using on-road air pollution measurements

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Traffic exposure zone (TEZ) definitions

TEZ 6 (traffic delay)

Stop and go traffic was thought to generate the largest pollutant levels of concern. The highest priority TEZ was based on modeled traffic delay in the traffic demand model[1]. Visual examination did not indicate any significant differences between peak morning and peak evening delays. The traffic delay was calculated for each segment in the traffic model using peak morning flow. It was desired for the calculation to be independent of traffic volume so the delay variables[2] were not used. Rather, segment travel times estimated for free flowing traffic[3] and those estimated during the morning peak flow were used[4]. The percent delay was calculated as:

$$Percent\ Delay = 100 * Average\left(\frac{AB\_AM\_TT - AB\_FF\_TT}{AB\_FF\_TT} + \frac{BA\_AM\_TT - BA\_FF\_TT}{BA\_FF\_TT}\right)$$

Direction specific variables for each segment are distinguished by the prefix AB and BA. The abbreviations AM, FF, and TT indicate morning peak, free flowing, and travel time, respectively. The variable AB_{AM_TT} in this equation represents the travel time along a segment during the morning peak in the AB direction. The remaining variables can be interpreted similarly. The left quantity in the parenthesis is the percent delay, as a fraction, in the AB direction; the right quantity is for the BA direction. For one way roads, the quantity for the direction without flow is dropped from the equation. Road segments with a delay greater the 35% were identified.

TEZ 5 (traffic volume)

Segments in the traffic demand model with high traffic volume were identified as those carrying more than 40 000 vehicles per day.

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[1] The free flowing variables are *ABFFTIME* and *BAFFTIME*, from the attribute table associated with the *2005 Hwy Network* data.
[2] The delay variables have names ending in DELAY (e.g., *ABAMDELAY*).
[3] The free flowing variables are *ABFFTIME* and *BAFFTIME*.
[4] The variables for peak flow travel time are ABCONGDELAY and BACONGDELAY.

TEZ 4 (transit authority bus routes)
In a previous study, stop-and-go traffic, which included transit routes, were shown to be correlated with wheezing in very young infants (Ryan et al., 2005). The routes for three transit authorities (Capital Area Transit for the Raleigh/Cary area, Durham Area Transit Authority, and Chapel Hill Transit) and two universities (Duke and North Carolina State University) were used. (Chapel Hill Transit is the principal campus bus service for the University of North Carolina.) The universities were in session for most of the monitoring time period and three of the routes were partially located on the three campuses thus making their use appropriate. The Triangle Transit Authority runs the regional bus lines; these routes were not used since they typically run on major roads captured in other TEZs.

TEZ 3 (signal light density)
The attribute data for the traffic demand model contains data for the roadways on signal light density in lights per mile. The segments were generalized to points 100 m apart keeping the signal light density variable. Kriging, using the 25 nearest neighbors, was employed on a grid of 200 m cells to generate a signal light density surface. This was filtered with a 5x5 median cross filter; an integer function was applied to reduce values to the nearest integer. Finally, cells that were less than one were set to null. A contour function was applied to convert the surface to polygons representing the signal light density zone, which was exported and brought back into ArcGIS.

TEZ 2 (urbanized area)
The urbanized area represents areas that are predominately urban, with a correspondingly denser road network and more traffic than the other areas in the study. These polygons are taken directly from the ESRI data.

TEZ1 (remainder of 3 county area)
Any area within the North Carolina counties of Durham, Orange, and Wake outside the RDU exclusion area and not assigned to another TEZ.