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The Near-Road Exposures and Effects of Urban Air Pollutants Study (NEXUS): Study design and methods

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Abstract

The Near-Road Exposures and Effects of Urban Air Pollutants Study (NEXUS) was designed to examine the relationship between near-roadway exposures to air pollutants and respiratory outcomes in a cohort of asthmatic children who live close to major roadways in Detroit, Michigan USA. From September 2010 to December 2012 a total of 139 children with asthma, ages 6–14, were enrolled in the study on the basis of the proximity of their home to major roadways that carried different amounts of diesel traffic. The goal of the study was to investigate the effects of traffic-associated exposures on adverse respiratory outcomes, biomolecular markers of inflammatory and oxidative stress, and how these exposures affect the frequency and severity of respiratory viral infections in a cohort of children with asthma. An integrated measurement and modeling approach was used to quantitatively estimate the contribution of traffic sources to near-roadway air pollution and evaluate predictive models for assessing the impact of near-roadway pollution on children's exposures. Two intensive field campaigns were conducted in Fall 2010 and Spring 2011 to measure a suite of air pollutants including $PM_{2.5}$ mass and composition, oxides of nitrogen (NO and NO_2), carbon monoxide, and black carbon indoors and outdoors of 25 participants' homes, at two area schools, and along a spatial transect adjacent to I-96, a major highway in Detroit. These data were used to evaluate and refine models to estimate air quality and exposures for each child on a daily basis for the health analyses. The study design and methods are

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described, and selected measurement results from the Fall 2010 field intensive are presented to illustrate the design and successful implementation of the study. These data provide evidence of roadway impacts and exposure variability between study participants that will be further explored for associations with the health measures.

Keywords

Traffic air pollution; Human exposure; Indoor air; Source–receptor relationships; Asthmatic children; Respiratory outcomes

1. Introduction

In recent years, a number of studies have shown that exposure to air pollutants in the immediate vicinity of large roadways is associated with a range of health effects, including adverse respiratory effects such as reduced lung function, decrements in lung growth and asthma (Anderson et al., 2011; Brauer et al., 2002; Brunekreef et al., 1997; Clark et al., 2010; Garshick et al., 2003; Gauderman et al., 2007; Gehring et al., 2002; HEI, 2009), and adverse cardiovascular (Adar et al., 2007; Maheswaran and Elliott, 2003; Peters et al., 2004) and reproductive effects (Brauer et al., 2008; Le et al., 2012; Ponce et al., 2005; Ritz et al., 2000; Wilhelm and Ritz, 2003). This has led to concerns about the potential for adverse health impacts on those who live, attend school, or work in locations near heavily traveled roads. The potential for significant near-road exposures has been raised in state and local decisions about transportation projects, including highways and freight terminals, and in decisions about the siting of schools. Data from the American Housing Survey, for example, indicate that over 40 million people in the United States live within 300 ft of a four-lane highway, railroad, or airport (U.S. Census, 2007). Clearly, exposure to air pollutants in the vicinity of major roadways is prevalent across the U.S. and elsewhere, particularly in urban areas where traffic and population density is highest. It is also a concern for people who live along corridors with significant trucking traffic and rail activities.

Emissions of traffic related air pollutants impact air quality and exposures near-roads, but it is not clear which pollutants or combination of pollutants elicit adverse health effects. Many studies have demonstrated spatial gradients of several traffic related air pollutants (e.g., NO_x, CO, elemental or black carbon, ultrafine and coarse particles, and mobile source air toxics) with elevated concentrations near roads that generally return to levels upwind of the roadway within a few hundred meters (Baldauf et al., 2008; Barzyk et al., 2009; Hagler et al., 2009; Hu et al., 2009; Kittelson et al., 2004a, b; Reponen et al., 2003; Thoma et al., 2008; Westerdahl et al., 2005; Zhou and Levy, 2007; Zhu et al., 2002, 2004, 2006). Most studies show small gradients of fine particulate matter ($PM_{2.5}$) concentrations downwind of roadways (~10% above background) whereas spatial gradients of ultrafine particles are as much as four times background and decrease to background after about 200 m (Karner et al., 2010; Reponen et al., 2003; Zhu et al., 2002). The extent of the spatial impacts of traffic related air pollutants is related to factors including the type of roadway, traffic volume and intensity, meteorology and background concentrations (Zhou and Levy, 2007; Zhu et al., 2004, 2006). The areal extent of traffic generated particles, especially ultra-fines, has been shown to vary diurnally and seasonally with the greatest spatial extent of the roadway plume typically occurring at night and during winter (Hu et al., 2009; Zhu et al., 2004, 2006). The composition of PM near roads is also altered by traffic emissions with higher concentrations of a number of metals including copper, iron, and antimony (Ntziachristos et al., 2007; Riediker et al., 2003) and certain organic compounds (Olson and McDow, 2009; Phuleria et al., 2007).

Previous epidemiological studies have largely relied on spatial approaches for exposure assessment to traffic including proximity-based, GIS-based and interpolation models (Jerrett et al., 2005). While each of these model types has been useful for health effect analyses, they are also limited because they do not explicitly allow for analysis of the temporal aspects (diurnal, weekday/weekend, etc.) of traffic-related air pollution on health effects. Rather, these approaches use surrogates or indicators of exposure that may reflect the magnitude of the intra-urban spatial variability due to traffic-related pollutants.

This paper describes the design and methods used in the Near-Road Exposures and Effects of Urban Air Pollutants Study (NEXUS). This community-based participatory research study was 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. NEXUS differs from previous studies in that an integrated measurement and modeling approach was utilized to characterize both the spatial and temporal variability of exposures to traffic-related air pollutants for the study cohort. Data are presented to provide evidence that the study design was appropriate and captured exposure variability between study participants. The exposure metrics, which are the focus of this paper, used a combination of monitoring data, air-quality modeling, receptor modeling and exposure modeling to produce several tiers of exposure estimates for use in subsequent health effect analyses.

2. Materials and methods

2.1. Study area and cohort

The NEXUS is being conducted in Detroit, Michigan. Recruitment of participants commenced in September, 2010, and most field work (other than follow-up to participants) will end in December, 2012. Children, ages 6–14, with persistent asthma were recruited to participate in the study from neighborhoods adjacent to the roadway segments as identified in Fig. 1. Children were recruited on the basis of the proximity of their home to the roadways according to three traffic categories:

1. High traffic/high diesel (HD): homes within 150 m of roads with >6000 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): homes within 150 m of roads with >90,000 AADT but <4500 commercial vehicles/day; and

3. Low traffic (LT): those at least 300 m from roads with >25,000 AADT.

Children in the LT group were drawn from the same neighborhoods and school catchment areas as the HD and LD segments, but live further from the high-traffic corridors thus minimizing possible confounding from unmeasured neighborhood-associated covariates. A total of 139 children were enrolled in NEXUS with approximately equal distributions across the three traffic categories.

2.2. Respiratory health assessment

The study focused on evaluating three domains of respiratory health effect potentially associated with exposures to near-road air pollutants: 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 of health measures and biomarkers relevant to pulmonary function were conducted for each child enrolled in NEXUS, including medication and health care use, diary reports of upper respiratory infection symptoms, fraction of exhaled nitric oxide (FeNO), urinary F2-isoprostanes, and nasal lavage. These assessments were performed during 14-day periods for each child in each season during the study period. Interviews with each child's caregiver were completed on a seasonal basis to collect additional information about the child's respiratory symptoms, health care utilization, medication usage, asthma control, missed school days, sleep quality, and other aspects.

2.3. Field sampling approach

Extensive air quality measurement data were collected during two intensive field sampling campaigns from September 25 to November 11, 2010 (Fall) and from March 28 to May 4, 2011 (Spring) in Detroit, MI. Fall and Spring are peak seasons for respiratory viruses. Table 1 summarizes the continuous and integrated measurement data that were collected at each location during and between the seasonal intensives, and the types of samplers and analytical methods used.

2.3.1. Residential monitoring—Traffic-related air pollutants were collected both inside and outside of a subset of 25 children's homes during the seasonal intensives. The subset of participants were selected for residential monitoring based on the traffic characteristics of nearby roadways, and included participants from each of the HD, LD and LT areas (Fig. 1). These measurements provided data for evaluating modeled estimates of concentrations and child-specific exposures of air pollutants.

Integrated measurements of $PM_{2.5}$, along with continuous measurements of BC, NO_x, CO and particle counts were collected simultaneously inside and outside of each home during the seasonal intensives (Table 1). These pollutants are commonly associated with mobile sources though they are not exclusively emitted by mobile sources. Air pollutant data were collected at up to four homes simultaneously for approximately 5-days and rotated to a different set of homes each week. Daily air exchange rate measurements were also collected for each home with indoor/outdoor monitoring to determine the home characteristics and operating conditions that influence the indoor infiltration of traffic-related air pollutants.

Asthma can be associated with triggers other than air pollution, such as mold. This important confounder may also sensitize an asthmatic to air pollution and contribute to asthma attacks. Floor dust samples were collected from the home of each NEXUS participant, and were analyzed for the presence of particular mold species for use as a metric in the analysis of health effects (Vesper et al., 2008).

2.3.2. Questionnaires and time–activity measurements—All NEXUS subjects completed questionnaires that provided data on building characteristics of the participant's home to estimate residential air exchange rates. The questionnaires also provided data to identify potential indoor sources of air pollutants (e.g., cooking, smoking). Daily time–activity diaries were collected for 7-days during each season for all NEXUS participants that indicated time spent indoors and outdoors at home and school, and in transit. In addition, a subset of participants wore GPS monitors and accelerometers for the same 7-day period as the time–activity diaries during each season to provide continuous location and physical activity level data.

2.3.3. Highway transect monitoring—Detailed measurements of the chemical composition of traffic-related pollutants in both the gas and particle phase were collected at multiple distances from a major highway in Detroit (I-96 site) to characterize the dispersion patterns of air pollutants adjacent to a heavily traveled highway (Fig. 1). The measurements collected during NEXUS at the I-96 site were complementary to a related study of near road mobile source air toxics (Henry et al., 2011; Kimbrough et al., 2008; U.S. EPA, 2011a). As shown in Table 1, NEXUS measurements were collected at sites located 10, 100, and 300 m north of I-96 (predominately downwind) and 100 m south of I-96 (predominately upwind). Continuous and sub-daily integrated measurements were utilized to capture impacts due to time-varying mobile source emissions and meteorology.

The majority of the measurements at the I-96 site during the NEXUS seasonal intensives were located at the site 100 m north of I-96, with selected monitoring at the other three locations. Sub-daily integrated PM samples for elemental and organic speciation were collected every other day during three sampling periods per day to separate the morning and evening peaks in commuting traffic. Two 12-hour samples of $PM_{2.5}$ and PM_{coarse} were collected using a dichotomous sampler for mass and composition analysis to compare with integrated and continuous measurements. Continuous measurements of $PM_{2.5}$ and PM_{coarse} mass were also made at the site 100 m north of I-96, along with continuous BC, particle counts and size distribution, NO_x and CO. Canister samples for volatile organic compounds (VOCs) were collected during the morning rush hour (6–10 am) every other day.

A limited set of measurements were collected during the months between intensives (Table 1) along with the companion air toxics study to provide longer term characterization of near-road source impacts.

2.3.4. School-based monitoring—Monitoring was conducted outdoors at two schools located near roadways during the NEXUS seasonal intensives (Table 1). Continuous measurements of BC, NO_x, CO and particle counts were collected at the schools throughout the seasonal intensives with the same equipment used for home-based measurements. The school-based monitoring also included many of the same integrated samplers used at the I-96 site 100 m downwind location to provide additional spatial characterization of traffic-related air pollutants across Detroit (Table 1). Sub-daily integrated PM samples for elemental and organic speciation were collected (3/day) as well as daily $PM_{2.5}$ and weekly PM_{coarse} samples.

2.4. Integrated measurement and modeling approach

A tiered approach was incorporated in the NEXUS design to assess traffic-related air pollutant exposures and their associations with observed health effects. The tiered exposure assessment approach uses a progression of data analysis as more complex data tiers (measured or modeled data) are generated, comparing each new data tier to the previous ones and, using available measurement data that is appropriate to evaluate the modeled exposure estimates. The following data “tiers” were included in the NEXUS design to examine the relative importance of different levels of complexity in exposure metrics for use in the health effects analyses: (1) ambient pollutant concentrations from existing monitoring sites and near-road data collected during the seasonal intensives; (2) GIS-based exposure indicators which incorporate data on proximity to major roadways, traffic data, land-use information and meteorology; (3) spatially and temporally refined modeled concentrations for each subject’s residence and school location; and (4) exposure estimates for each subject based on residential factors, modeled residential concentrations and time spent in different locations (home, school, near roadways).

Source–receptor modeling of both the continuous and integrated measurement data is used to quantitatively estimate the contribution of traffic sources (Duvall et al., 2012; Hammond et al., 2008; Henry et al., 2011; Olson et al., 2012). As illustrated in Fig. 2, air pollution dispersion models (AERMOD/AERLINE) are used to estimate near-road spatial gradients for traffic-related air pollutants at each of the children’s residences and schools across the study domain (Cook et al., 2008; Isakov et al., 2009). AERMOD (Cimorelli et al., 2005; Perry et al., 2005) simulates near-source impacts from stationary sources, whereas AERLINE (Venkatram et al., 2009) simulates near-road impacts from mobile sources. To estimate total air concentrations, the local scale AERMOD and AERLINE outputs are combined with an estimate of background concentrations obtained using a statistical approach based on ambient monitoring data (Ivy et al., 2008). The exposure model for individuals (EMI) is used to estimate residential air exchange rates, concentrations of traffic-related air pollutants inside each child’s home using the spatially and temporally refined dispersion model estimates, and personal exposures due to time spent in various microenvironments such as home, school and in-transit (Breen et al., 2010; Jerrett et al., 2005; U.S. EPA, 2011b). The microenvironment tracker (MicroTrac) model is used to estimate the time spent in the microenvironments from position and speed time-lines derived from personal GPS data loggers and marked building boundaries obtained from Google Earth (Breen et al., 2010). Model performance is evaluated using measurements from the seasonal intensives. The models are refined based on the evaluation, and applied to estimate exposures to traffic-related pollutants for each child for the duration of the health study. In addition to the AERMOD/AERLINE and EMI modeled estimates, metrics of exposure based on GIS data and questionnaire information are developed and compared to the more complex modeling approaches for assessing exposure to traffic-related pollution in the health analysis.

2.5. Toxicological impacts of near-road and industrial sources

In conjunction with the epidemiological analyses in vitro and in vivo toxicology analyses of PM provided comparative toxicity of local (industrial and mobile) and regional PM source impacts. Samples of coarse, fine and ultrafine particles were collected using a ChemVol (Demokritou et al., 2002) and a Sioutas sampler (Misra et al., 2002) on a wind directional basis. Two ChemVol sampling heads were used to collect separate samples when winds were upwind versus downwind of the roadway; the Sioutas sampler diverted the air stream from the sampling head under upwind conditions thus collecting particles only when winds were from the roadway. For in vitro analysis, human airway epithelial cells were exposed to extracted particles and levels of inflammatory markers were assessed. For in vivo analysis, mice with allergic asthma were instilled with extracts of collected coarse, fine, and ultrafine PM after which bronchoalveolar lavage was conducted and proinflammatory markers were assessed.

3. Results and discussion

The results shown in this paper focus on a preliminary assessment of the traffic-related exposure categories described in Section 2.1, and they demonstrate successful implementation of the NEXUS. Two types of measurement data are discussed in the following sections: 24-h integrated filter-based PM mass and BC data collected using Harvard impactors (Section 3.2), and continuous 5-min BC data collected using Magee AE51 portable aethalometers (Section 3.3). Both types of instruments were deployed at the subset of NEXUS participant homes with indoor and outdoor measurements, at the two school locations, and at the I-96 site. These data provide evidence of roadway impacts on the measured concentrations and indicate that variations in exposures between study participants are evident. In addition, the data provide ample information for model evaluation and comparison of the various exposure tiers in characterizing the exposure variability for the study population.

3.1. Data collection

Data collection rates were generally >90% for integrated samples and several of the continuous based measurements during both the Fall and Spring intensives (Table 2). The low (<75%) data collection rates for some of the continuous measurements were largely due to instrument malfunctions requiring substantial down-time for repair. In many cases the data collection rates improved substantially during the Spring intensive.

Integrated PM samples were analyzed for elemental composition and to determine source markers for near-roadway impacts, as well as impacts for local industrial emissions and regional transport of pollutants. Table 3 shows selected elements quantified by HR-ICPMS using two filter extraction procedures, deionized water and hot acid (Graney et al., 2004), for the 24-h $PM_{2.5}$ samples collected at the NEXUS homes, schools, and I-96 100 m downwind site during Fall 2010. The majority of the $PM_{2.5}$ samples were above detection limits using the water extraction procedure for elements often associated with brake and tire wear (Ba, Zn), resuspended road dust (Pb), industrial emissions (Cd, Pb, Fe, Mn), regional transport (S), and a few crustal elements typical of wind-blown soil (Sr, Ca). The hot acid extraction procedure increased the percent of samples above detection limits for other crustal elements found in soil (La, Ce, Si, Ti) as well as other elements typically associated with fuel-oil combustion (Ni, V).

Organic speciation of the 3/day high volume integrated $PM_{2.5}$ samples collected at the I-96 100 m downwind and school sites also provided source markers for combustion emissions associated with traffic. Filters were extracted for organic speciation using a mixture of hexane, methanol and dichloromethane (1:1:1) followed by GC–MS analysis (Olson and McDow, 2009). As shown in Table 4, nearly all samples collected during the rush hour and daytime periods were above detection limits for 15 organic PM species. Chrysenes, especially 3-methyl chrysene, are markers of diesel combustion and benzo(g,h,i)perylene is a marker of gasoline emissions.

3.2. Integrated $PM_{2.5}$ and black carbon

The 24-h integrated $PM_{2.5}$ mass data from the Fall 2010 field intensive illustrate the large temporal variability in air pollutant concentrations typical of this season in a midwestern US urban area such as Detroit. Fig. 3(a) displays the $PM_{2.5}$ mass concentrations at the two schools and the I-96 site where daily measurements were collected throughout the Fall 2010 study period. Each site is representative of one of the traffic exposure categories described in Section 2.1. The Maybury school is categorized as high diesel (HD) and located near the intersection of several interstate highways that experience elevated diesel traffic due to the border crossing between the US and Canada (Ambassador Bridge) located a few km to the southeast. This site is also located closest to large industrial point sources in Detroit to the southwest and northwest. Previous studies have shown the impact of local industrial sources and diesel traffic on air pollutant concentrations at this location (Hammond et al., 2008). The I-96 site is categorized as a low diesel site (LD) and located 100 m to the north of I-96 that typically has high vehicle traffic but lower commercial or diesel traffic. The Ludington school is categorized as a low traffic site (LT) as it is located in northwest Detroit and is farthest from interstates, major roadways and point sources.

Average $PM_{2.5}$ concentrations (± std. dev.) for the 7 week Fall 2010 field intensive were 9.4 (±6.0), 8.3 (±6.1) and 8.2 (±6.1)μg/m^3 at Maybury (n=43), I-96 (n=44), and Ludington (n=42), respectively. $PM_{2.5}$ mass concentrations in Detroit are dominated by regional components such as sulfate, nitrate and ammonium ion (Williams et al., 2009); therefore, a 15% higher average $PM_{2.5}$ concentration at the Maybury school compared to the other sites is a substantial increment. These averages reflect the general trend seen in Fig. 3(a) of similar $PM_{2.5}$ concentrations across all three sites on most days, with elevated $PM_{2.5}$ concentrations at the Maybury school site on several days indicative of local source contributions superimposed on a regional background signal. Fig. 3(b) highlights a one week period when $PM_{2.5}$ concentrations differed across the sites, and includes $PM_{2.5}$ concentrations measured out-doors at 3 participant’s homes during this week. Two of the participant’s homes, designated S-1 and S-2, were located in close proximity and to the south of I-94 (S-1<150 m; S-2<50 m), a major interstate roadway with high diesel traffic that runs southeast–northwest through Detroit (Fig. 1). The third participant’s home, designated N-1, was located on the opposite side (north side) of the interstate from the other two homes and farther away (>300 m). The monitoring at the participant's homes during this week further illustrates the high degree of spatial variability observed in $PM_{2.5}$ mass concentrations.

The corresponding 24-h $PM_{2.5}$ black carbon (BC) concentrations for the three sites during Fall 2010 are displayed in Fig. 3(c). The figure shows an even stronger trend of higher $PM_{2.5}$ BC at the Maybury school site on most days. Average $PM_{2.5}$ BC concentrations (± std. dev.) were 1.5 (±1.0), 1.2 (±0.9) and 1.0 (±0.7)$\mu g/m^3$ for Maybury, I-96, and Ludington, respectively. Fig. 3(d) shows further evidence of elevated BC concentrations outdoors at the homes near the HD roadway during the week with high spatial differences observed between the monitoring sites.

3.3. High-time resolution black carbon

Continuous high time resolution concentration data were also collected at all the NEXUS monitoring sites to determine the temporal variability in mobile source air pollutants due to diurnal patterns in traffic emissions and the influence of variations in meteorology (wind speed and wind direction). Fig. 4 provides an example of how receptor modeling of the high time resolution data was used to identify and quantify local source impacts such as major roadways. This figure is output from the sustained wind incidence method (SWIM) (Vedantham et al., 2012) applied to the 5-min BC data collected outdoors at each of two NEXUS participant's homes (S-1 and N-1). The two homes are located on opposite sides of I-94, approximately 15 km to the northeast of the center of Detroit (Fig. 1). Wind speed and wind direction data (5-min) measured at the I-96 site were input to SWIM along with the BC data from the homes to determine the contribution of BC concentrations from various wind directions. SWIM uses kernel smoothing to apportion air pollution concentrations into sectors defined by trends in the wind speed and direction. In Fig. 4, sectors were visually defined based on the grouping of impact areas associated with directionally varying BC concentrations.

During this week of the study, winds were primarily from the south-to-west with little to no wind from the east as shown by the wind rose in Fig. 4. The predominant winds likely transported BC from a mixture of urban sources in Detroit, including diesel truck emissions from I-94 and the Ambassador Bridge area. The darker shaded areas in Fig. 4 represent the directions from which higher concentrations of BC impacted the homes. Generally, the BC concentrations at home S-1 were higher than at N-1 with average concentrations of 420 and 268 ng/m^3, respectively. The SWIM results in Fig. 4 suggest this trend was dominated by the impact of I-94 on the spatial variation of BC concentrations. For both homes, approximately 45% of the mean BC concentration is explained by contributions from the SW. The contributions of BC from the N and W sectors for home S-1 results in higher average BC concentrations than at home N-1 during SW winds. This suggests an impact due to proximity from the roadway.

Traffic-related air pollutants were also measured inside NEXUS participant's homes to examine pollutant infiltration behavior and the levels the asthmatic children were exposed to while indoors at home. As an example, indoor and outdoor BC data are shown in Fig. 5 for homes S-1 and N-1 during a 12-h period beginning at midnight on Monday, Nov. 1, 2010.

These data show generally higher outdoor BC concentrations at home S-1 closer to and south of I-94, particularly during the typical morning rush hour period (~6–10 AM). Indoor BC concentrations are generally stable in the early AM and increase correspondingly with outdoor BC concentrations, however with fewer steep peaks. Both homes had relatively low air exchange rates (~0.7 h^{-1}) measured for this day. A large indoor source peak was observed in home S-1 during the late morning hours, illustrating the difficulty in determining the impact of traffic sources on indoor levels when indoor sources such as smoking and cooking can also contribute to levels of traffic-related pollutants such as BC in the residential environment.

3.4. Data analysis objectives and future work

The contribution of traffic sources to near-roadway air pollution will be estimated by analysis and modeling of measurement data collected during NEXUS. These results will be used to evaluate the predictive modeling tools for assessing the impact of near-roadway pollution on children's exposures and resulting respiratory effects. The primary data analyses objectives include: (1) evaluate traffic-related exposure categories using data collected outdoors at the children's homes, schools and the I-96 site; (2) investigate source impacts and pollutant relationships at various distances from I-96, a major highway in the study domain; (3) characterize pollutant variability due to traffic-related sources compared to industrial sources in the mixed-industrial airshed of Detroit, MI; and (4) compare toxicological outcomes for near-road and industrial sources. Achieving the full range of analysis objectives requires detailed chemical analysis of integrated samples, analyses of continuous air pollution and meteorology data, and extensive air quality dispersion and exposure modeling. The results of these analyses will be detailed in future publications.

The study was designed to evaluate contrasting traffic exposures and the preliminary review of data presented in this paper indicates the a priori identification of exposure categories was appropriate. Both $PM_{2.5}$ mass and BC concentrations exhibited spatial variations that are consistent with roadway and diesel impacts expected throughout the study domain. The contribution of traffic-related sources is being evaluated using receptor models and the comprehensive measurement data from the homes, schools and the I-96 spatial transect sites.

A key component of the integrated exposure–health analyses is the time-series nature of the study and the development of modeled exposure estimates. The children's respiratory outcomes are being followed over about a two-year period with twice-daily measures of lung function for approximately 2 weeks in each season; seasonal assessments of lung function, markers of inflammation and oxidative stress (e.g. FeNO), and nasal lavage; and the same measures as the seasonal health assessments with the reported onset of a respiratory virus. Modeled estimates of daily child-specific exposures are being used in the analyses of health effects. Statistical models to determine the associations between exposures and effects are adjusted for relevant covariates, e.g., age, gender, ethnicity/race, family socioeconomic status, baseline asthma severity, season, meteorological variables, presence of mold and smokers in the home, presence of gas heating or cooking in the home, ownership of pets, atopy, neighborhood characteristics (e.g., violence, concerns about safety), influenza vaccination status, and other potential cofactors.

The NEXUS provides exposure estimates of near-road air pollution for the analysis of respiratory outcomes in asthmatic children. The tiered exposure assessment produces exposure metrics of varying spatial and temporal detail to be evaluated against health effects data. An integrated monitoring and modeling approach provide insight into the appropriate level of exposure information necessary for epidemiology studies of respiratory health effects. These analyses should be useful for improving exposure assessments in future air pollution epidemiology studies, by illuminating the level of complexity and spatiotemporal resolution required in the exposure metrics to successfully link with health studies. The indoor and outdoor measurements allow us to determine house-specific infiltration rates for each pollutant, which are critical parameters needed to estimate exposures to air pollutants. The results developed for each traffic exposure group allow us to test for differences between the LD, HD and LT areas using analyses paired in time, which accounts for a substantial component of the temporal variability. In addition, the results from the toxicology assays provide additional insight into the spatial and seasonal differences in particles near-roads that may contribute to adverse respiratory outcomes in the traffic exposure groups. The overall results from the NEXUS will reduce uncertainty in health risk assessments related to ambient pollution and provide useful information for federal and state/local air quality management strategies.

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HIGHLIGHTS

- This study examined exposures to traffic related air pollutants and respiratory outcomes in asthmatic children.
- An integrated measurement and modeling approach was used to estimate exposures from traffic sources.
- Data were collected indoors and outdoors of participants' homes, at two schools, and adjacent to a major interstate.
- Data revealed evidence of roadway impacts and variability between participants.

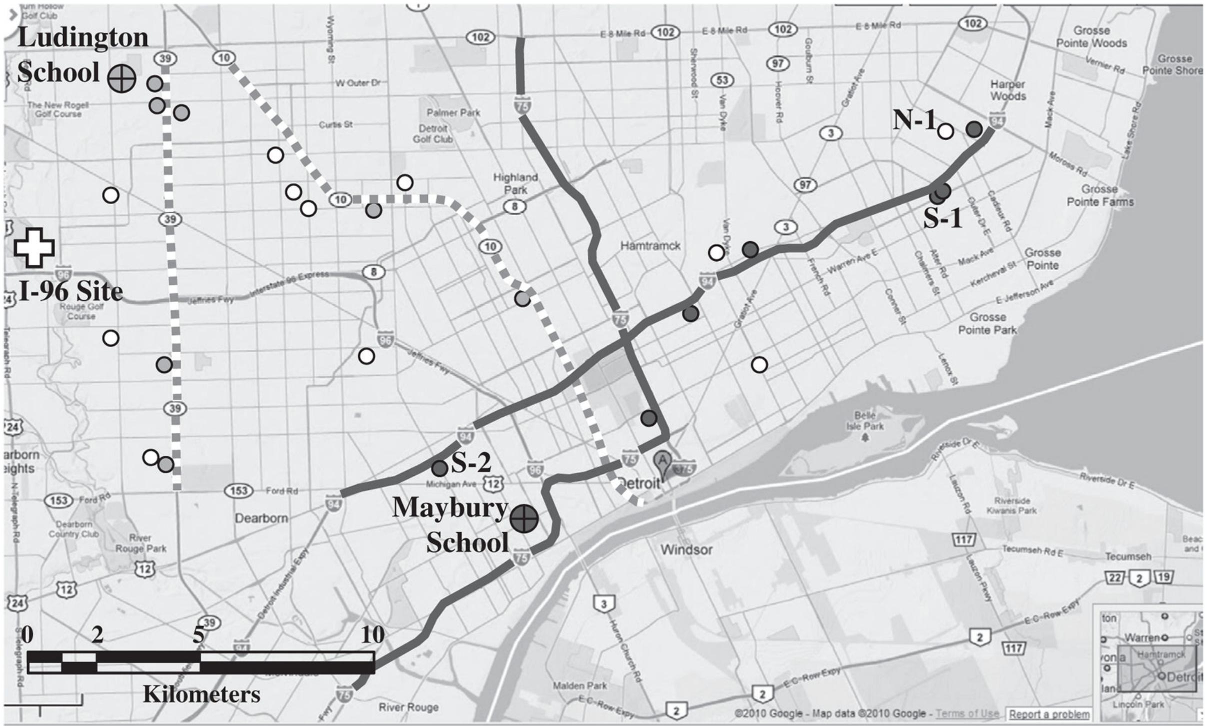

Fig. 1.

Location of roadway segments around which children were recruited to participate in NEXUS and the locations of homes, schools and the I-96 site where traffic-related air pollutants were measured (see Section 2.3). Data from homes N-1, S-1 and S-2 are discussed in Sections 3.2 and 3.3.

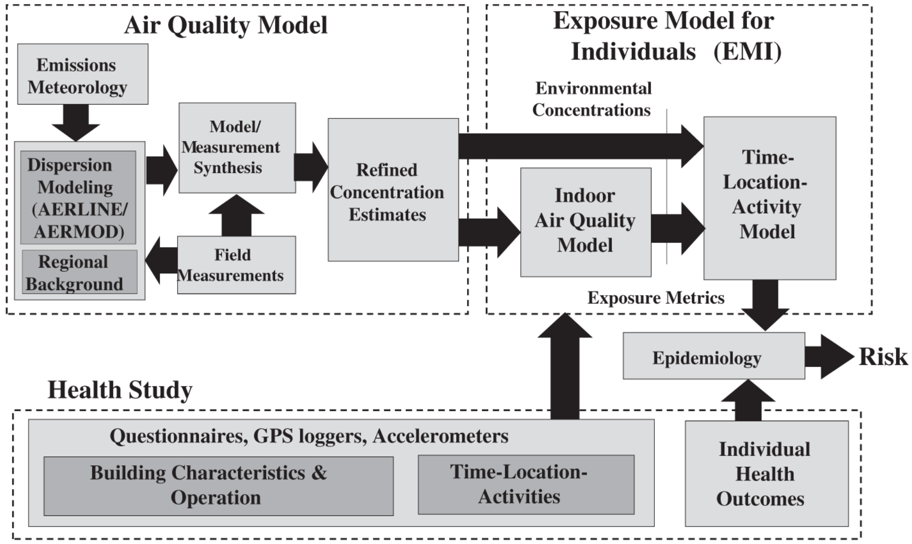

Fig. 2.

Linked air quality and exposure models and their data inputs to estimate exposure metrics for epidemiological analysis.

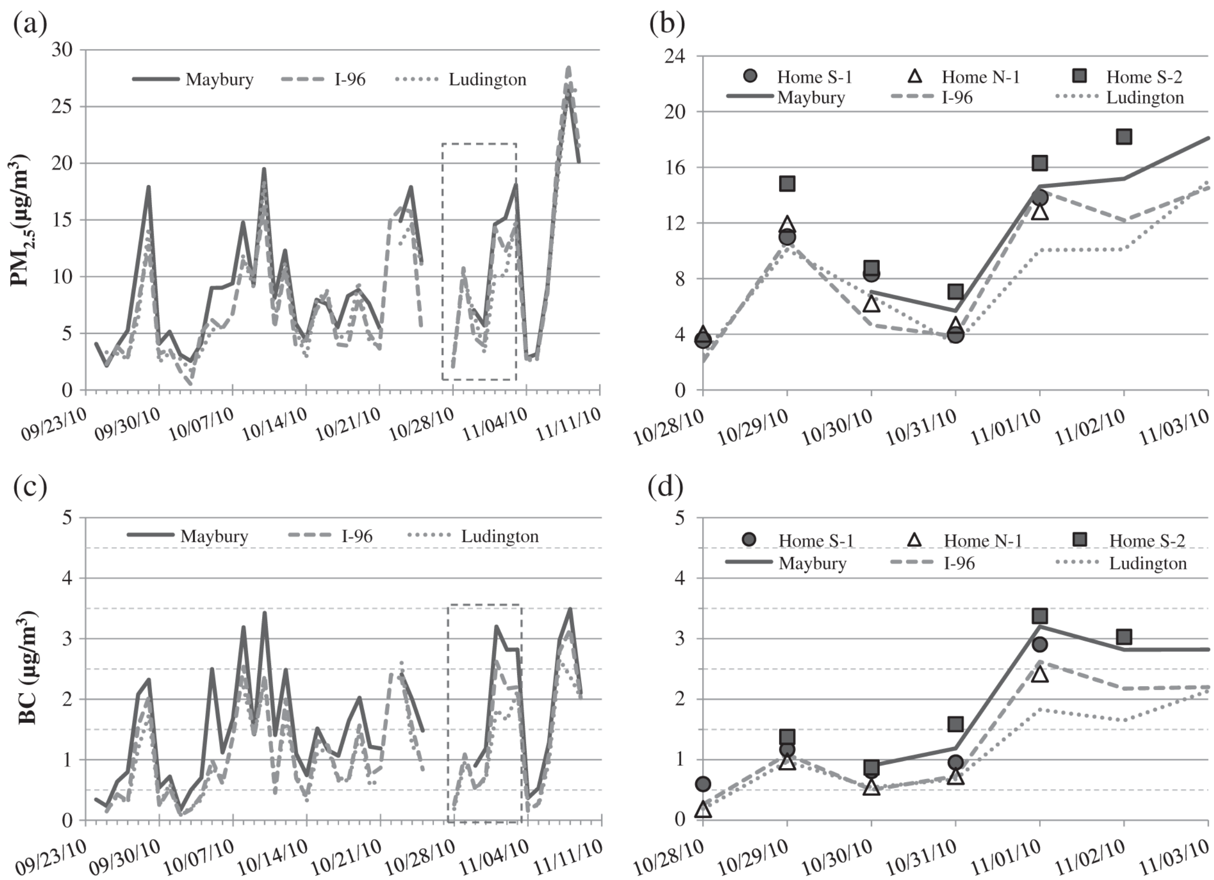

Fig. 3.

Daily integrated (24 h) $PM_{2.5}$ concentrations (μg/m^3) during the Fall 2010: (a) $PM_{2.5}$ mass with week 6 data highlighted in dashed box, (b) $PM_{2.5}$ mass for week 6 with data from two HD homes (S-1 and S-2) and one LT home (N-1), (c) $PM_{2.5}$ black carbon (BC) with week 6 data highlighted in dashed box, and (d) $PM_{2.5}$ BC for week 6 with data from homes S-1, S-2 and N-1.

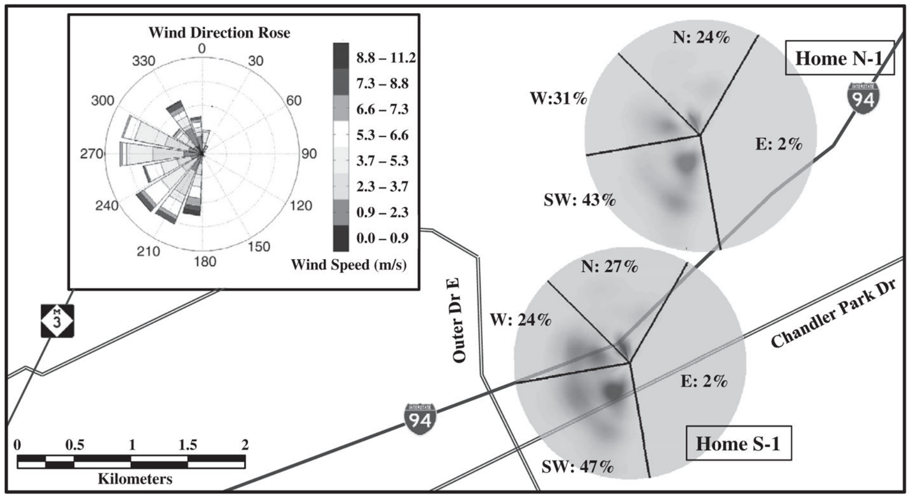

Fig. 4.

Example of sector apportionment and wind rose analysis of continuous black carbon concentrations measured simultaneously outdoors at two homes on different sides of I-94 for approx. 5 days during the Fall 2010. Detailed roadways have been removed to maintain participant confidentiality.

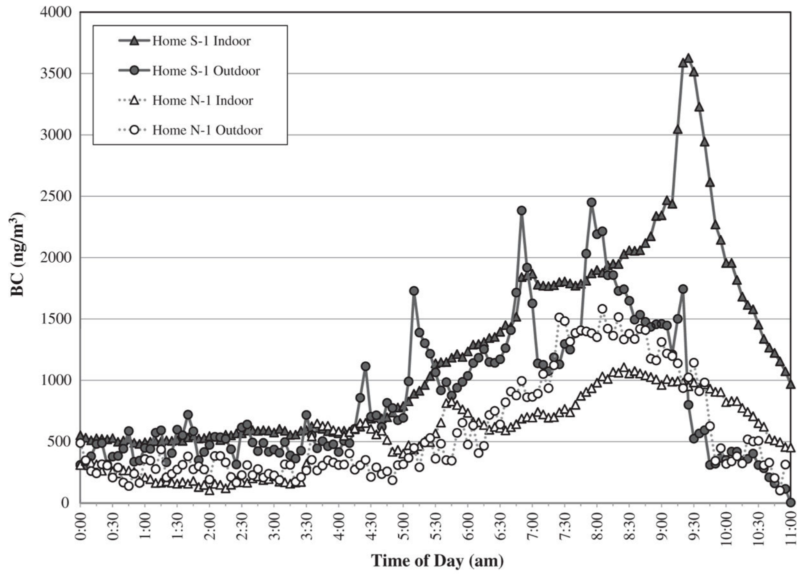

Fig. 5.
Early morning black carbon (BC) concentrations measured continuously indoors and outdoors of two homes.

Table 1

List of data measured, sampler, averaging time, analytical method and locations used during NEXUS.

Data measured	Sampler	Averaging time	Analytical method	Homes	Schools	I-96 sites (distance and direction from)			
						10 m N	100 m N	300 m N	100 m S
$PM_{2.5}$ mass, elements, black carbon (BC)	Harvard impactor (10 LPM)	24-h	GM, ED-XRF, ICP-MS, OT	I, O	X		X		
Black carbon	Magee micro aethalometer AE51	1-min	IR absorption	I, O	X		X		
Oxides of nitrogen ($NO+NO_2$)	2B technologies 400/401	1-min	UV absorption	I, O	X		X		
Carbon monoxide (CO)	Langan T15v	1-min	Electrochem.	I, O	X		X		
Particle number	TSI P-Trak	1-min	CPC	I, O	X[e]		X[e]		
PM_{coarse} elements	Leith–Wagner passive sampler	7-day	SEM		X	X	X	X	X
Air exchange rate	PFT source and receptor tubes	24-h	GC–MS	I					
Mold in floor dust	MiTest	5-min	qPCR	I					
Temperature and relative humidity	Onset U10-003	5-min	Thermocouple	I					
$PM_{2.5}$ organics	Tisch sampler (226 LPM)	3/day[c] (1-in-2 day)	GC–MS		X		X		X
$PM_{2.5}$ inorganics	Prototype sampler (113 LPM)	3/day[c] (1-in-2 day)	GM, ED-XRF and ICP-MS		X		X		
C_2 to C_{14} VOCs	Summa canisters	6–10 am (1-in-2 day)	GC–MS		X		X		
Wind speed and direction	RM Young sonic anemometer	10 Hz	Speed of sound		X	X	X	X	X
PM_{coarse}, $PM_{2.5}$, ultrafine PM elements and toxicology	Sioutas multi-slit impactor (400 LPM)	48-h (2-in-3 day)	ICP-MS, RT-PCR, ELISA		X[f]		X		
PM_{coarse}, $PM_{2.5}$, ultrafine composition[a]	DRUM sampler (10 LPM)	3-h	S-XRF		X[g]	X	X	X	X
PM_{coarse}, $PM_{2.5}$ mass and elements[b]	Dichot (16.7 LPM)	12-hr[d]	ED-XRF and ICP-MS			X	X	X	X
Black carbon (BC)[b]	Magee aethalometer AE22	5-min	IR absorption			X	X	X	X
Wind speed and direction[b]	RM Young wind vane	1-min	Cup and vane				X		
Carbon monoxide (CO)[b]	Thermo	1-min	NDIR photometry		X[h]	X	X	X	X
Oxides of nitrogen (NO and NO_2)[b]	Thermo	1-min	Chemiluminescence		X[h]	X	X	X	X
Sulfur dioxide (SO_2)[b]	Thermo	1-min	Fluorescence		X[h]	X	X	X	X
Ozone (O_3)	Thermo	1-min	UV Photometry				X		

Data measured	Sampler	Averaging time	Analytical method	Homes	Schools	I-96 sites (distance and direction from)			
						10 m N	100 m N	300 m N	100 m S
PM_{coarse}, $PM_{2.5}$, ultrafine PM elements and toxicology[b]	ChemVol (900 LPM)	48-h (2-in-3 day)	ICP-MS, RT-PCR, ELISA				X		
Particle size distribution	SMPS, APS	5-min	CPC and optical counter				X		
PM_{coarse} and $PM_{2.5}$ mass[b]	API 602+	1-h	β-gauge				X		
$PM_{2.5}$ mass	SHARP	1-min	Nephelometer and β-gauge				X		X

Abbreviations: PM = particulate matter; VOCs = volatile organic compounds; PFT = perfluorocarbon tracer; DRUM = Davis rotating drum unit for monitoring; SMPS = scanning mobility particle sizer; APS = aerosol particle sizer; API = ; SHARP = synchronized hybrid ambient real-time particle monitor; I = indoor; O = outdoor; GM = gravimetric mass; ED-XRF = energy dispersive X-ray fluorescence; S-XRF = synchrotron X-ray fluorescence; ICP-MS = inductively couple plasma-mass spectroscopy; OT = optical transmittance; IR = infrared; UV = ultraviolet; CPC = condensation particle counter; SEM = scanning electron microscopy; GC–MS = gas chromatography–mass spectroscopy; qPCR = quantitative real-time polymerase chain reaction; RT-PCR = reverse transcription polymerase chain reaction; ELISA = enzyme linked immunosorbent assay; NDIR = non-dispersive infrared; and CL = chemiluminescence. X indicates that the data were measured at the specified location.

[a] During Fall intensive only.

[b] Samplers also operated between intensives.

[c] 6–10 am, 10 am–4 pm and 4 pm–6 am.

[d] 24-h between intensives.

[e] During Spring intensive only.

[f] Maybury only.

[g] Indoor and outdoor at Maybury, outdoor at Ludington.

[h] Maybury during Spring intensive only.

Table 2

Sample and data capture rate (% of total possible sampling periods collected) of critical measurements for residential exposure assessments and traffic-related impacts (Fall 2010/ Spring 2011).

Data measured	Averaging time	Home indoor	Home outdoor	Maybury	Ludington	I-96 100 m N
Black carbon	1-min	91/95	91/89	88/87	88/90	98/92
Nitrogen oxides	1-min	58/84	82/82	84/88	71/93	92/98
Carbon monoxide	1-min	89/97	91/96	91/88	86/91	97/98
Particle number	1-min	52/77	58/96	[a]/73	[a]/76	[a]/50
Wind speed and direction	1-min	*a*	*a*	91/99	92/99	99/99
$PM_{2.5}$ mass	24-h	95/87	96/87	91/94	91/100	96/94
$PM_{2.5}$ organics	4–14 h	*a*	*a*	90/88	86/90	94/90
$PM_{2.5}$ inorganics	4–14 h	*a*	*a*	91/88	90/96	91/100
Air exchange rate	24-h	97/91	*a*	*a*	*a*	*a*

[a]Samples/data were not collected.

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Table 3

Percent of Fall 2010 $PM_{2.5}$ samples above the detection limit for elements measured using high resolution ICP-MS of two successive extractions (DI water and hot acid).

Element	DI water extraction[a]			Hot acid extraction[b]		
	Schools and I-96	Home indoor	Home Outdoor	Schools	Home and I-96 indoor	Home outdoor
Sr	81	97	95	84	98	98
Cd	59	61	72	60	67	79
Ba	99	100	100	99	100	100
La	1	2	52	46	64	77
Ce	1	17	51	51	58	75
Pb	98	100	100	98	100	100
Na	83	90	98	86	90	99
Al	70	79	84	100	100	100
Si	7	17	20	65	76	86
S	98	99	100	98	99	100
Ca	98	100	100	98	100	100
Ti	42	31	3	98	99	98
V	69	67	55	74	81	70
Cr	62	45	59	95	100	100
Mn	98	99	100	98	100	100
Fe	98	99	97	99	100	100
Ni	33	19	12	65	63	53
Cu	99	100	100	100	100	100
Zn	98	100	100	100	100	100
K	98	100	100	98	99	100
As	83	85	82	86	87	88
Se	23	23	7	32	32	18

[a] Sonication for 3-h in deionized (DI) water followed by 24-h extraction at room temperature.

[b] 2% HNO_3 and 1% HCl acids sonicated at 70 °C for 3 h followed by 9-d room temperature extraction (see Graney et al., 2004 for more details).

Table 4

Percent of $PM_{2.5}$ samples above the detection limit for organic compounds measured by GC–MS.

Compound	Morning rush hours (6–10 am)	Daytime (10 am–4 pm)
Chrysene	100	100
3-Methyl chrysene	98	96
Benzo[b]fluoranthene	100	100
Benzo[k]fluoranthene	100	98
Benzo[e]pyrene	100	100
Benzo[a]pyrene	100	98
Perylene	100	98
Norhopane	100	98
Hopane	100	98
Homohopane	100	98
Indeno[1,2,3-cd]pyrene	100	100
Benzo[g,h,i]perylene	100	100
Dibenz[a,h]anthracene	100	98
Picene	98	96
Coronene	100	98