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

Submission date: July 31, 2013. Word Count: 5317.

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ABSTRACT

Vehicular traffic is a major source of ambient air pollution in urban areas, and traffic-related air pollutants, including carbon monoxide, nitrogen oxides, particulate matter under 2.5 microns in diameter ($PM_{2.5}$) and diesel exhaust emissions, have been associated with a number of 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 regional) sources. While dispersion models have been widely used to evaluate air quality strategies and policies, and they are capable of representing the spatial and temporal variation in near-road environments, to date their use 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 (NEXUS) air pollution epidemiology study, which is examining 139 children with asthma or symptoms consistent with asthma, most of whom live near major roads in Detroit, Michigan. Air pollutant concentrations are estimated using a hybrid modeling framework that included detailed inventories of mobile and stationary sources at local and regional scales, RLINE, AERMOD and CMAQ dispersion models, and monitored observations of pollutant concentrations. The temporal and spatial variability in emissions and exposures is characterized over the 2.5-year study period and at over 300 home and school locations. The paper highlights issues in developing and understanding the significance of traffic-related exposures using dispersion models in urban scale exposure assessments and epidemiology studies.

INTRODUCTION

Background

Vehicles are a major source of air pollutants including nitrogen oxides (NO_x), carbon monoxide (CO), particulate matter ($PM_{2.5}$) 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, card1iovascular morbidity and mortality, adverse birth outcomes, and cognitive decline (*3*-*5*).

Vulnerable individuals who are particularly susceptible to adverse health impacts of traffic-related air pollutants due to personal, environmental and socio-economic 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 high traffic roads. Importantly, many individuals living in high traffic areas are non-White and low income (*6*), characteristics that are associated with susceptibility to the adverse effects of air pollution. In the US, an estimated 40 million people in the U.S. 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 regarding the health impacts of traffic-related air pollutants is the lack of information regarding pollutant exposure. Data provided by ambient air quality monitoring networks, 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 (currently unregulated), VOCs, NO, and polycyclic aromatic hydrocarbons (PAHs), 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 exposure due to traffic, mostly using proximity-, GIS- or interpolation-based methods. While often useful for health effects analyses, these methods result in surrogates or indicators of exposure that do not capture the temporal patterns (e.g., diurnal, weekday/weekend, and seasonal trends) demonstrated by traffic-related air pollution. Unfortunately, the use of personal exposure measurements, exposure biomarkers, or sufficiently localized indoor or ambient monitoring measurements is not feasible or practical given the number of subjects and duration of most health studies, as well as other limitations. Thus, there remains a need for methods and data to obtain more accurate temporally and spatially resolved information regarding exposures to traffic-related air pollutants. By reducing the spatial and temporal errors in exposure estimates for subjects in epidemiology, risk assessment and other types of studies (*17*-*19*), such information should significantly improve our 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, MI 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 exposure for the children that reflect the complex and often dramatic spatial and temporal patterns associated with traffic-related air pollutants. This paper summarizes the modeling system used to estimate ambient pollutant concentrations in NEXUS. It describes the development of a comprehensive mobile and stationary source inventory, 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 to statistical land use regression models that provide long-term averages. A broader discussion of the scope of NEXUS is provided elsewhere (*20*). The present paper is relevant to urban scale dispersion modeling of air pollutants, and it focuses on deriving 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 (CBPR) study designed to examine the relationship between near-roadway exposures to air pollutants and adverse respiratory health outcomes in a cohort of asthmatic children who live close to major roadways in Detroit, MI. A community-based steering committee was established, and the study design and protocols were developed with the committee's input and consent. Children, ages 6-14, with asthma or symptoms of asthma were recruited to participate in the study on the basis of the proximity of their home to the major roads in three traffic categories: (1) High traffic/high diesel (HD), defined as homes within 150 m of roads with >6,000 commercial vehicles/day (commercial annual average daily traffic; CAADT) and >90,000 total vehicles/day (annual average daily traffic; AADT); (2) High traffic/low diesel (LD), defined as homes within 150 m of roads with >90,000 AADT and <4,500 commercial vehicles/day; and (3) Low traffic (LT) 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 in the LT group were drawn from the same neighborhoods and school catchment areas as the HD and LD segments, but lived further from the high-traffic corridors. A total of 139 children were enrolled and participated in NEXUS with approximately equal distributions across the three traffic categories from September 2010 to December 2012. The study population was predominantly minority. (Non-Hispanic Blacks constituted 82% of the participants, Hispanics 8%, Non-Hispanic Whites 4%, and Other/Multiracial 6%.) Many households were poor, and a third of families reported annual household incomes below $15,000.

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

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 medication and health care use, diary reports of upper respiratory infection symptoms, fraction of exhaled nitric oxide (FeNO), urinary F2-isoprostanes, and nasal lavage samples. Additional information obtained included asthma control and symptoms associated with obstructive sleep apnea.

Hybrid dispersion modeling

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

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 (SEMCOG), 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 9701 links. The traffic activity by vehicle class was based on travel demand models with input by US EPA and the Michigan Department of Transportation. AADT values were allocated to 8 vehicle classes (e.g., heavy-duty diesel, light-duty gasoline) and adjusted to obtain hourly estimates using month-of-year, day-of-week, and hour-of-day temporal allocation factors on a link-specific basis. Where 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 using MOVES2010a as a function of average speed, ambient temperature, season, and road type.

Stationary sources such as stacks from manufacturing facilities were modeled using AERMOD, source locations, emission rates, and other information obtained from the latest (2008) official National Emissions Inventory (NEI). The regional background contribution was estimated using a combination of the Community Multiscale Air Quality (CMAQ) model and the Space/Time Ordinary Kriging (STOK) model. Two CMAQ model simulations were conducted: the baseline simulation represented all emissions in a broad region (covering the eastern US); the second removed all anthropogenic emissions in the NEXUS study domain. The ratios of concentrations predicted by CMAQ in these two simulations in the Detroit region along with AQS 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 participants' 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 homes and schools attended by the children in NEXUS, and the modeled road network. The city of Detroit covers 355 km^2; the road network (shown in the figure) 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.

T\he 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. Frequently, major roads were represented using multiple links at any particular location, i.e., interstate highways were represented using separate links for each direction and 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 (left) shows the distribution of home-to-road distances for the larger roads. Considering children in homes recruited near high traffic roads, the median distance was 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 distribution of home-to-road distances in high and low diesel categories was similar. Considering all 218 home locations, 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 (right) shows the distribution of school-to-road distances. The median distance to major roads was 617 m (road links with AADT > 40,000). However, a subset of schools was much closer, e.g., 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 very 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, e.g., HD, are likely to experience a range of traffic-related exposures and health impacts given the large range of distances represented in an exposure category, e.g., 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 is 473 tons/yr (product of annual average emission rates and link lengths, summed across all links). As a check, $PM_{2.5}$ emission results were compared to emission inventories compiled for Wayne County and southeast Michigan as part of the State Implementation Plan (SIP). In 2005, primary on-road $PM_{2.5}$ emissions in Wayne County (a slightly larger area than Detroit) were estimated to be 792 tons/yr (*27*). In the 7-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 ton yr^{-1}, which are projected to drop to 1,633 tons yr^{-1} in 2018 (*28*). This region is considerably larger than the NEXUS the study area, e.g., VMT in the study area is only 17% of that in the 7-county area. While these various estimates use different time periods, different regions, and different models (MOBILE6 and MOVES), the NEXUS emission estimates appear consistent and reasonable with respect to those in the SIP inventory.

A breakdown of the Detroit emission inventory is shown in Figure 3. This 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 gas 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, derived from the modeling system described previously.

Temporal variation of mobile emissions

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

Figure 4 (right) shows hour-to-hour pattern of $PM_{2.5}$ emissions. Weekdays show a bimodal pattern, reflecting morning and afternoon rush hour, while weekends show a single broader afternoon mode. $PM_{2.5}$ emissions are significantly reduced on weekends, especially on Sunday, reflecting lower volume of traffic and 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 non-diesel vehicles (mostly passenger cars). These diurnal trends reflect averaging of emissions in each of the eight vehicle classes, which can vary more dramatically by hour and day type. For example, compared to weekdays, heavy duty diesel truck volume is significantly reduced on weekends, light duty gasoline vehicle volume is somewhat reduced (the temporal patterns shifts dramatically to a single mode); and motorcycle volume is similar (reflecting an increase in recreational riding). Overall, this analysis indicates the importance of temporal variation at monthly, daily and hourly levels. Further, all road types (as defined by NFC) have essentially similar patterns (not shown).

Estimated $PM_{2.5}$ concentrations at homes and schools

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

Figure 5 shows annual average $PM_{2.5}$ levels at the high traffic homes (both high and low diesel), as red circles that are plotted against distance from the classifying road. The figure also shows $PM_{2.5}$ levels at the low traffic homes as blue diamonds; these homes are unranked by distance (plotted simply in the modeled sequence). The $PM_{2.5}$ estimates, which include contributions from road, area, point, and regional sources, range from 12 to 24 $\mu g/m^3$. Concentrations at the high traffic homes are elevated by an average of 2 $\mu g/m^3$ above levels 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, like the previous figure, but shows contributions due to only local (Detroit area) traffic emissions. In this case, $PM_{2.5}$ contributions from traffic ranged from 2 to 9 $\mu g/m^3$ at the high traffic homes, significantly elevated compared to 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 there is considerable scatter, produced by the joint effects of multiple roads and road geometry, varying traffic and emissions, and meteorology. Each elevated point on the figure 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 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, nonroad, area, point and regional contributions) is shown as a green circle. The 2010 average monitored concentration is shown as blue circles. The circle's area is proportional to the concentration, as indicated in the scale. The left circular plot shows the wind direction probability in 16 sectors. The right circular plot 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 TEOM (continuous) measurements; otherwise sites use FRM (filter-based) measurements. (Some sites have both TEOM and FRM monitors.)

Figure 7 indicates that $PM_{2.5}$ concentrations are higher near major roadways (red circles), particularly I-75, M-39 and M-10 corridors due to traffic. Homes and schools very near to major roads, crossings of major roads, or very near mid-sized 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, also reflected in the similar levels at most of the monitoring sites (blue circles), largely a result 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, time series of pollutant concentration maps are available online (posted at http://www.youtube.com/watch?v=5vZ0lG5T7wc). Movies showing concentrations for each day in 2010 and 2011 indicate very dramatic changes in concentrations.

CONCLUSIONS

This paper has highlighted several key elements in developing and understanding the significance of traffic-related exposures using 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 using 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-hour 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, MI; the short-term estimates are designed to match the daily health measures collected from the children. NEXUS is developing yet more refined exposure measures that account for varying air exchange rates of different types of buildings, time-activity-patterns of study participants, and other factors affecting exposure to air pollutants. This exposure information is being utilized to investigate the association of traffic-related air pollutants with the measured health outcomes (information to 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 regarding 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. Ultimately, the research findings can be used by environmental, transportation and land use planners in developing policies and guidelines that maintain and enhance public health, for example, by determining appropriate buffers and separation distances between highways and schools, hospitals and housing, and by establishing health protective ambient and emission standards for traffic-related air pollutants.

ACKNOWLEDGEMENTS

We thank Alan Vette, Gary Norris, Steve Perry, and Dave Heist at US EPA, Laprisha Berry Vaughn, Sonya Grant, Chris Godwin, Graciela Mentz, Xiaodan Ren, Irme Cuadros and other staff at the University of Michigan, and Brian Naess, Mohammad Omary, Kevin Talgo, Alejandro Valencia, Yasuyuki Akita and Marc Serre of the University of North Carolina at Chapel Hill. We are grateful to the NEXUS participants and their families who assisted us with the collection of these data. Community Action Against Asthma is a community-based participatory research partnership aimed at investigating the influence of environmental factors on childhood asthma. We acknowledge the contributions of all of the partners involved in this collaborative effort: Arab Community Center for Economic and Social Services; Community Health & Social Services Center; Detroit Department of Health and Wellness Promotion; Detroit Hispanic Development Corporation; Detroiters Working for Environmental Justice; Friends of Parkside; Latino Family Services; Southwest Detroit Environmental Vision; Warren/Conner Development Coalition; Institute for Population Health, and the University of Michigan Schools of Public Health and Medicine. The study was conducted under support of National Institute of Environmental Health Sciences, National Institutes of Health grants R01-ESO14566, R01-ESO14677, R01-ES016769, and P30ES017885. The US Environmental Protection Agency through its Office of Research and Development partially funded the research described here under cooperative agreement R834117 (University of Michigan). It has been subjected to Agency review and approved for publication.

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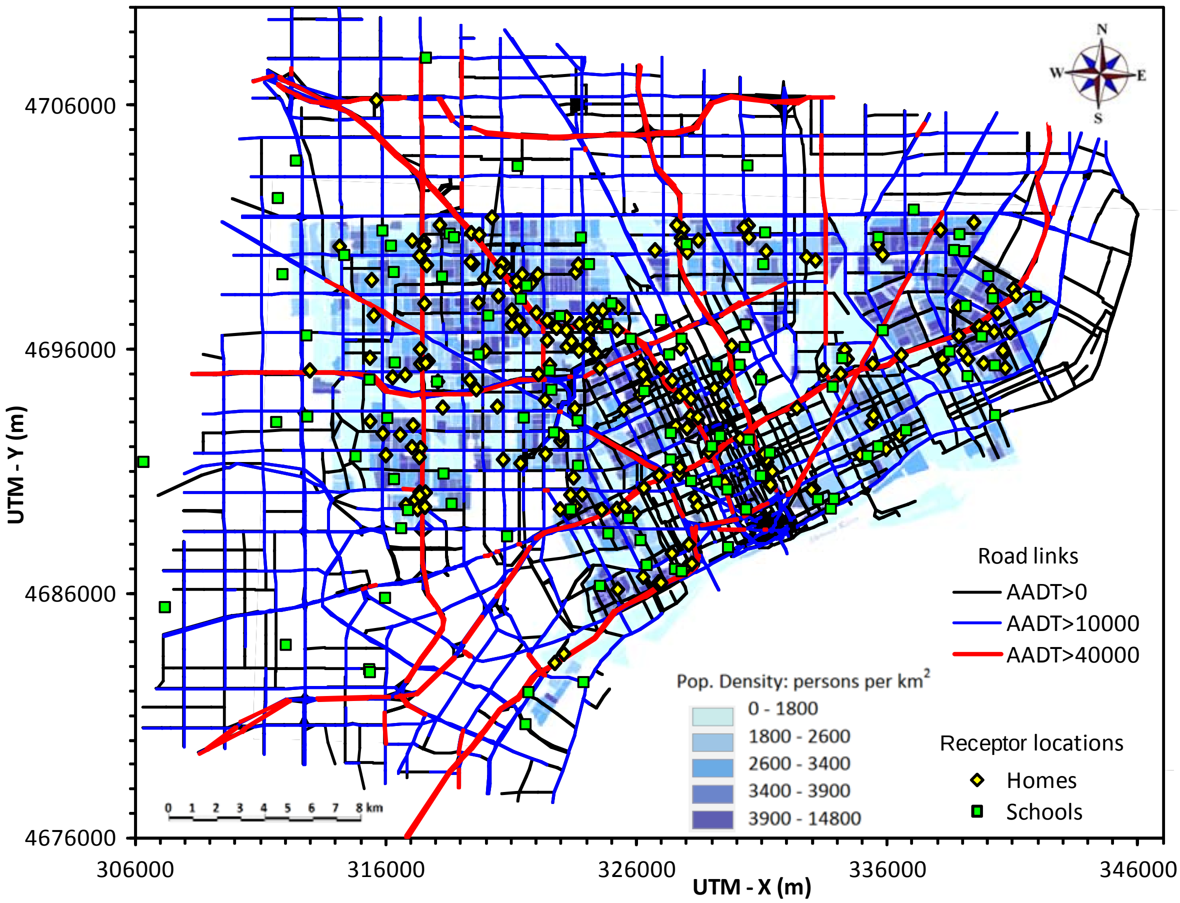
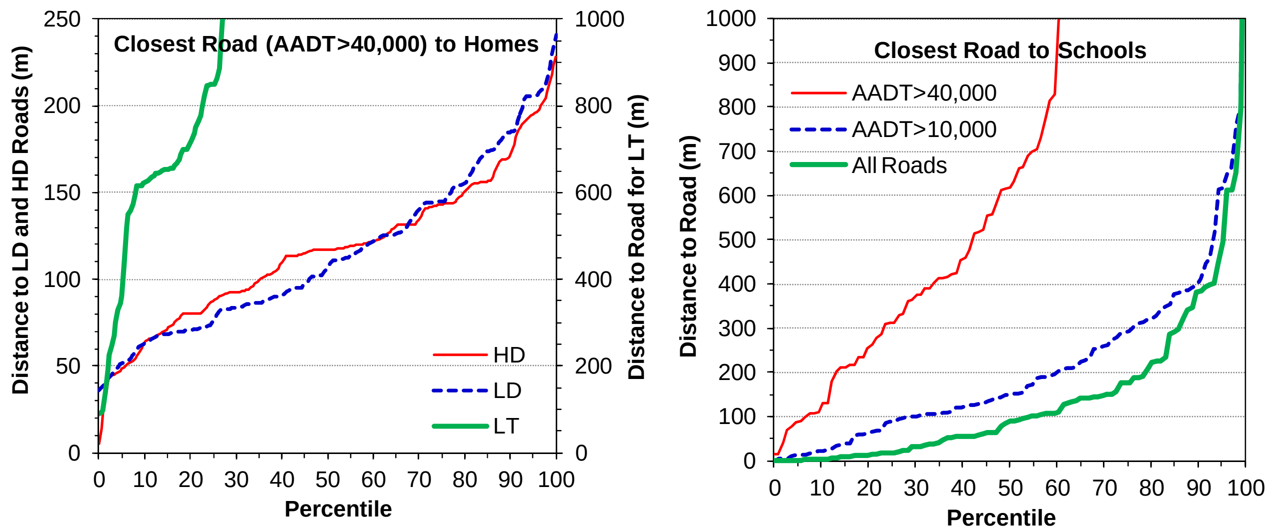


FIGURE 1 Map of modeled road network in Detroit area containing 9,701 links, and locations of 218 homes and 107 schools of participants in NEXUS. Shaded area defines city of Detroit.



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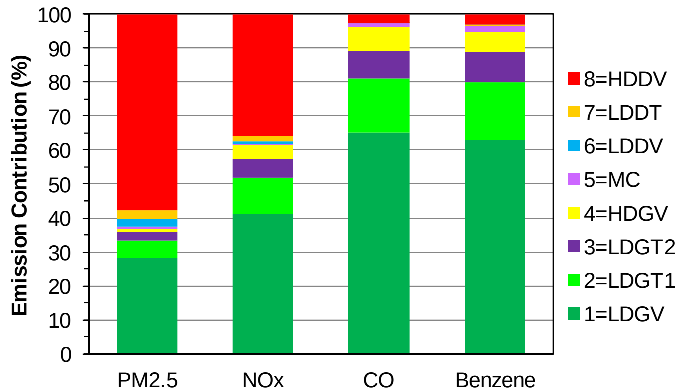

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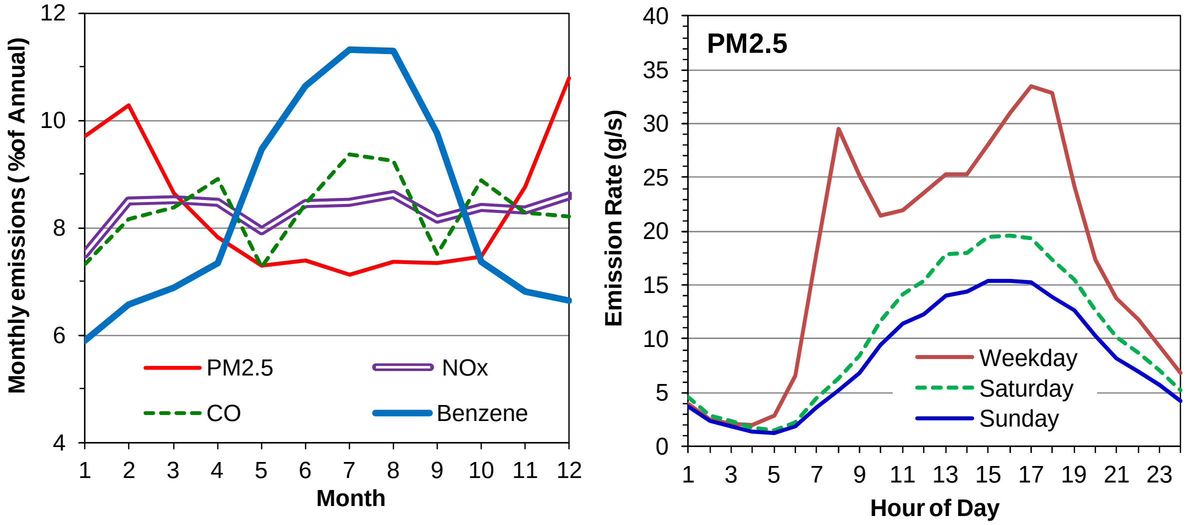
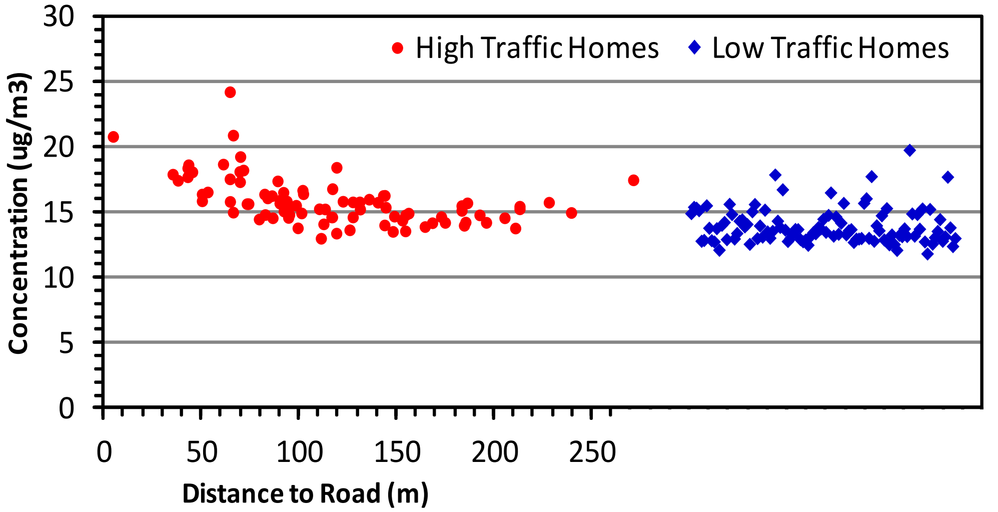


FIGURE 4. Left: Monthly variation of emissions of four pollutants across the Detroit road network (1=January ... 12 = December). Right: Hourly variation of $PM_{2.5}$ emissions across the Detroit road network for weekdays, Saturdays and Sundays, averaged across 2010 (1=1 AM ... 24 = 12 AM).



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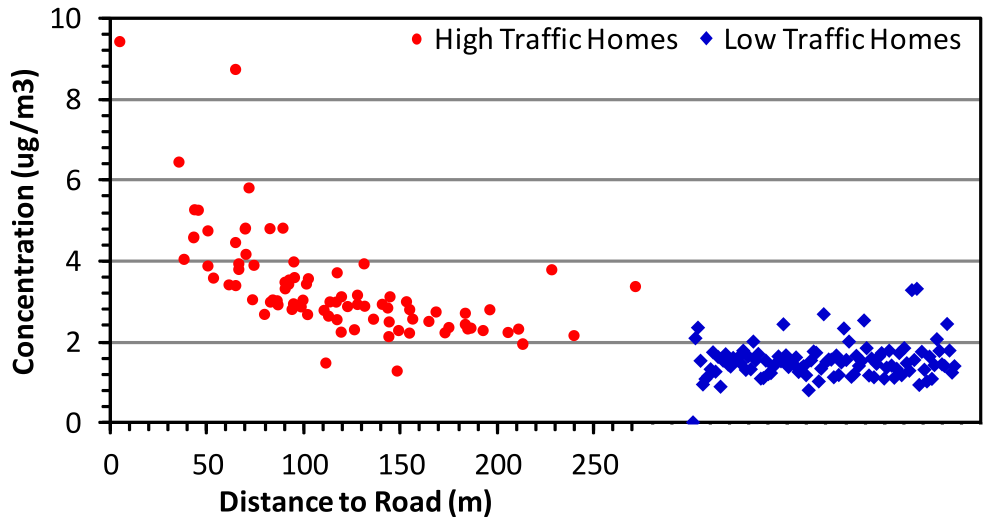

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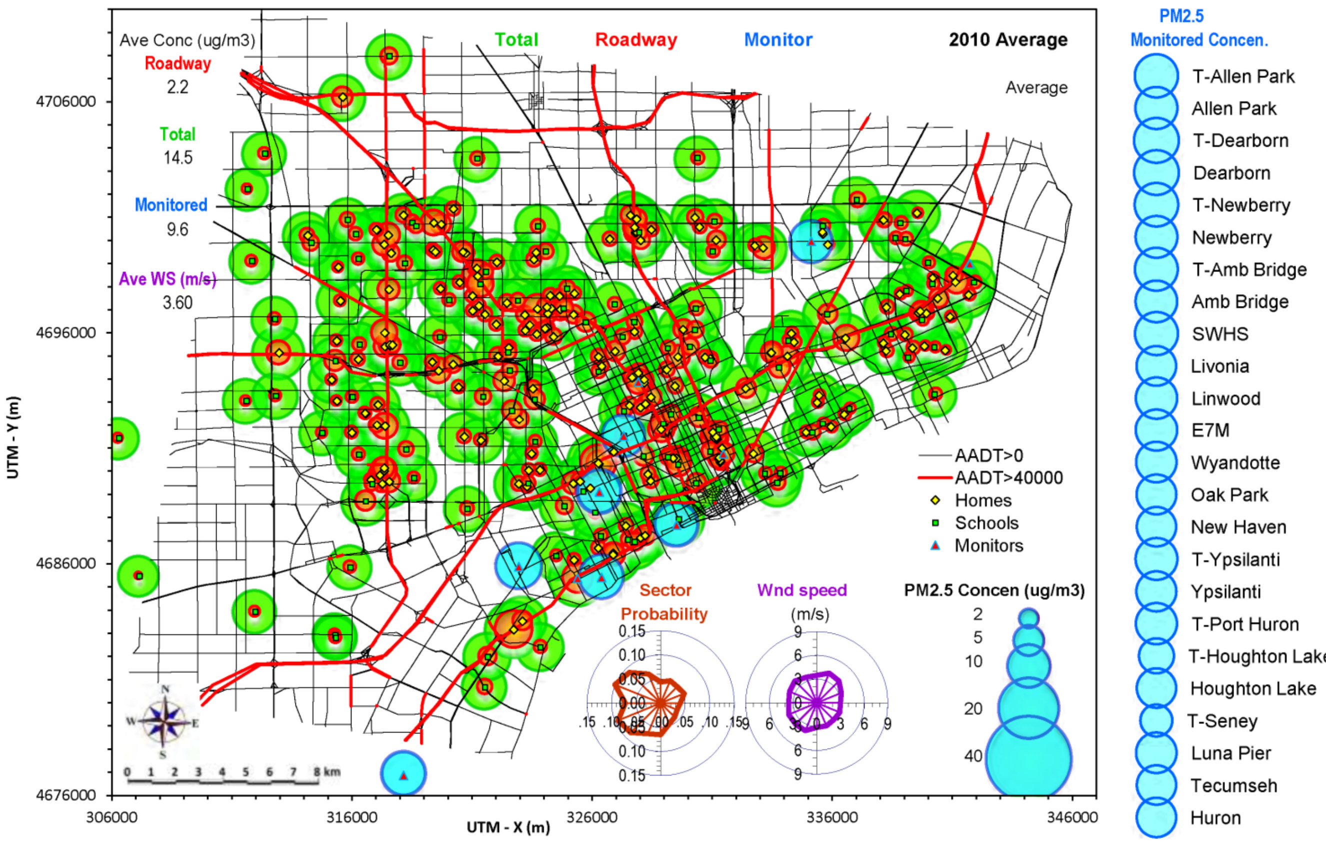

FIGURE 7. Spatial pattern of annual average $PM_{2.5}$ concentrations at each home and school location, as well as concentrations monitored at fixed sites in the region. (See text).

TABLE 1 Summary of modeled road network in Detroit. NFC is national function class using MDOT designations. Count is number of links. Length is link-based in km. Lane length is km of traffic lanes. AADT is average number of vehicles per day. VKT is vehicle kilometers traveled per day.

		Segment		Road Length		Lane Length		Average	VKT	
NFC	Road Type	Count (no.)	Fraction (%)	Total km	Fraction (%)	Total (km)	Fraction (%)	AADT (veh/hr)	Total (VMT*1000)	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	-	34,674	100.0

TABLE 2 Annual 2010 total emission estimates for the NEXUS road network inventory.

Mobile emissions/Current4/mission_generator_v17_year_9701links-multiple pollutants.

NFC	Road Type	PM2.5		NOx		CO		Benzene	
		(ton/year)	(%)	(ton/year)	(%)	(ton/year)	(%)	(ton/year)	(%)
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

List of captions/legends:

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