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Dispersion Modeling of Traffic-Related Air Pollutant Exposures and Health Effects Among Children with Asthma in Detroit, Michigan

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Abstract

Vehicular traffic is a major source of ambient air pollution in urban areas. Traffic-related air pollutants, including carbon monoxide, nitrogen oxides, particulate matter less than 2.5 μm in diameter, and diesel exhaust emissions, have been associated with adverse human health effects, especially in areas near major roads. In addition to emissions from vehicles, ambient concentrations of air pollutants include contributions from stationary sources and background (or

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regional) sources. Although dispersion models have been widely used to evaluate air quality strategies and policies and can represent the spatial and temporal variation in environments near roads, the use of these models in health studies to estimate air pollutant exposures has been relatively limited. This paper summarizes the modeling system used to estimate exposures in the Near-Roadway Exposure and Urban Air Pollutant Study, an epidemiological study that examined 139 children with asthma or symptoms consistent with asthma, most of whom lived near major roads in Detroit, Michigan. Air pollutant concentrations were estimated with a hybrid modeling framework that included detailed inventories of mobile and stationary sources on local and regional scales; the RLINE, AERMOD, and CMAQ dispersion models; and monitored observations of pollutant concentrations. The temporal and spatial variability in emissions and exposures over the 2.5-year study period and at more than 300 home and school locations was characterized. The paper highlights issues with the development and understanding of the significance of traffic-related exposures through the use of dispersion models in urban-scale exposure assessments and epidemiology studies.

Vehicles are a major source of air pollutants, including oxides of nitrogen (NO_x), carbon monoxide (CO), particulate matter (PM) less than 2.5 μm in diameter ($PM_{2.5}$), and volatile organic compounds (VOCs) (1, 2). Because vehicle emissions are released at or near ground level and mostly in urban areas, exposure to traffic-related air pollutants is widespread. Exposure to traffic-related air pollutants has been associated with a range of adverse health effects, such as exacerbation of asthma, asthma onset, impaired lung function, cardiovascular morbidity and mortality, adverse birth outcomes, and cognitive decline (3–5).

Vulnerable individuals who are particularly susceptible to the adverse health impacts of traffic-related air pollutants because of personal, environmental, and socioeconomic factors include the young and the elderly; individuals with existing cardiovascular or respiratory diseases, such as asthma; and individuals living, working, or frequenting locations near roads with high levels of traffic. Many individuals living in high-traffic areas are nonwhite and low income (6), characteristics that are associated with susceptibility to the adverse effects of air pollution. In the United States, an estimated 40 million people live within 100 m of major roads, railways, or airports (7), and millions more commute on major roads, suggesting the importance of exposure to traffic-related air pollutants for public health.

A major challenge for scientific investigations of the health impacts of traffic-related air pollutants is the lack of information on pollutant exposure. Data provided by networks monitoring ambient air quality, including the new near-road monitoring network (8), are helpful for understanding pollutant exposure; however, these networks are not designed to provide the spatial coverage and often the temporal resolution needed to evaluate population exposures to traffic-related air pollutants. In particular, traffic-related air pollutants found at elevated levels near roads, including $PM_{2.5}$, ultrafine PM (which is currently unregulated), VOCs, nitric oxide, and polycyclic aromatic hydrocarbons, demonstrate steep gradients in concentrations and typically reach background levels at distances of 150 to 200 m from the road (9–16).

Most epidemiology studies have relied on several approaches to estimate exposures due to traffic, mostly proximity-, geographic information system-, or interpolation-based methods.

Although they are often useful for analyses of health effects, these methods result in surrogates or indicators of exposure that do not capture the temporal patterns (e.g., diurnal, weekday or weekend, and seasonal trends) demonstrated by traffic-related air pollution. The use of personal exposure measurements, exposure biomarkers, or sufficiently localized indoor or ambient monitoring measurements is, unfortunately, not feasible or practical, given the number of subjects and the duration of most health studies, as well as other limitations. Thus, the need for methods and data to obtain more accurate temporally and spatially resolved information on exposures to traffic-related air pollutants remains. Reductions in the spatial and temporal errors in exposure estimates for subjects in epidemiology, risk assessment, and other types of studies (17–19) will allow such information to improve significantly understanding of the health effects associated with traffic-related air pollutants.

OBJECTIVES

The Near-Road Exposures to Urban Air Pollutant Study (NEXUS) is investigating whether children with asthma living in close proximity to major roadways in Detroit, Michigan, experience greater health impacts associated with air pollutants than those living farther away, particularly near roadways with high levels of diesel traffic (20). NEXUS is using air quality modeling to estimate exposures for the children that reflect the complex and often dramatic spatial and temporal patterns associated with traffic-related air pollutants. A broader discussion of the scope of NEXUS is provided elsewhere (20).

This paper summarizes the modeling system used to estimate ambient pollutant concentrations in NEXUS. It describes the development of a comprehensive inventory from mobile and stationary sources, dispersion modeling of local and regional sources, and its application to the health study. This paper emphasizes the temporal and spatial variability of exposures in NEXUS, the differences between alternate exposure metrics, and the use of simulation models to provide daily estimates of pollutant exposures and source apportionments compared with those from statistical land use regression models that provide long-term averages. The present paper is relevant to urban-scale dispersion modeling of air pollutants, and it focuses on the derivation of exposures of traffic-related air pollutants that are applicable to both risk and epidemiology studies.

METHODS

Study Population and Health Assessment

NEXUS is a community-based participatory research study designed to examine the relationship between exposures to air pollutants near roadways and adverse respiratory health outcomes in a cohort of asthmatic children who live close to major roadways in Detroit. A community-based steering committee was established, and the study design and protocols were developed with the committee’s input and consent. Children ages 6 to 14 years with asthma or symptoms of asthma were recruited to participate in the study on the basis of the proximity of their homes to major roads in three traffic categories: (*a*) homes near high traffic and high-diesel traffic, defined as homes within 150 m of roads with >6,000 commercial vehicles per day (commercial annual average daily traffic) and >90,000 total vehicles per day [annual average daily traffic (AADT)]; (*b*) homes near high traffic and low-diesel traffic, defined as homes within 150 m of roads with >90,000 AADT and <4,500 commercial vehicles per day; and (*c*) homes near roads with low traffic, defined as homes located >300 m from roads with >25,000 AADT and greater than 500 m from roads with >90,000 AADT.

To minimize possible confounding from unmeasured neighborhood-associated covariates, children whose homes were in the low-traffic group were drawn from the same neighborhoods and school catchment areas as those whose homes were in the high-diesel and low-diesel segments but lived farther from the high-traffic corridors. A total of 139 children were enrolled and participated in NEXUS from September 2010 to December 2012, and the distributions across the three traffic categories were approximately equal. The study population was predominantly minority: non–Hispanic blacks constituted 82% of the participants, Hispanics constituted 8%, non–Hispanic whites constituted 4%, and individuals of other races or multiracial individuals constituted 6%. Many households were poor, and a third of the families reported annual household incomes of less than $15,000.

During the course of the study, a number of children moved, and the evaluation used all residences reported for the children. Because of the moves, a total of 218 residence locations were considered. Each location was geographically coded by use of a handheld GPS unit placed near the front door of each residence. These children attended 107 schools, which were similarly geographically coded.

Respiratory health effects potentially associated with exposures to traffic-related air pollutants were characterized on a seasonal basis over a 14-day period for each child. Health measures evaluated included asthma aggravation (lung function and symptoms), inflammation and oxidative stress responses (exhaled nitric oxide and nasal cytokines), and respiratory viral infections (frequency, severity, and type). Seasonal assessments also included the collection of information on medication and health care use and diary reports of symptoms of upper respiratory tract infection, determination of the fraction of exhaled nitric oxide and urinary F_2-isoprostane levels, and the collection of nasal lavage samples. Information on means of asthma control and symptoms associated with obstructive sleep apnea was also obtained.

Hybrid Dispersion Modeling

Air pollutant concentrations and exposures for the children in NEXUS were estimated by use of dispersion models, including AERMOD (21, 22) and RLINE (23, 24). RLINE is a research-level, line source dispersion model being developed by the U.S. Environmental Protection Agency's Office of Research and Development as a part of the ongoing effort to further develop tools for the comprehensive evaluation of the impacts of air quality in the environment near roads.

Traffic activity and primary mobile source emissions were estimated to produce a spatially and temporally resolved mobile source emissions inventory giving hourly pollutant emissions by vehicle class and road link, as described elsewhere (25, 26). Road network data, obtained from the Southeast Michigan Council of Governments, included link locations, number of lanes, roadway type (e.g., freeway, arterial), AADT, and average speed (for four periods over the day) for each of 9,701 links. The traffic activity by vehicle class was based on travel demand models with input by the U.S. Environmental Protection Agency and the Michigan Department of Transportation. AADT values were allocated to eight vehicle classes (e.g., heavy-duty diesel, light-duty gasoline) and adjusted to obtain hourly estimates by the use of month-of-year, day-of-week, and hour-of-day temporal allocation factors on a link-specific basis. Whenever possible (mainly for Interstates), estimated vehicle flows were checked against monitored traffic counts. Emission factors representative of vehicle classes in the study area were calculated through the use of the MOVES2010a mobile source emissions model as a function of average speed, ambient temperature, season, and road type.

Stationary sources of pollutants, such as stacks from manufacturing facilities, were modeled by the use of AERMOD, source locations, emission rates, and other information obtained from the latest (2008) official National Emissions Inventory. The regional background contribution was estimated using a combination of the Community Multiscale Air Quality (CMAQ) model and the Space/Time Ordinary Kriging model. Two CMAQ model simulations were conducted: the baseline simulation represented all emissions in a broad region (covering the eastern United States), and the second removed all anthropogenic emissions in the NEXUS study domain. The ratios of the concentrations predicted by CMAQ in these two simulations in the Detroit region along with air quality system measurements in the region were used to estimate background pollutant concentrations at the NEXUS study locations.

The modeling provided hourly pollutant concentrations for CO, NO_x, $PM_{2.5}$, and benzene. The hourly concentrations were processed to calculate daily and annual average exposure metrics for each study participant’s home and school location for use in the epidemiologic analyses.

RESULTS

Study Region and Road Network

Figure 1 shows the study area, including the locations of the homes of the children in NEXUS and the schools that they attend, and the modeled road network. The city of Detroit covers 355 km^2; the road network (shown in Figure 1) covers nearly 800 km^2. The road network extended at least 5 km beyond the locations of the NEXUS homes. A few children attended schools at the periphery of or outside the modeled area.

The modeled road network is summarized in Table 1. It consisted of 9,701 links representing 3,109 km of roads, including all but the smaller and numerous local roads. Major roads were frequently represented by the use of multiple links at any particular location; that is, Interstate highways were represented by the use of separate links for each direction as well as each service road (Table 1 reflects this classification).

Proximity of Homes and Schools to Roads

By design, many of the children in NEXUS lived very close to major roads. Figure 2*a* shows the distribution of home-to-road distances for the larger roads. When children in homes recruited near high-traffic roads are considered, the median distances were 117 and 107 m in the high-diesel and low-diesel categories, respectively. One house was as close as 5 m from a high-traffic road. The distributions of home-to-road distances in the high- and low-diesel categories were similar. When all 218 home locations are considered, the median home-to-road distance for links with AADT exceeding 40,000 (typically, one direction on a high-traffic road) was 326 m. This included many homes in the low-traffic category, which were at least 500 m from high-traffic roads.

Figure 2*b* shows the distribution of school-to-road distances. The median distance to major roads (road links with AADT of >40,000) was 617 m. However, a subset of schools was much closer; for example, 13% were within 200 m and 8% were within 100 m. The closest school was only 14 m from a high-traffic road.

The distributions of home and school distances to roads depicted in Figure 2 indicate that the exposure assessment must address a wide range of conditions, including exposures at some homes and schools that are very close to major roads. They also suggest that children in a particular exposure category, for example, areas with high-diesel traffic, are likely to experience a range of traffic-related exposures and health impacts, given the large range of distances represented in an exposure category, for example, 5 to 200 m; that is, exposures within an exposure category are not homogeneous.

Traffic-Related Emissions

Emission totals for four pollutants by road type are shown in Table 2. For example, the total $PM_{2.5}$ emissions from all road links are 473 tons per year (the product of annual average emission rates and link lengths summed across all links). As a check, $PM_{2.5}$ emission results were compared with the emission inventories compiled for Wayne County, Michigan, and southeast Michigan as part of the State Implementation Plan. In 2005, primary on-road $PM_{2.5}$ emissions in Wayne County (which has an area slightly larger than that of Detroit) were estimated to be 792 tons per year (27). In the seven-county southeast Michigan region, the 2008 inventory gives a vehicle population of 3.65 million, 44.2 billion vehicle miles traveled, and $PM_{2.5}$ emissions of 4,360 tons per year; but $PM_{2.5}$ emissions are projected to drop to 1,633 tons per year in 2018 (28).

This region is considerably larger than the NEXUS study area; for example, the number of vehicle miles traveled in the study area is only 17% of that in the seven-county area. Although these various estimates use different time periods, different regions, and different models (MOBILE6 and MOVES mobile source emissions models), the NEXUS emission estimates appear to be consistent and reasonable with respect to the State Implementation Plan inventory.

A breakdown of the Detroit emission inventory is shown in Figure 3. Figure 3 indicates that heavy-duty diesel vehicles (HDDV) are responsible for 58% of $PM_{2.5}$, 36% of NO_x, and 3% of CO and benzene emissions. In contrast, light-duty gasoline vehicles (LDGV) emit 28% of

$PM_{2.5}$, 41% of NO_x, 65% of CO, and 63% of benzene. These percentages represent the average contribution across the Detroit network for calendar year 2010 and are derived from the modeling system described above.

Temporal Variation of Mobile Source Emissions

The mobile source emission inventory represents the temporal variation at the monthly, daily, and hourly levels. The monthly variation in emission rates for four pollutants is shown in Figure 4*a*. Trends differ by pollutant, and in some cases, the temporal variation is substantial. $PM_{2.5}$ emissions are approximately 30% higher during the colder months.

Figure 4*b* shows the hour-to-hour pattern of $PM_{2.5}$ emissions. Weekdays show a bimodal pattern, reflecting morning and afternoon peak hours, whereas weekends show a single broader afternoon mode. $PM_{2.5}$ emissions are significantly reduced on weekend days, especially Sundays, reflecting the lower volume of traffic, especially diesel vehicles. The differences between weekday and weekend emissions for CO and benzene are smaller, reflecting the larger share of these emissions emitted by nondiesel vehicles (mostly passenger cars). These diurnal trends reflect the averaging of emissions in each of the eight vehicle classes, which can vary more dramatically by hour and day type. For example, compared with the volume on weekdays, the heavy-duty diesel truck volume is significantly reduced on weekends, the light-duty gasoline vehicle volume is somewhat reduced (the temporal patterns shift dramatically to a single mode), and the motorcycle volume is similar (reflecting an increase in recreational riding). Overall, this analysis indicates the importance of the temporal variation at the monthly, daily, and hourly levels. Furthermore, all road types (as defined by national function class) have essentially similar patterns (data not shown).

Estimated $PM_{2.5}$ Concentrations at Homes and Schools

This section focuses on the annual average (2010) $PM_{2.5}$ exposures at homes and schools predicted by the hybrid modeling system described earlier.

Figure 5 shows the annual average $PM_{2.5}$ levels at the high-traffic homes (both high and low diesel), which are plotted against distance from the classifying road. Figure 5 also shows $PM_{2.5}$ levels at the low-traffic homes; these homes are unranked by distance (the results are simply plotted in the modeled sequence). The $PM_{2.5}$ estimates, which include contributions from road, area, point, and regional sources, range from 12 to 24 $\mu g/m^3$. The concentrations at the high-traffic homes are elevated by an average of 2 $\mu g/m^3$ above those at the low-traffic homes. As expected, the distance-to-road trend is not strong for total $PM_{2.5}$ from all sources, yet homes within 100 m of a major road had elevated concentrations.

Figure 6 shows annual average $PM_{2.5}$ levels at high- and low-traffic homes, as in Figure 5, but shows the contributions due to only local (Detroit-area) traffic emissions. In this case, $PM_{2.5}$ contributions from traffic at the high-traffic homes ranged from 2 to 9 $\mu g/m^3$, concentrations that are significantly elevated compared with those for the low-traffic homes, most of which received only 1 to 2 $\mu g/m^3$ from traffic emissions. The concentration–distance trend is strong for the high-traffic homes, although considerable scatter exists. The scatter is produced by the joint effects of multiple roads and road geometry, various levels of traffic and emissions, and meteorology. Each point on Figure 6 indicating an elevated concentration was investigated, and the concentrations were attributable to emissions from one and often several nearby roads.

Figure 7 displays the spatial pattern of annual average $PM_{2.5}$ concentrations at each home and school location, as well as the concentrations monitored at fixed (permanent) sites in the region. At each location, the concentration attributable to traffic emissions is shown as a red circle, and the total concentration (sum of road, non-road, area, point, and regional contributions) is shown as a green circle. The 2010 average monitored concentrations are shown as blue circles. The circle's area is proportional to the concentration, as indicated in the scale. The left circular plot at the bottom shows the wind direction probability in 16 sectors. The right circular plot at the bottom shows the average wind speed in 16 sectors for the period displayed. The blue circles at the right are concentrations at (named) monitoring sites in Detroit and elsewhere in Michigan (most are off the map). The prefix T denotes measurements obtained by use of a tapered element oscillating microbalance (continuous); otherwise, the sites use measurements obtained by the federal reference method (filter based). (Some sites have both tapered element oscillating microbalance and federal reference method monitors.)

Figure 7 indicates that $PM_{2.5}$ concentrations are higher near major roadways (red circles), particularly the I-75, M-39, and M-10 corridors, and are present because of traffic. Homes and schools very near major roads, crossings of major roads, or midsized roads can also have elevated levels of traffic-related air pollutants. In contrast, the spatial variation of the total $PM_{2.5}$ concentration (green circles) is small and is also reflected in the similar levels at most of the monitoring sites (blue circles), largely because of the regional (background) contributions of $PM_{2.5}$.

Temporal variation is an important factor in air pollutant characterization. It is not displayed in Figure 7. However, maps of the time series of pollutant concentrations are available online (posted at http://www.youtube.com/watch?v=5vZ0lG5T7wc). Movies showing the concentrations for each day in 2010 and 2011 indicate dramatic changes in concentrations.

CONCLUSIONS

This paper has highlighted several key elements in the development and understanding of the significance of traffic-related exposures through the use of dispersion models in an urban-scale exposure and epidemiology application. It has summarized the development and use of a detailed emission inventory and dispersion model to estimate ambient air pollution concentrations. Many exposure metrics can be derived by use of this bottom–up approach, and model outputs can be matched to the desired temporal and spatial resolution. As an example, this paper has discussed both long- and short-term (annual and 24-h average) pollutant concentrations estimated at the homes and schools of the NEXUS participants, a group of children with asthma living near major roads in Detroit; the short-term estimates are designed to match the daily health measures collected for the children.

NEXUS is developing yet more refined exposure measures that account for various rates of air exchange in different types of buildings, the time–activity patterns of study participants, and other factors affecting exposure to air pollutants. This exposure information is being used to investigate the association of traffic-related air pollutants with the measured health outcomes (and this information will be reported subsequently). These analyses will provide further evaluation of the utility of the new exposure metrics and the exposure modeling system.

The modeling system used in NEXUS provides new information on exposure to traffic-related air pollutants. For example, it shows the dramatic spatial and temporal variation of pollutant concentrations attributable to traffic-related emissions, information not captured by simpler exposure metrics, such as traffic intensity and distance to roads. The research findings can ultimately be used by environmental, transportation, and land use planners in developing policies and guidelines that maintain and enhance public health, for example, by determination of appropriate buffers and separation distances between highways and schools, hospitals, and housing and through the establishment of health-protective ambient and emission standards for traffic-related air pollutants.

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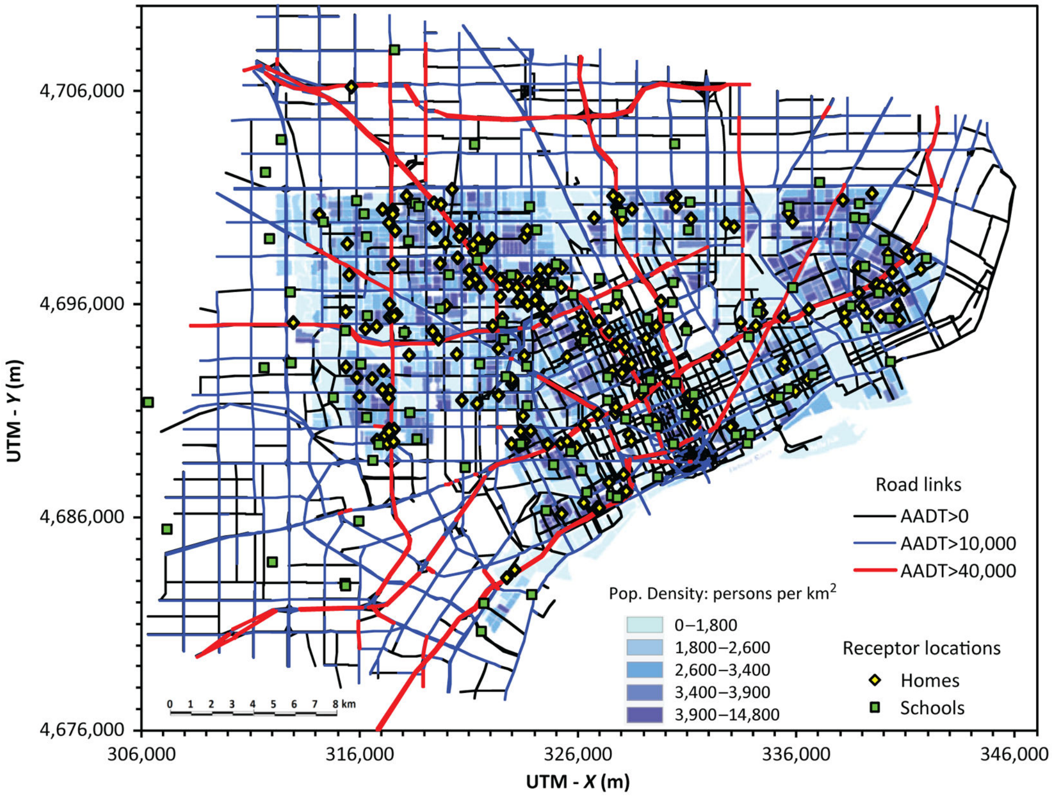

FIGURE 1.

Modeled road network in Detroit area containing 9,701 links and locations of 218 homes and 107 schools of participants in NEXUS (shaded area = city of Detroit; pop. = population; UTM = universal transverse Mercator units).

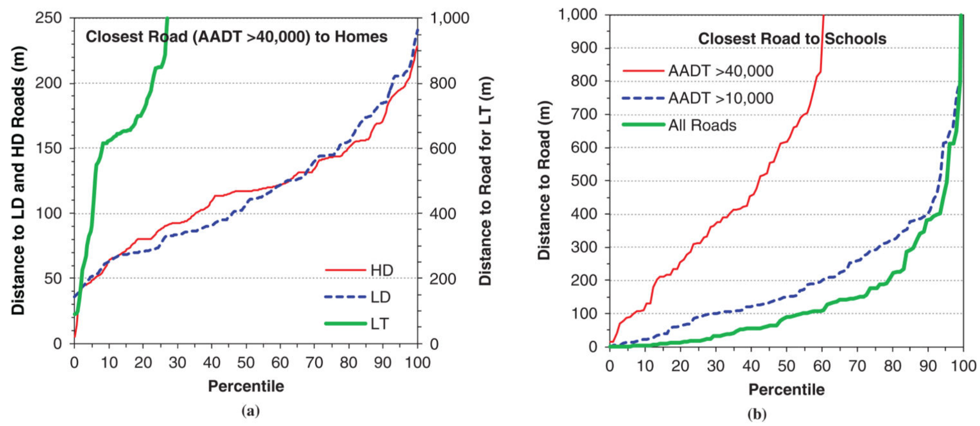

FIGURE 2.

Distribution of (*a*) 218 residence-to-road distances for road links with AADT >40,000, grouped by initial classification of the home as high diesel (HD), low diesel (LD), and low traffic (LT) (home classifications are preliminary and based on initial geographically coded estimates from ArcGIS), and (*b*) 107 school-to-road distances for road links with AADTs >40,000 or >10,000 and all roads.

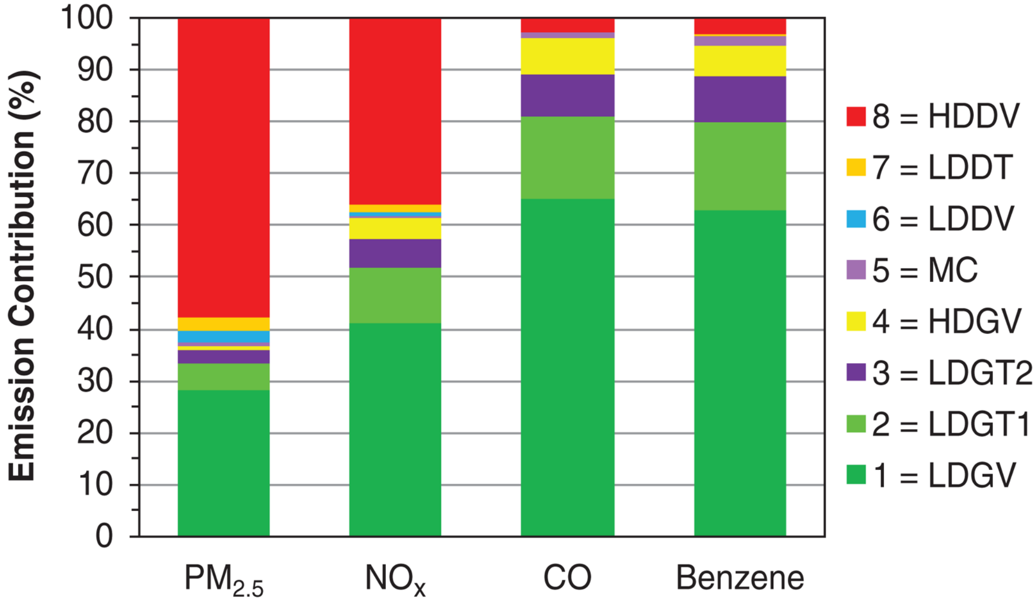

FIGURE 3.

Fraction of traffic emissions attributable by vehicle class (HDDV = heavy-duty diesel vehicles; LDDT = light-duty diesel trucks; LDDV = light-duty diesel vehicles; MC = motorcycles; HDGV = heavy-duty gasoline vehicles; LDGT2 = light-duty gasoline trucks type 2; LDGT1 = light-duty gasoline trucks type 1; LDGV = light-duty gasoline vehicles).

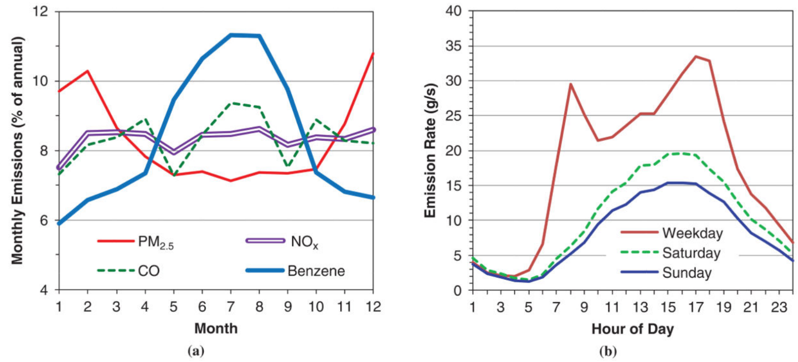

FIGURE 4.

Variation of emissions across Detroit road network: (*a*) monthly of four pollutants (numbers on *x*-axis refer to month, e.g., 1 = January, 2 = February) and (*b*) hourly of $PM_{2.5}$ emissions for weekdays, Saturdays, and Sundays, averaged across 2010 (numbers on *x*-axis refer to times on 24-h time system).

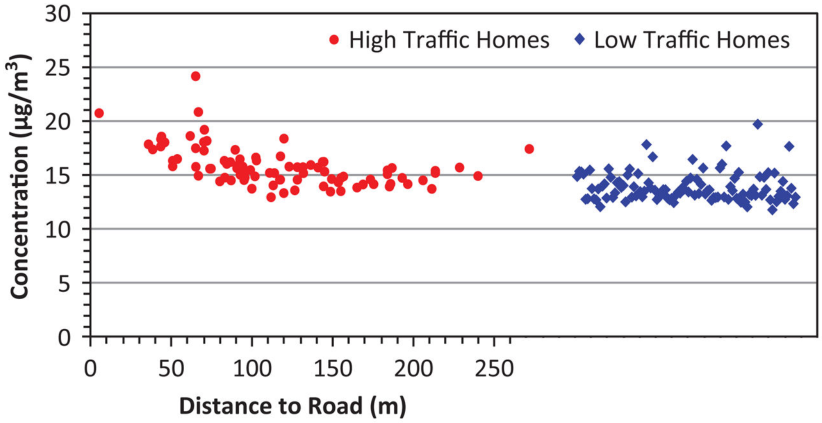

FIGURE 5.

Annual average $PM_{2.5}$ concentrations at high-traffic homes by distance to road and at low-traffic homes (unranked by distance) (concentrations including contributions from road, nonroad, area, point, and regional sources).

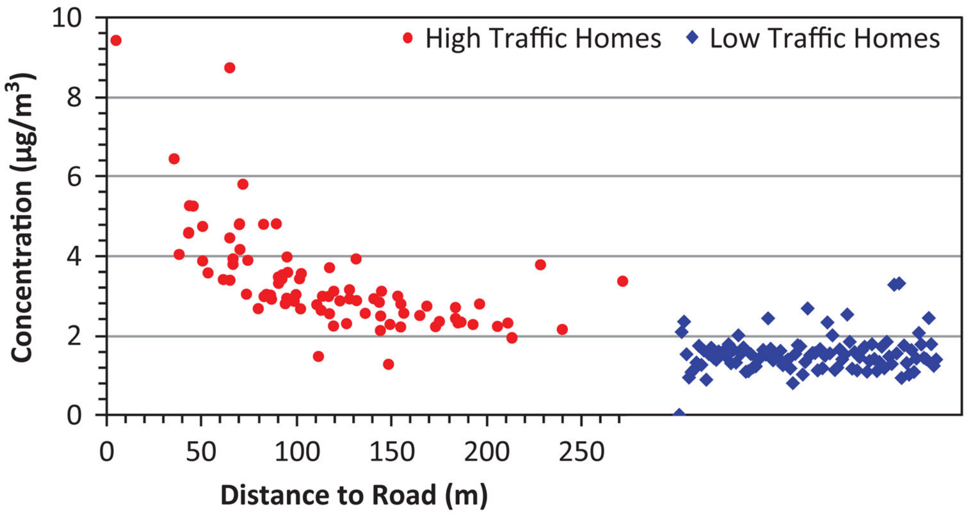

FIGURE 6.

Traffic-related annual average $PM_{2.5}$ concentrations at high-traffic homes by distance to road and at low-traffic homes (unranked by distance) (concentrations due only to roadway emissions in Detroit area).

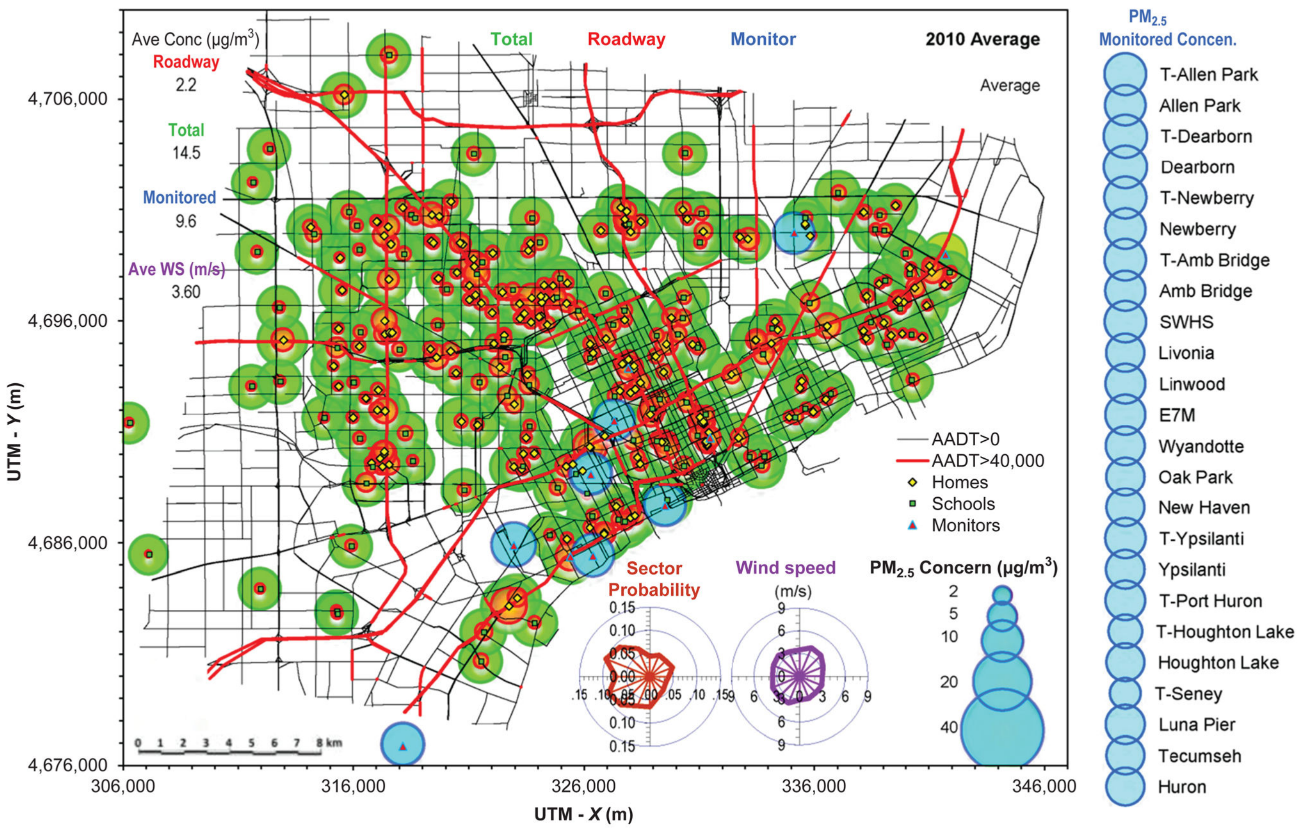

FIGURE 7.

Spatial pattern of annual average $PM_{2.5}$ concentrations at each home and school location, as well as concentrations monitored at fixed sites in the region (conc and concen = concentration; ave = average; WS = wind speed; SWHS = Southwest High School; E7M = East Seven Mile).

TABLE 1

Summary of Modeled Road Network in Detroit

		Segment		Road Length		Lane Length			VKT	
NFC	Road Type	Count (no.)	Fraction (%)	Total km	Fraction (%)	Total (km)	Fraction (%)	Average AADT (vph)	Total (KT * 1,000)	Fraction (%)
11	Interstate	967	10.0	453	14.6	1,195	13.0	30,370	11,887	34.3
12	Other freeway	368	3.8	155	5.0	403	4.4	32,729	4,216	12.2
14	Other principal arterial	2,952	30.4	894	28.8	3,388	36.9	19,189	10,958	31.6
16	Minor arterial	2,465	25.4	744	23.9	2,314	25.2	11,082	5,446	15.7
17	Major collector	2,786	28.7	775	24.9	1,739	18.9	4,629	2,139	6.2
19	Minor collector	52	0.5	16	0.5	31	0.3	2,818	20	0.1
90	Bridge	3	0.0	2	0.1	8	0.1	17,792	7	0.0
0	Other	108	1.1	71	2.3	102	1.1	0	0	0.0
Total		9,701	100.0	3,109	100.0	9,179	100.0	na	34,674	100.0

Note: Count is number of links. Length is link based and is provided in kilometers. Lane length is number of kilometers of traffic lanes. no. = number; vph = vehicles per hour; NFC = national function class using Michigan Department of Transportation designations; VKT = vehicle kilometers traveled per day; na = not applicable.

TABLE 2

Annual 2010 Total Emission Estimates for NEXUS Road Network Inventory

		$PM_{2.5}$		NO_x		CO		Benzene	
NFC	**Road Type**	**Tons/Year**	**Percentage**	**Tons/Year**	**Percentage**	**Tons/Year**	**Percentage**	**Tons/Year**	**Percentage**
11	Interstate	94.0	19.9	2,923	19.9	8,766	15.6	14.03	14.2
12	Other freeway	108.0	22.8	3,837	26.1	14,980	26.6	23.77	24.1
14	Other principal arterial	147.8	31.2	4,471	30.4	18,850	33.4	34.68	35.2
16	Minor arterial	74.1	15.6	2,234	15.2	9,442	16.8	17.40	17.6
17	Major collector	49.1	10.4	1,238	8.4	4,275	7.6	8.62	8.7
19	Minor collector	0.5	0.1	13	0.1	46	0.1	0.09	0.1
90	Bridge	0.0	0.0	0	0.0	0	0.0	0.00	0.0
0	Other	0.0	0.0	0	0.0	0	0.0	0.00	0.0
Total		473.40	100.0	14,715	100.0	56,358	100.0	98.59	100.0