Honing the Methods: Assessing Population Exposures to Motor Vehicle Exhaust

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All authors contributed to this review. All authors read and approved the final manuscript.

List of Abbreviations

ATMS - Advanced Traffic Management Systems

CEC - Commission for Environment Cooperation

CMEM - Comprehensive Modal Emissions Model

GIS - Geographic information system

SAVIAH - Small Area Variations in Air Pollution and Health

TEM - Transmission electron microscopy

TRAPCA - Traffic-Related Air Pollution on Childhood Asthma

VMT - Vehicle Miles Traveled

VOCs - Volatile Organic Compounds

Abstract

There is a growing need to better assess population exposures to motor vehicle exhaust in proximity to major roads and highways. This need is driven in part by emerging policy requirements for more targeted assessments of localized public health impacts related to road expansions and increasing commercial transportation. There is also growing momentum in the scientific community for improved methods in measuring local exposures as well as discerning which constituents of the vehicle exhaust mixture may exert greater public health risks for those who are exposed to a disproportionate share of roadway pollution. To help elucidate the current state-of-the-science in exposure assessments along major roadways and help inform decision makers of research needs and trends, we provide an overview of the emerging policy requirements, along with a conceptual framework for motor vehicle exhaust exposure assessments that can help inform policy decisions. We also identify the strengths and weaknesses of the individual elements within the conceptual framework for exposure assessments that may serve to guide future efforts to strengthen approaches for assessing public exposures to motor vehicle exhaust.

Background

There is an emerging need within the public health policy arena to gather greater information on local health effects associated with air pollution in communities immediately adjacent to major traffic arteries. This emphasis arises from a growing number of studies that have raised concerns regarding possible associations between proximity to high volume motor vehicle traffic (and its associated emissions) and increased risk of cardiovascular and respiratory diseases and cancer health endpoints [1–6], as well as studies describing the increased concentrations of air pollutants measured in close proximity to major roads. These studies have led government officials, health and environmental advocates, and researchers to consider the implications of these findings on the broader policy agenda.

As an example, California recently adopted a law requiring assessments of the public health impacts at proposed school sites attributable to high traffic roadways. The new law prohibits the approval of school sites within 500 feet of the edge of the closest traffic lane of a freeway or other busy traffic corridor unless the school district determines that air quality levels at the proposed site do not pose either a significant short-term or long-term risk to pupils [7].

In many metropolitan areas, residents living close to major roadways are often minority or low income populations, raising concerns of environmental justice and the role of air pollution and socioeconomic conditions on health [8, 9]. These population groups may be exposed to other health risks in the environment and in occupational settings, have poor nutritional status and limited access to health care, or have a higher prevalence of some underlying diseases relevant to air pollution health effects. Factors such as these may act as effect modifiers to air pollution exposures from proximity to major traffic roadways, thus increasing the potential health effects.

Diesel emissions are a significant contributor to mobile source emissions in North America and they dominate trade-related emissions. In 1998, California listed diesel particulate emissions as a toxic air contaminant in recognition of its potential to cause cancer [10] and in 2002 the US Environmental Protection Agency declared diesel emissions a likely human carcinogen [11]. Diesel exhaust therefore raises concerns over whether communities in close proximity to major trade routes and congested border crossings are shouldering a disproportionate burden of the health risks associated with increased trade-related transportation. Cities with busy border crossings are receiving particular attention due to heavy truck traffic, long lines of diesel trucks, and long idling times [12–14].

The increasing pressures of urban sprawl are likely to continue the expansion of high traffic roadways and a concomitant increase in vehicle miles traveled (VMT), placing continued emphasis on health concerns related to population exposures to traffic exhaust [8]. The policy of promoting the infilling of residential housing in urban central core areas, while beneficial for the economic revitalization of these areas and reducing urban sprawl and VMT, could also increase the population potentially exposed to high levels of motor vehicle emissions, especially from heavy-duty vehicles.

In light of the emerging need to better understand local health impacts of vehicle exhaust, the Commission for Environmental Cooperation (CEC) has undertaken a review of methods to assess population exposures along major traffic arteries. The federal governments of Canada, Mexico and the United States created the CEC in 1993 under an environmental side agreement to the North American Free Trade Agreement with an objective to "promote sustainable development based on cooperation and mutually supportive environmental and economic policies" [15].

To frame the issues and assess the current state of the science, the CEC sponsored a two-day workshop in September 2003 in Montreal, Canada, on "Methodologies to Assess Vehicle Exhaust Exposure." A panel of experts from government, academia, and private sector consulting in Canada, Mexico and the United States attended the workshop to discuss approaches and elements of various approaches for assessing the public's exposure to vehicle exhaust. This article is a reflection of the knowledge and understanding that was shared at the workshop and provides a review of the methodologies for assessing population exposures to motor vehicle exhaust along major transportation corridors.

This review focuses on the functional elements of methods to assess population exposures. There are a number of other external factors, such as socioeconomic status, behavioral habits, and pre-existing health conditions, which can affect health outcomes from exposures to vehicle exhaust. These are recognized but not discussed at length here, and they are the subject of other reviews (see [9] and references therein).

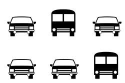
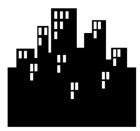
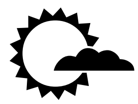
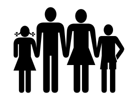
Conceptual Framework

In order to help provide a path forward in developing local population exposure assessments to help meet emerging policy needs, we offer a conceptual framework for understanding the process of exposure assessment, while at the same time attempting to convey the many challenges involved in performing such an analysis. After we present this framework, we will describe some specific tools and techniques that can help estimate population exposures to motor vehicle pollution in proximity to major traffic corridors.

In general, there are two reasons for conducting an exposure assessment: 1) as part of epidemiological studies linking observations of respiratory disease, cancer, and other health endpoints with the causes of illness; and 2) for environmental risk assessments in evaluating and quantifying the risks to a population that stem from a given source of pollution. The objective, whether an epidemiological study or a risk assessment, and the magnitude of available resources will influence the choice and rigor of the methodology employed for assessing exposures.

Our conceptual framework, summarized in **Figure 1**, begins with the emissions generated by an individual vehicle (Factor 1). A host of factors are known to influence an individual vehicle's emissions performance, such as the age of the vehicle, the fuel burned, the condition and performance of the vehicle's pollution control systems, engine load, driving cycle, and other factors. Laboratory testing attempts to capture these factors by simulating typical drive cycles on a chassis or engine dynamometer for tailpipe emissions. Evaporative, running and refueling losses can also be evaluated in laboratory settings, but the methods are often difficult and cumbersome and not very representative of real-world conditions. Alternatively, emissions may be measured in real-world situations by fast-response monitoring of individual vehicles while in use [16] or by on-road emissions measurement systems [17].

Figure 1. Conceptual Framework for Assessing Population Exposures to Motor Vehicle Exhaust. [A host of factors influence population exposures to motor vehicle air pollution and their associated adverse health outcomes. Our conceptual framework summarizes the key factors influencing the degree of exposure from the source of emissions (motor vehicles) to the receptor population.]

Emissions		Dispersion & Transformation			Exposure	Health Outcomes
Factor 1	**Factor 2**	**Factor 3**	**Factor 4**		**Factor 5**	**Factor 6**
						
Individual vehicle emissions are influenced by a variety of factors: Vehicle load Vehicle temperature (i.e., cold starts) Maintenance Fuel characteristics Pollution control systems Tampering Speed	Collectively, vehicle traffic emissions in a given location will depend on the: Number of miles traveled by vehicles in use The types and ages of vehicles on the road Road grade Congestion Traffic signals	Roadway features influence pollution transport and dispersion: Street canyons Sound barriers Tunnels Wind breaks Topography, such as valleys	Atmospheric transformation and decay will influence the spatial and temporal concentrations of pollution: Sunlight Temperature Humidity Wind speed and direction Mixing height The mix of chemicals in the atmosphere and their chemical reactions Deposition	inhaled concentration	The level of exposure will depend on the activity patterns of the individual and the time spent in different microenvironments: People are using different types of transportation and moving between different cities, within cities, and between work, home, school, etc. Within a vehicle and other micro-environments, pollutants can concentrate at higher than ambient levels	Personal factors will influence whether an adverse health outcome results from pollutant exposure: Socioeconomic position Behavioral habits (e.g., smoking, nutrition) Pre-existing conditions and illnesses Genetic susceptibility Age

Vehicle traffic emissions (Factor 2) reflect the collective performance of hundreds or thousands of vehicles traveling a given roadway under specific driving conditions (e.g., congestion). Emission factor models, like the US Environmental Protection Agency's MOBILE model, are designed to estimate motor vehicle emissions based on a myriad of inputs and assumptions such as fleet characterization, vehicle miles traveled, vehicle starts and stops, driving speeds, the deterioration rates of pollution control systems, and other factors. Real-world monitoring such as remote sensing campaigns, tunnel studies, or fuel-based emissions inventories [18, 19] are alternative approaches that can be used to estimate emissions. Each of these alternative methods also has limitations and uncertainties that should be considered in developing a mobile source inventory.

For some applications, however, the emission factors generated by the MOBILE model may not provide the detailed characteristics required for a smaller scale, such as a 2 km stretch of road. However, the latest version, MOBILE6, includes emission factors specific to different roadway types and congestion levels. EPA is also developing its next generation mobile source emissions model, MOVES, which estimates emissions based on modes of vehicle operation. MOVES will allow for the calculation of emission factors at a range of geospatial scales. In addition to these efforts, other microscale emission factor models have been developed [20, 21].

Vehicle count by type of vehicle can also be logged and then used as model input. The Georgia Tech Research Partnership has been developing the MEASURE model, a research-grade motor vehicle emissions model within a geographic information system (GIS) framework [22]. The GIS framework of the model allows the linkage of typical travel demand model outputs, simulation model outputs, or monitored Advanced Traffic Management Systems (ATMS) traffic volume estimates. The MEASURE model contains several "modal approaches" to estimate emissions as a function of vehicle fleet technology and vehicle operating "mode," representing a range of vehicle operating conditions such as cruise, acceleration, deceleration, idle, and power demands leading to fuel enrichment. Also recently developed is the Comprehensive Modal Emissions Model (CMEM), jointly developed by the University of California-Riverside and the University of Michigan. CMEM is a modal model that estimates fuel consumption and gaseous pollutant emissions based on physical principles, and is calibrated with a data set of 300 vehicles driven on a variety of driving cycles. CMEM has recently been paired with TRANSIMS, a model developed by Los Alamos National Laboratory that simulates the travel behaviors of an urban population as cellular automata [23]. TRANSIMS determines vehicle activities, and this output provides necessary input data for CMEM-based emission calculations, which are expressed in real-time. One has to keep in mind, however, that these models require significant input data.

Traffic count data can be useful for better estimating vehicle emissions along specific roadways, but there can be problems in finding data for a relatively recent time period, or the data may be limited to short time periods (e.g., 12 hours), raising concerns regarding their applicability for long-term exposure assessments.

Once tailpipe or evaporative emissions enter the atmosphere, geographic features (Factor 3) as well as local weather and atmospheric conditions (Factor 4) will influence pollution chemistry, transport and dispersion. Researchers sometimes use dispersion modeling to predict the fate and transport of airborne pollutants by accounting for these variables.

It is important to note the varying characteristics of the urban pollution mix. The spatial patterns exhibited by ambient air pollutants will vary depending on the compounds in question. Secondary pollutants, which form in the atmosphere from precursor pollutants, may be more evenly distributed across a city. An important exception is ozone in the immediate vicinity of major roadways where it will exhibit lower concentrations relative to a more even distribution further away. The local roadway ozone deficit is due to the molecule's rapid destruction by short-lived nitric oxide (NO) present in fresh vehicle emissions. Under the assumption of an even distribution, spatially averaged ambient concentrations of secondary pollutants may provide a reasonably accurate estimate of individual exposures to these types of pollutants. Primary pollutants, which are directly emitted by local sources, such as elemental carbon, carbon monoxide (CO), sulfur dioxide (SO_2), nitric oxide, and to a lesser extent nitrogen dioxide (NO_2), from motor vehicles, will show wider spatial variability across a city. Because of this spatial variability, spatial average ambient concentrations of primary emissions will be far less reliable in estimating the actual magnitude of individual exposures.

Ambient air pollution will also exhibit temporal variability, influencing individual exposures. This includes long-term trends in air quality, seasonal variations in air pollution concentrations, day-to-day variability, as well as diurnal variations in air pollution levels. Depending on the nature of the exposure assessment, it may or may not be necessary to account for these different categories of temporal variability and averaging times. For example, long-term variability in air pollution exposures may be significant in a longitudinal study that would be able to capture chronic health effects, but for a study assessing acute health effects, such as emergency room visits, exacerbation of asthmatic symptoms or daily mortality, daily variations in air pollution levels would be the exposure of interest.

Personal exposures to motor–vehicle-related air pollution (Factor 5) will depend on the activity patterns of the individual in question, the interaction between these activities and traffic sources, and the contribution of indoor sources to personal exposures of the pollutants in question. Throughout a given day, individuals may be exposed to very different levels of air pollutants, depending on the different microenvironments in which they spend their time, their proximity to pollution sources, their smoking habits, and their in-job exposures. These microenvironmental exposures compose an individual's integrated personal exposure. As emphasized above, this variability may be more or less pronounced, depending on the pollutant in question. (We suggested in the discussion above that secondary pollutants will tend to be evenly distributed across a city, while primary pollutants exhibit greater spatial variability.) Extending the inquiry to encompass a wider portion of an individual's life introduces additional levels of complexity due to the mobility of individuals and long-term changes in factors 1–3. The longer the duration of inquiry, the higher the probability that study subjects will have moved from one city to another, or within a city, with the potential for significant variations in the levels of exposure.

Personal exposure monitors that can directly measure individual exposures are available for many pollutants, such as for some gases (ozone, nitrogen oxides, sulfur dioxide), particulate matter ($PM_{2.5}$, PM_{10}), elemental/organic carbon (EC/OC) [24–26] as well as for multiple pollutants simultaneously (particulate matter, criteria gases and EC/OC) [27]. Time-activity diaries have been used to "track" individual activity patterns [28]. By combining the individual diary information with measurements or estimates of ambient and microenvironmental pollution concentrations, researchers can assess individual exposures. Also, time-activity diaries and microenvironmental measurements combined with personal exposure monitoring data may be used to evaluate the main determinants of personal exposures [29, 30]. Researchers have also made use of GPS tracking devices fitted to study participants to assist in estimating exposures [31]. Again, long-term exposure assessments face a greater challenge, requiring information on the subjects' residential history as well as the pollution characteristics of the different microenvironments in which subjects spend their time [32].

Factor 6, the variables influencing whether an adverse health outcome is triggered by the exposure, extends beyond the realm of the exposure assessment. We include it within the conceptual framework, however, to provide a more complete model and to acknowledge that components of factor 5 may be systematically different for individuals of different ages and underlying disease status. The occurrence of an adverse health outcome will vary depending on age, nutrition, and genetics of the individual exposed to the pollution.

Many different approaches have been used to estimate exposures to traffic-related air pollution for epidemiological studies and environmental risk assessments, often with tradeoffs between the specificity of the exposure assessment and the ability to extend the study to large populations. We now turn our focus to the specific tools and techniques for estimating exposures to motor vehicle pollution, which we broadly categorize as: 1) surrogate techniques, 2) modeling techniques, and 3) measurement techniques. In many cases, an exposure assessment will rely on more than one of these approaches as an integral part of the study, or use several approaches as a separate substudy, assessing the distribution of error in the primary exposure estimates.

Surrogate Techniques

Perhaps the most straightforward of the exposure assessment methodologies is what we have termed the "surrogate" approach: indicators of the relative concentrations of pollution that an individual or population is exposed to. The surrogate approach may be useful as a proxy for exposure assessment to vehicle emissions in studies with relatively large sample sizes.

Examples of surrogate techniques include both subjective and objective measures of nearby traffic intensity. Some subjective approaches used self-reported measures of nearby traffic intensity or local knowledge of congested roads to gauge statistical relationships between illness and proximity to high volumes of motor vehicle traffic [33–35]. Studies have asked participants to report the distance from their home to the nearest major roadway, the occurrence of traffic jams near their home, estimates of truck or bus traffic at their home address, speed limit on street of home address, traffic annoyance scores and perception of traffic exhaust. For instance, in a survey of approximately 39,000 subjects, Ciccone et al. [33] found strong associations between childhood respiratory disorders and high truck traffic density in the area of residence.

Other studies have used objectively-determined exposure measures, such as traffic density on the residential street [36], the distance between residence and the nearest highway or busy road [37–39], total traffic within a certain radius [40,41], and distance-weighted traffic density [42].

These examples focus exclusively on a subset of the Factor 2 variables, specifically the number of vehicles in use and the level of congestion. As suggested by our conceptual framework, there are many more variables that will ultimately determine the level of individual exposures that are not reflected in these metrics, highlighting their potential limitations. Depending on the objective of the exposure assessment and study, however, they may be adequate for their intended use.

In terms of identifying areas likely to have higher levels of air pollution within a city, workshop participants suggested that local transportation planners would be capable of identifying the most congested areas of the city. These then would be areas of special concern to determine if exposures are also high. Despite its "low-tech" approach, this technique may be sufficiently suited to the purpose at hand (e.g., when targeting air quality improvement projects, or screening areas for a more detailed study).

If the objective is to evaluate alternative transportation projects rather than existing conditions, the surrogates approach may not be helpful. For assessing a set of alternative scenarios or future conditions, other techniques are needed, including modeling of potential vehicle emissions within the various scenarios and their dispersion into surrounding communities.

Modeling Techniques

The modeling techniques can be divided into two basic categories: 1) regression or GIS modeling approaches, and 2) dispersion modeling.

Regression Modeling Approaches

Researchers are increasingly relying on regression modeling to estimate individual exposures for epidemiological studies. In some cases, GIS is used to compute independent variables for inclusion in these regression models. Two examples of these approaches are the TRAPCA (Traffic-Related Air Pollution on Childhood Asthma) and SAVIAH (Small Area Variations in Air Pollution and Health) studies.

The TRAPCA [1,43,44] and SAVIAH [45–47] exposure assessment approaches were developed as a means to estimate individual exposures to air pollutants for use in large epidemiological studies. The TRAPCA and SAVIAH approaches allow for individual exposures to be modeled based upon regression of measured air pollutant concentrations against surrogate variables in a GIS framework. The specific use of traffic-related surrogate variables allows these methods to develop exposure estimates that are specific to traffic-related pollutants.

The SAVIAH study found significant variation in NO_2 concentrations across individual European cities [47]. The study relied on geographic modeling to develop individual estimates of exposures based on NO_2 concentration measurements at a limited number of sites and prediction of these measured concentrations using geographic data such as nearby traffic intensity, population density, and altitude. Using regression models relating the measured concentrations with the geographic variables, estimates of exposures were then generated for locations where no measurements were made.

Using a similar approach, but extending the methodology to particles, the TRAPCA study found substantial variability in measured annual average concentrations of NO_2, $PM_{2.5}$ and “soot” (an elemental carbon surrogate) at 40 sites in each of the three study locations. Pollutant concentrations varied by a factor of two for $PM_{2.5}$, a factor of three to four for “soot,” and by a factor of four for NO_2. In all of the study areas, a major fraction of this variability was explained by the available geographic variables, such as population density and proximity to major roadways.

The basic approach employed in the SAVIAH and TRAPCA studies involved the measurement of long-term average air pollution concentrations at monitoring sites that were specifically selected to characterize the complete range of within-city variability in air pollution concentrations. At these same monitoring locations, geographic variables (e.g., traffic and population density) were calculated. A regression model then related the measured air pollutant concentrations with the geographic data to enable air pollutant concentrations to be predicted for additional locations where no monitoring data are available, such as the home addresses of study participants. Address locations of study participants were input into the regression model and exposure estimates were calculated for each individual address within a GIS framework. Lifetime exposure histories for study participants could then be calculated for those who move by computing new exposure estimates for each new address. A related approach used a combination of regression modeling and surrogate techniques to take into account local air pollution (proximity to major roads) and background air pollution in a cohort mortality study [3, 48]. In this multivariate analysis, the surrogate variable (living near a major road) was associated with a significantly increased risk of cardiopulmonary mortality, while the modeled exposure variable (background air pollution) was not.

Workshop participants emphasized several of the challenges involved in using geographic information in estimating exposures. For instance, many geocoding services do not accurately or consistently place addresses in their actual physical locations. Because of the near-field pollutant distribution observed along roadways it was suggested that the address locations of study participants be accurately geocoded to within 20–30 meters. Moreover, the road network used to model traffic exposures must be consistent with the database used to geocode addresses.

Dispersion Modeling

In dispersion modeling, emissions parameters are input into dispersion or other types of atmospheric models to predict the concentrations of pollutants at individual “receptor” points. For example, CALINE 4, built on Gaussian dispersion models, can predict the concentrations of air pollutants downwind of a road segment using emission factors (emissions/length of road) and meteorological data [49].

Dispersion models require large amounts of location-specific input data such as detailed information on the specific makeup of the motor vehicle fleet, the specific emissions of representative vehicle types, traffic volumes, and detailed meteorological and topographical information. Workshop participants raised particular concerns regarding the applicability of vehicle emissions estimates based on laboratory testing, which may not provide an accurate representation of variable driving conditions in the real world. The presence of “high emitters” (typically vehicles that may be older, poorly maintained, or tampered with) as well as the emergence of new technology vehicles complicate estimates of vehicle emissions under variable driving conditions for a variety of air pollutants.

Dispersion models are commonly used in the evaluation of air quality management programs and for environmental risk assessments. They have not been used with great frequency in epidemiological studies. The LUCAS study in Stockholm [50] and a Danish study of traffic pollution and childhood cancer in Copenhagen and in several rural areas in Denmark [51] are exceptions. Both studies used dispersion modeling to estimate concentrations of NO_2. As part of the Danish study, dispersion modeling estimates were compared with measured NO_2 concentrations at 200 addresses in Copenhagen and in several rural areas in Denmark. The analysis suggested that the model calculations using traffic data and physical characteristics for the area at the each address reproduced well the observed concentrations.

Measurement Techniques

The measurement techniques rely on actual measurements of traffic-related air pollution, with data collected from air quality monitoring networks or personal samplers. By working directly with measured concentrations of pollution, the measurement techniques essentially bypass the many complexities involved in estimating motor vehicle emissions and the subsequent transport and dispersion of pollutants. There remain, however, several important challenges.

The same pollutants that are generated by motor vehicles are also produced by a variety of other sources. Consequently, it is not possible, with monitoring data alone, to accurately resolve the fraction of the observed ambient concentrations, and subsequent population exposures, that are due to vehicle emissions versus other predominant sources (this limitation also applies to regression modeling approaches). The answers to this question, however, can be refined through the inclusion of other data such as emissions inventories and meteorological measurements. Receptor-based methods (“receptor models”), which typically require more detailed chemical characterization of $PM_{2.5}$, PM_{10} or volatile organic compounds (VOCs), are a useful tool for source apportionment. Combining all of the available information and methods for both particulate and gaseous pollutants is expected to lead to the greatest degree of understanding. This work is difficult, however, requiring considerable effort, resources, and experience. Furthermore, while some aspects of such an effort will be similar from location to location, detailed interpretations can be expected to be site-specific and also potentially time-specific (i.e., only valid for the time period for which the measurements were collected).

Some of the options for apportioning ambient pollutant concentrations to motor vehicles, include:

1) Comparing simultaneous measurements of pollutants from multiple sites where at least one site is located for maximum impact from known traffic sources and the others are not impacted by these sources. This could include upwind versus downwind sites, or near-source sites versus sites representing regional or urban background.

2) Comparisons of different time periods at a single site known to be influenced by traffic (e.g., rush hour times versus non-rush hour times, weekday versus weekend, daytime versus nighttime).

3) Running averages of real-time continuous measurements with sub-hourly resolution. For example, concentrations from hourly running averages represent a larger 'footprint' of the source area than the instantaneous measurements. Subtraction of the two can indicate the impact of the local traffic source on ambient concentrations.

4) Variations in concentrations as a function of wind direction can also lead to valuable inferences regarding the contribution from a source of concern. For nearby sources, a simple pollution schematic ("rose") that bins [groups] hourly data by wind-direction sector may reveal higher concentrations from specific directions that may include point sources or major roadways. This requires hourly resolution (or better) for particulate matter and wind direction measurements.

Numerous epidemiological studies have relied on ambient monitoring data to determine average exposure levels. The American Cancer Society (ACS) and Harvard 6-Cities studies [52, 53] are two of the most widely cited studies of the effects of air pollution exposure on human health outcomes due to the studies' cohort designs and very large sample sizes. The studies used single long-term average pollution concentration values measured at fixed ambient monitoring sites for each urban area to characterize the exposure of study populations. Cross-sectional studies or smaller sample-sized studies, however, have taken a more targeted approach. For example, Krämer et al. [54] measured personal and outdoor pollutant concentrations in a study of children living near major roads in two urban areas and one suburban area. Outdoor concentrations of NO_2 were correlated with a traffic index based on the traffic density at the home address (r=0.70). Outdoor NO_2 concentrations at the front of the children's homes were associated with atopy and allergic symptoms.

Janssen et al. [55] conducted a study involving children from 24 schools situated within 400 meters of 22 different motorway stretches. The pollutants $PM_{2.5}$, NO_2 and benzene were measured inside and outside all 24 schools. The study, based on a measurements approach, found that concentrations of air pollutants inside and outside schools near motorways were significantly associated with distance, traffic density and composition, and percentage of time downwind, suggesting that these variables can be used as surrogates for traffic-related air pollution exposure assessments.

A limited number of studies have assessed exposures by conducting extensive ambient monitoring throughout the entire region of interest (i.e., at multiple grid locations or at the home address of all study subjects) [54, 56]. Short of such an extensive monitoring effort, researchers have interpolated ambient concentrations based on measurements collected by air quality monitoring sites or networks [57, 58]. The interpolation of monitoring data is not able to identify small-scale variations in concentrations, given the density of most typical monitoring networks and given the spatial distribution of traffic sources.

Within-city Spatial Variability in Pollutant Concentrations

These more-refined measurement programs to support epidemiological research are supported by a growing appreciation for spatial variability in air pollution concentrations within urbanized areas [47, 51, 59, 60]. Recent information has suggested greater than expected levels of variation in ambient air pollutant concentrations within a city. Several studies have documented within-city variability in ozone concentrations [61] mainly as a result of variability in nitric oxide (NO) levels—an ozone-quenching substance when its concentration is relatively high compared to reactive hydrocarbons. Additional studies have documented important variations in concentrations of a variety of gaseous and particle species within cities, especially related to the location of motorized traffic, e.g., city center versus suburb [51, 59, 60, 62].

Recent research has also found that some types of vehicle-related air pollution are likely to be localized (within a few hundred meters) near heavily traveled roadways. Studies conducted by Levy et al. [31] and Zhu et al. [63] found concentrations of ultrafine particles and CO dropped to background levels 200–300 meters downwind of a freeway and another study found a similar pattern for NO_2 [62]. In a study by Hitchins et al. [64], concentrations of submicron particles dropped by approximately 50 percent at locations 150 meters away from a road. These studies suggest that concentrations of at least some pollutants from motor vehicle exhaust decline substantially with increasing distance. Consequently, fixed-site monitoring stations for these types of pollutants may not accurately represent near-field pollutant concentrations from motor vehicle exhaust.

In addition, researchers are finding elevated concentrations of pollution in smaller micro-environments. For example, studies conducted on California and Mexico City roadways have measured pollution levels several times higher within a car or public transit vehicle as compared to the air outside the vehicle, ranging from two to ten times greater [65, 66]. The studies in California found that the air in cars driven during peak traffic periods contained nearly twice the pollution of those driven during less congested times [66]. Studies conducted in the Mexico City metropolitan area have found that personal $PM_{2.5}$ and CO exposures in commuters using public transportation were highest during morning rather than evening peak hours, in agreement with higher morning than evening fixed-site monitoring station peak levels [67, 68].

By relying on air quality monitoring data, the measurement techniques avoid the many complexities involved with estimating source-specific emissions and pollutant dispersion. On the other hand, reliance on ambient monitoring data provides limited ability to attribute pollutants to specific sources. In formulating strategies to address the risks to human health, it is important to know the sources of pollution.

Components of the motor vehicle emissions mixture: Diesel exhaust

Diesel exhaust exposure is an issue of particular concern and workshop participants discussed available methods for its assessment and characterization. Most participants felt that the available techniques are not yet sufficient to specifically assess population exposures to diesel exhaust. In the past, elemental carbon (EC) was used as a marker of vehicular diesel fuel combustion. While elemental carbon may be a useful marker for occupational exposures to diesel exhaust when diesel engines are the dominant source of particles, it lacks the sensitivity and specificity needed for a signature of diesel exhaust in ambient exposure settings, which typically include elemental carbon from other combustion sources. For example, gasoline combustion and many industrial and non-vehicle combustion processes also produce EC emissions, so EC is not a reliable “unique” identifier to distinguish diesel–powered vehicle emissions from other vehicle and non-vehicle sources [69].

In 2002, the Health Effects Institute held a workshop addressing the topic of “Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies” [70]. Workshop attendees and speakers included experts involved in developing methodologies to determine human exposures to vehicle exhaust and assessing the limitations associated with the various exposure assessment methods. One key area of focus was the development of validated markers or set of markers (“signature”) to distinguish diesel exhaust from gasoline exhaust and other air pollution types.

The concept for determining a “vehicle exhaust signature” implies the identification of compounds found in ambient air that, when measured in combination, can act as a unique set of markers for vehicle fuel combustion. To date, it is currently not possible to assess accurately an individual’s exposure to vehicle exhaust in ambient air containing pollutants from several sources. As such, it is desirable to identify compounds found in ambient air that, although individually may not be specific for a particular pollution source, taken together can act as a “signature” of vehicle fuel combustion with a high degree of confidence.

An ideal signature or marker for diesel and gasoline vehicle exhaust would be: 1) specific to the vehicle-related combustion source, 2) feasible to measure, 3) able to be generated from routinely collected data, 4) have an appropriate cost, and 5) be relatively insensitive to engine technology and fuel characteristics. In an effort to develop vehicle exhaust signatures or individual markers, researchers are investigating a number of promising research avenues, although none is yet ready for general use. Instruments such as the aerosol mass spectrometer (AMS) provide detailed information about the chemical composition and physico-chemical properties of particulate matter (i.e., size distribution, positive or negative ion mass spectra) [71–73]. Transmission electron microscopy (TEM) has been used to characterize the morphology of particles emitted by vehicle engines [74]. There are also data analysis (statistical) methods applicable to using chemical markers as a proxy for inferring exposures to vehicle emissions [75].

Ideally, if a chemical marker is used to estimate human exposures to vehicle exhaust, this “inferred” estimate should be accompanied by an associated estimate of measurement error, and there are a number of factors contributing to potential measurement errors. These include spatial and temporal variations in ambient particulate matter and their component levels, variable engine operating conditions [76], and limited spatial and temporal scales of the collected data sets.

There have been recent advancements in the development of chemical signatures or markers for vehicle exhaust. Hopanes and steranes found in motor vehicle engine lubricating oil may be useful as unique “marker” constituents in vehicle-derived particulate matter from combustion [77]. Researchers have demonstrated the utility of the molecular marker method in collecting field samples for source apportionment in epidemiological studies, supplemented with elemental carbon measurement data [77, 78]. Confidence in this exposure estimate might be increased by including other measurements of particle characteristics, such as particle number concentration and size distribution.

Although signature or marker approaches are advancing, none of the methods currently satisfies all five of the previously listed criteria for useful exhaust signatures or markers. The remaining challenges include the feasibility of measurements (complex instrumentation and experimental set-up, operational expertise), data analysis capabilities (specialized skills required for analysis and interpretation of key dataset values), and appropriate cost (lengthy experimental set-up, analysis time, skilled worker salaries).

Conclusions and Recommendations

Each technique for assessing population exposures to motor vehicle pollution has its own set of strengths and weaknesses. These include: 1) feasibility, defined in terms of cost and data availability, 2) accuracy, 3) temporal resolution, 4) spatial resolution, 5) the pollutants available for analysis, and 6) sensitivity (ability to detect a response over noise or variability of measurements). In **Table 1**, we summarize the different approaches discussed throughout this article according to these key criteria. Ultimately, it is the objective of the study that will influence the choice of methodology employed for assessing exposures.

Based on the current state-of-the-science in local population exposure assessments to vehicle exhaust, workshop participants raised a number of points that form the basis for recommendations of future work. With respect to the objective of the Commission for Environmental Cooperation to promote sustainable development in the context of expanding international trade, there are several areas that can help identify, prioritize, and assess populations that are at a disproportionately greater risk as a result of expanded trade-related traffic. These include populations living in close proximity to congested border crossings as well as along major highways carrying expanded trade-related traffic. The following recommendations are in the context of these situations, but they can also be generalized to vehicle exhaust exposure assessments at other locations.

It is important to continue work on developing a diesel vehicle exhaust signature, particularly in light of congested border crossings and expanded trade-related truck traffic in major trade corridors. In addition, improved information on idling emissions from vehicles is needed, which is a salient point with regard to locations having frequent traffic congestion and idling trucks. For mobile source emission models, there is a continuing need to improve vehicle emission factors, vehicle fleet composition data, and driving cycle parameters. Further improvements can be made by collecting location-specific traffic count data from traffic planners or other relevant authorities, or as part of the exposure assessment study if no relatively recent traffic count data exist.

It will be informative to evaluate the feasibility of applying a standard exposure assessment methodology across different and widely separated locations. A standard approach may help identify differing impacts at locations of concern, such as border crossings, which could arise from differences in local ambient pollution composition, rather than arising as an artifact of different assessment approaches. For example, differences in diesel fuel sulfur content or in diesel engine emission standards across different regions may be reflected in local ambient air concentrations where trucks frequently idle or travel.

Table 1. Summary Table of Approaches to Population Exposure Assessments for Vehicle Exhaust

Methodology	Strengths	Weaknesses
Surrogate Approaches	• Generally the least resource intensive and therefore rank high in terms of feasibility. • Applicable for urban-wide assessments. • Best suited for analysis of existing conditions. • Focused by design on long-term concentrations.	• Not appropriate for assessment of individual roads. • Do not necessarily account for changes in existing conditions. • Generally deficient in terms of short-term variability. • Do not address individual pollutants, which can be a serious shortcoming for researchers seeking to link a specific pollutant to a health risk. • Surrogate techniques that incorporate subjective assessments suffer from potential for bias.
Dispersion Models	• May be most appropriate for modelling of specific scenarios (forecasting) and a limited number of roads. • Useful for transportation planning agencies that may already possess much of the input data required. • Have the ability to evaluate short-term changes in pollutant concentrations (e.g., hourly, seasonal, day of week profiles) as long as appropriate temporally-resolved input data (traffic counts, emissions factors, meteorology) are available.	• Resource intensive, requiring large amounts of location-specific input data such as detailed information on the specific makeup of the motor vehicle fleet, the specific emissions of representative vehicle types, traffic volumes, and detailed meteorological and topographical information. • Difficult to apply across entire metropolitan areas.
Regression or GIS Modeling	• Very feasible to perform a regression analysis based on existing data and variables within a GIS framework (e.g., distance to nearest highway).	• More rigorous analyses based on actual traffic counts and spatial measurements can significantly increase the required resources.
Personal Monitoring	• Best suited for model development and to validate modelling approaches. • Best suited for epidemiological studies. • Data can be collected for individual study participants. • Depending on the pollutant, personal monitors have the potential to provide greater temporal resolution (but not always). • Passive samplers are available that can measure VOCs, NO_2, SO_2, ozone, and aldehydes.	• Feasible only for relatively small subsets of the population. • Because of the size of some continuous samplers (e.g. CO, NO_2, and PM), subjects may not follow a regular daily routine when wearing a personal monitor, biasing the resulting data. • Less temporal resolution with passive samplers that require longer integration periods (e.g. 24 hours).
Ambient Monitoring	• Established monitoring networks can contain consistent information on long-term air pollution trends at specific locations. • Capable of high-temporal resolution for a large number of air pollutants. • Where pre-existing monitoring already done for regulatory purposes, it can be a low-cost source of monitoring information for exposure assessment studies.	• Typically lacks sufficient spatial coverage on its own to capture within city variability of air pollution levels. • Relevance of ambient air monitoring data for measuring exposures to motor vehicle pollution varies depending on the location of the site(s), the temporal and chemical resolution of the data, and the amount of data available.

Additional work should be done to investigate the importance of time-resolved ambient air monitoring data that may help reveal different health effects or reinforce existing studies. Some health effects from short-term peak exposures may not appear in exposure assessments using long-term ambient air concentration averages. The importance of time-resolved air monitoring data, however, may depend on the relevant health effect being investigated. For example, for studies of asthma exacerbations, short-term temporal resolution may be more important, whereas for cancer studies, annual averages may be sufficient.

Also relevant to the potential usefulness of time-resolved air monitoring data is a recommendation to develop siting criteria for air monitors to be located in special areas of concern, such as near schools or congested border crossings. In these locations, time-resolved data could be important, depending on where people are spending their time in relation to the ebb and flow of local traffic patterns. Having monitors located in representative sites for population exposures to vehicle exhaust is clearly an important assessment need. For personal monitoring, efforts to improve the capabilities of monitors in terms of the pollutants they measure, their temporal resolution, and reducing their weight are important and should continue.

Researchers should work with transportation planners to identify potential “hot spots” along existing major routes or at sites of proposed highway expansion projects as candidates for exposure assessments. Investigators can use dispersion or GIS modeling approaches to help identify populations that may be affected by toxics and other vehicle emissions. Exposure assessments can be aided by efforts to further hybrid strategies incorporating both spatial and temporal variability and specific exhaust components to improve their accuracy. It will be important to verify and improve road spatial accuracy for inputs into GIS modeling techniques in order to reduce uncertainties from roadways located incorrectly. Roadways mislocated by only a few hundred meters can significantly change estimates of population exposures in the local area.

Because of the complexities of modeling techniques and their inputs, there will always be some level of uncertainty in their use for exposure assessments. As an aid to decision makers and transportation planners in light of continuing uncertainties, it will be useful to provide in any assessment a general background that includes a description of toxics and other air pollutants in the environment, as well as a general description of sensitive populations to these contaminants. There may already be locally specific information available in terms of monitoring or modeling, and these should be included in the general background. Within this context, the background can also include a discussion of reasonably foreseeable changes in traffic volume or congestion that can alter the amount of toxics and air pollutants emitted from local traffic. Specific examples of these types of exhaust-related contaminants are benzene and diesel particulate matter. By providing this general context, decision makers and transportation planners will have an improved understanding of the local context in which to evaluate the results of location-specific exposure assessments and their uncertainties in relation to sensitive populations exposed to vehicle exhaust.

References

1. Brauer M, Hoek G, van Vliet P, Meliefste K, Fischer PH, Wijga A, Koopman LP, Neijens HJ, Gerritsen J, Kerkhof M, Heinrich J, Bellander T, Brunekreef B: Air pollution from traffic and the development of respiratory infections and asthmatic and allergic symptoms in children. *Am J Respir Crit Care Med* 2002, 166: 1092–98.

2. Creason J, Neas L, Walsh D, Williams R, Sheldon L, Liao D, Shy C: Particulate matter and heart rate variability among elderly retirees: the Baltimore 1998 PM study. *J Expo Anal Environ Epidemiol* 2001, 11: 116–22.

3. Hoek G, Brunekreef B, Goldbohm S, Fischer P, van den Brandt PA: Association between mortality and indicators of traffic-related air pollution in the Netherlands: a cohort study. *Lancet* 2002, 360: 1203–9.

4. Lin S, Munsie JP, Hwang SA, Fitzgerald E, Cayo MR: Childhood asthma hospitalization and residential exposure to state route traffic. *Environ Res* 2002, 88: 73–81.

5. Schwartz J, Morris R: Air pollution and hospital admissions for cardiovascular disease in Detroit, Michigan. *Am J Epidemiol* 1995, 142: 23–35.

6. Zanobetti A, Schwartz J, Dockery DW: Airborne particles are a risk factor for hospital admissions for heart and lung disease. *Environ Health Perspect* 2000, 108: 1071–77.

7. California Senate Bill 352: *California Statutes Chapter 668.* Sacramento, California; 2003.

8. Frumkin H: Urban sprawl and public health. *Public Health Reports* 2002, 117: 201–17.

9. O'Neill MS, Jerrett M, Kawachi I, Levy JI, Cohen AJ, Gouveia N, Wilkinson P, Fletcher T, Cifuentes L, Schwartz J, with input from participants of the Workshop on Air Pollution and Socioeconomic Conditions: Health, wealth, and air pollution: advancing theory and methods. *Environ Health Perspect* 2003, 111: 1861–70.

10. State of California Air Resources Board: *Resolution 98-35.* Sacramento, California; 1998 <http://www.arb.ca.gov/regact/diesltac/res98-35.pdf>.

11. US Environmental Protection Agency, Office of Research and Development, National Center for Environmental Assessment: *Health Assessment Document for Diesel Engine Exhaust*. Washington, DC. 2002.

12. Diamond G, Parker M: Preliminary air quality assessment related to traffic congestion at Windsor’s Ambassador Bridge. Southwestern Region, Ontario Ministry of the Environment. PIBS 4624e. 2004 <http://www.ene.gov.on.ca/envision/techdocs/4624e.pdf>.

13. Lwebuga-Mukasa JS, Ayirookuzhi SJ, Hyland A: Traffic volumes and respiratory health care utilization among residents in close proximity to the Peace Bridge before and after September 11, 2001. *J Asthma* 2003, 40: 855–64.

14. Romieu I, Ramirez-Aguilar M, Moreno-Macias H, Barraza-Villarreal A, Hernandez-Cadena L, Carbajal-Arroyo L: Working paper: health impacts of air pollution on morbidity and mortality among children in Ciudad Juárez, Chihuahua, México. Commission for Environmental Cooperation. Montreal Quebec; 2003. <http://www.cec.org/pubs_docs/documents/index.cfm?varlan=english&ID=1347>.

15. North American Agreement on Environmental Cooperation, Article 1; 1993.

16. Pokharel SS, Bishop GA, Stedman DH, Slott R: Emissions reductions as a result of automobile improvement. *Environ Sci Technol* 2003, 37: 5097–5101.

17. Norbeck JM, Miller JW, Welch WA, Smith M, Johnson K, Pankratz D: Develop On-Road System for Emissions Measurement from Heavy-Duty Trucks. *Final Report, South Coast Air Quality Management District Contract 20906*. 2001 <http://www.cert.ucr.edu/research/pubs/trailer_build_fr_20906b.pdf>.

18. Gertler AW, Gillies JA, Pierson WR, Rogers CF, Sagebiel JC, Abu-Allaban M, Coulombe W, Tarnay L, Cahill TA: Real-world particulate matter and gaseous emissions from motor vehicles in a highway tunnel. *Health Effects Inst* 2002, 107: 5–56; discussion 79–92.

19. Singer BC, Harley RA: A fuel-based inventory of motor vehicle exhaust emissions in the Los Angeles area during summer 1997. *Atmos Environ* 2000, 34: 1783–95.

20. Singh RB, Colls JJ: Development and preliminary evaluation of a particulate matter emission factor model (PMFAC) for European motor vehicle emission. *J Air Waste Manage* 2000, 50: 1805–17.

21. Singh RB, Huber AH, Braddock JN: Development of a microscale emission factor model for particulate matter for predicting real-time motor vehicle emissions. *J Air Waste Manage* 2003, 53: 1204–17.

22. Fomunung I, Washington S, Guensler R, Bachman W: Performance evaluation of MEASURE emission rates: a comparison to MOBILE5A. In *Proceedings of the 78th Annual Meeting of the Transportation Research Board: 2000; Washington, DC.* 2000 <http://transaq.ce.gatech.edu/guensler/publications/proceedings/trb00%20fomunung.pdf>.

23. Los Alamos National Laboratory: *TRANSIMS documentation*. 2003 <http://transims.tsasa.lanl.gov/>.

24. Clayton CA, Pellizari ED, Rodes CE, Mason RE, Piper LL: Estimating distributions of long-term particulate matter and manganese exposures for residents of Toronto, Canada. *Atmos Environ* 1999, 33: 2515–26.

25. Howard-Reed C, Rea AW, Zufall MJ, Burke JM, Williams RW, Suggs JC, Sheldon LS, Walsh D, Kwok R: Use of a continuous nephelometer to measure personal exposure to particles during the US Environmental Protection Agency Baltimore and Fresno Panel studies. *J Air Waste Manage* 2000, 50: 1125–32.

26. Thomas KW, Pellizzari ED, Clayton C, Whitaker DA, Shores RC, Spengler JD, Özkaynak H, Froehlich SE, Wallace LA: Particle total exposure assessment methodology (PTEAM) 1990 study: method performance and data quality for personal, indoor and outdoor monitoring. *J Expo Anal Environ Epidemiol* 1993, 3: 203–26.

27 Demokritou P, Kavouras IG, Ferguson ST, Petroukis P: Development and laboratory performance evaluation of a personal multipollutant sampler for simultaneous measurements of particulate and gaseous pollutants. *Aerosol Sci Technol* 2001, 35: 741–52.

28. Zmirou D, Gauvin S, Pin I, Momas I, Just J, Sahraoui F, Le Moullec Y, Brémont F, Cassadou S, Albertini M, Lauvergne N, Chiron M, Labbé A: Five epidemiological studies on transport and asthma: objectives, design and descriptive results. *J Expo Anal Environ Epidemiol* 2002, 12: 186–96.

29. Rojas-Bracho L, Suh HH, Catalano PJ, Koutrakis P: Personal $PM_{2.5}$ and PM_{10} exposures and their relationships with personal activities for chronic obstructive pulmonary disease patients living in Boston. *J Air Waste Manage* 2004, 54: 207–17.

30. Sarnat JA, Schwartz J, Catalano PJ, Suh HH: Gaseous pollutants in particulate matter epidemiology: confounders or surrogates? *Environ Health Perspect* 2001, 109: 1053–61.

31. Levy J, Bennett D, Melly S, Spengler J: Influence of traffic patterns on particulate matter and polycyclic aromatic hydrocarbon concentrations in Roxbury, Massachusetts. *J Expo Anal Environ Epidemiol* 2003, 13: 364–71.

32. Kunzli N, Tager IB: Long-term health effects of particulate and other ambient air pollution: research can progress faster if we want it to. *Environ Health Perspect* 2000, 108: 915–18.

33. Ciccone G, Forastiere F, Agabiti N, Biggeri A, Bisanti L, Chellini E, Corbo G, Dell'Orco V, Dalmasso P, Volante TF, Galassi C, Piffer S, Renzoni E, Rusconi F, Sestini P, Viegi G: Road traffic and adverse respiratory effects in children. *Occup Environ Med* 1998, 55: 771–78.

34. Duhme H, Weiland SK, Keil U, Kraemer B, Schmid M, Stender M, Chambless L: The association between self-reported symptoms of asthma and allergic rhinitis and self reported traffic density on street of residence in adolescents. *Epidemiology* 1996, 7: 578–82.

35. Weiland SK, Mundt KA, Rückmann A, Keil U: Self-reported wheezing and allergic rhinitis in children and traffic density on street of residence. *Ann Epidemiol* 1994, 4: 243–47.

36. Savitz DA, Feingold L: Association of childhood cancer with residential traffic density. *Scand J Work Environ Health* 1989, 15: 360–63.

37. Brunekreef B, Janssen NA, de Hartog J, Harssema H, Knape M, van Vliet P: Air pollution from truck traffic and lung function in children living near motorways. *Epidemiology* 1997, 8: 298–303.

38. Livingstone AE, Shaddick G, Grundy C, Elliott P: Do people living near inner city main roads have more asthma needing treatment? Case control study. *BMJ* 1996, 312: 676–77.

39. van Vliet P, Knape M, de Hartog J, Janssen N, Harssema H, Brunekreef B: Motor vehicle exhaust and chronic respiratory symptoms in children living near freeways. *Environ Res* 1997, 74: 122–32.

40. English P, Neutra R, Scalf R, Sullivan M, Waller L, Zhu L: Examining associations between childhood asthma and traffic flow using a geographic information system. *Environ Health Perspect* 1999, 107: 761–67.

41. Wilkinson P, Elliott P, Grundy C, Shaddick G, Thakrar B, Walls P, Falconer S: Case-control study of hospital admission with asthma in children aged 5–14 years: relation with road traffic in northwest London. *Thorax* 1999, 54: 1070–74.

42. Langholz B, Ebi KL, Thomas DC, Peters JM, London SJ: Traffic density and the risk of childhood leukemia in a Los Angeles case-control study. *Ann Epidemiol* 2002, 12: 482–87.

43. Brauer M, Hoek G, Van Vliet P, Meliefste K, Fischer P, Gehring U, Heinrich J, Cyrys J, Bellander T, Lewne M, Brunekreef B: Prediction of long term average particulate air pollution concentrations by traffic indicators for epidemiological studies. *Epidemiology* 2003, 14: 228–39.

44. Hoek G, Meliefste K, Cyrys J, Lewné M, Brauer M, Fischer P, Gehring U, Heinrich J, van Vliet P, Brunekreef B: Spatial variability of fine particle concentrations in three European countries. *Atmos Environ* 2002, 36: 4077–88.

45. Briggs DJ, Collins S, Elliott P, Fischer P, Kingham S, Lebret E, Pryl K, van Reeuwijk H, Smallbone K, van der Veen A: Mapping urban air pollution using GIS: a regression-based approach. *Int J Geographical Information Science* 1997, 11: 699–718.

46. Briggs DJ, de Hoogh C, Gulliver J, Wills J, Elliott P, Kingham S, Smallbone K: A regression-based method for mapping traffic-related air pollution: application and testing in four contrasting urban environments. *Sci Total Environ* 2000, 253: 151–67.

47. Lebret E, Briggs DJ, Collins S, van Reeuwijk H, Fischer P, Smallbone K, Harssema H, Kriz B, Gorynski P, Elliott P: Small area variations in ambient NO_2 concentrations in four European areas. *Atmos Environ* 2000, 34: 177–85.

48. Hoek G, Fischer P, van den Brandt P, Goldbohm S, Brunekreef B: Estimation of long-term average exposure to outdoor air pollution for a cohort study on mortality. *J Expo Anal Environ Epidemiol* 2001, 11: 459–69.

49. Benson P: CALINE4 - a dispersion model for predicting air pollution concentrations near roadways. *Final report prepared by California Department of Transportation,* FHWA/CA/TL-84/15, revised November 1986 and June 1989.

50. Bellander T, Berglind N, Gustavsson P, Jonson T, Nyberg F, Pershagen G, Jarup L: Using geographic information systems to assess individual historical exposure to air pollution from traffic and house heating in Stockholm. *Environ Health Perspect* 2001, 109: 633–39.

51. Raaschou-Nielsen O, Hertel O, Vignati E, Berkowicz R, Jensen SS, Larsen VB, Lohse C, Olsen JH: An air pollution model for use in epidemiological studies: evaluation with measured levels of nitrogen dioxide and benzene. *J Expo Anal Environ Epidemiol* 2000, 10: 4–14.

52. Dockery DW, Pope AC, Xu X, Spengler JD, Ware JH, Fay ME, Ferris BG, Speizer FE: An association between air pollution and mortality in six US cities. *N Engl J Med* 1993, 329: 1753–59.

53. Pope CA, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, Thurston GD: Lung cancer, cardiopulmonary mortality and long-term exposure to fine particulate air pollution. *JAMA* 2002, 287: 1132–41.

54. Krämer U, Koch T, Ranft U, Ring J, Behrendt H: Traffic-related air pollution is associated with atopy in children living in urban areas. *Epidemiology* 2000, 11: 64–70.

55. Janssen NAH, van Vliet PHN, Aarts F, Harssema H, Brunekreef B: Assessment of exposure to traffic related air pollution of children attending schools near motorways. *Atmos Environ* 2001, 35: 3875–84.

56. Hirsch T, Weiland SK, von Mutius E, Safeca AF, Grafe H, Csaplovics E, Duhme H, Keil U, Leupold W: Inner city air pollution and respiratory health and atopy in children. *Eur Respir J* 1999, 14: 669–77.

57. Brown PJ, Le ND, Zidek JV: Multivariate spatial interpolation and exposure to air-pollutants. *Can J Stat* 1994, 22: 489–509.

58. Li KH, Le ND, Sun L, Zidek JV: Spatial-temporal models for ambient hourly PM_{10} in Vancouver. *Environmetrics* 1999, 10: 321–38.

59. Bernard NL, Astre CM, Vuillot B, Saintot MJ, Berber MJ: Measurement of background urban nitrogen dioxide pollution levels with passive samplers in Montpellier, France. *J Expo Anal Environ Epidemiol* 1997, 7: 165–78.

60. Cyrys J, Heinrich J, Brauer M, Wichmann HE: Spatial variability of acid aerosols, sulfate and PM10 in Erfurt, Eastern Germany. *J Expo Anal Environ Epidemiol* 1998, 8: 447–64.

61. Liu LJS, Rossini AJ: Use of kriging models to predict 12-h mean ozone concentrations in metropolitan Toronto—a pilot study. *Environment International* 1996, 22: 677–92.

62. Gilbert NL, Woodhouse S, Stieb DM, Brook JR: Ambient nitrogen dioxide and distance from a major highway. *Sci Total Environ* 2003, 312: 43–46.

63. Zhu Y, Hinds WC, Kim S, Sioutas C: Concentration and size distribution of ultrafine particles near a major highway. *J Air Waste Manage* 2002, 52: 1032–42.

64. Hitchins J, Morawska L, Wolff L, Gilbert D: Concentration of submicrometer particles from vehicle emissions near a major road. *Atmos Environ* 2000, 34: 51–59.

65. Fernández-Bremauntz A, Ashmore MR: Exposure of commuters to carbon monoxide in Mexico City II. Comparison of in-vehicle and fixed-site concentrations. J Expo Anal Environ Epidemiol 1995, 5: 447–64.

66. South Coast Air Quality Management District: *AQMD Fact Sheet: Study of air pollution levels inside vehicles.* 1999 <http://www.aqmd.gov/news1/1999/in_car_facts.htm>.

67. Gómez-Perales JE, Colvile RN, Nieuwenhuijsen MJ, Fernández-Bremauntz A, Gutiérrez-Avedoy VJ, Páramo-Figueroa VH, Blanco-Jiménez S, Bueno-López E, Mandujano F, Bernabé-Cabanillas R, Ortiz-Segovia E: Commuters' exposure to $PM_{2.5}$, CO, and benzene in public transport in the metropolitan area of Mexico City. Atmos Environ 2004, 38: 1219–29.

68. Secretaría de Medio Ambiente y Recursos Naturales, Instituto Nacional de Ecología: *Segundo almanaque de datos y tendencias de la calidad del aire en seis ciudades mexicanas* [in Spanish], Mexico City; 2003.

69. HEI Diesel Epidemiology Working Group: *Research Directions to Improve Estimates of Human Exposure and Risk from Diesel Exhaust, Special Report;* Health Effects Institute: Boston, MA; 2002.

70. Health Effects Institute: *Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston MA; 2003.

71. Guazzotti SA, Prather KA: Using individual particle signatures to discriminate between HDV and LDV emissions. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies*. Boston, MA: Health Effects Institute; 2003.

72. Worsnop DR, Canagaratna M, Jayne J, Jimenez J: Characterization of vehicle emissions and urban aerosols by an aerosol mass spectrometer (AMS). In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

73. Ziemann PJ, Tobias HJ, Sakurai H, McMurry PH, Kittelson DB: On-line mass spectral analysis of thermally evaporated diesel exhaust particles. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

74. Blom DA, Storey JME, Graves RL: Morphological aspects of combustion particles. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

75. Smith RL: Data analytic procedures for monitoring specific pollutants in epidemiological studies. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

76. Kittelson DB: Some characteristics of diesel and gasoline particulate emissions. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

77. Fujita E, Zielinska B: Chemical characterization of on-road motor vehicle PM emissions. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.

78. Schauer JJ: Diesel exhaust signatures for source attribution: parts 1 & 2. In *HEI Communication 10: Improving Estimates of Diesel and Other Emissions for Epidemiologic Studies.* Boston, MA: Health Effects Institute; 2003.