High Resolution Spatial and Temporal Mapping of Air Pollution in Detroit

Project Final Report

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Executive summary

Traffic-related emissions are one of the most important air pollution sources in most urban areas including Detroit, Michigan. Traffic-related emissions include carbon monoxide (CO), oxides of nitrogen (NO, NO_2), volatile organic compounds (VOCs such as benzene), and particulate matter under 2.5 micrometers in diameter ($PM_{2.5}$). Traffic-related air pollutant concentrations are highest near major roadways, although their influence is felt throughout the urban area. Several traffic-related air pollutants, including CO, $PM_{2.5}$ and NO_2, are governed by the US Clean Air Act and its Amendments, which set ambient concentration limits (the National Ambient Air Quality Standards) and exhaust emission limits. Many studies have linked concentrations of these pollutants to a variety of adverse health impacts, e.g., respiratory and cardiovascular disease.

At present, information regarding the share of pollution that is attributable to traffic is limited. Indicators or surrogate metrics like proximity to roads can be overly simplistic and often inadequate. While several air pollutants are regularly monitored at several locations in large cities, the number of monitoring locations is never adequate to show the spatial patterns.

This project uses physically-based simulation models to estimate hourly, daily (24 hr), and annual average pollutant concentrations at high spatial and temporal resolution in Detroit, Michigan that result from traffic, specifically, tailpipe emissions from cars, buses, trucks and motorcycles. This reports presents results for the year 2010 for two pollutants, $PM_{2.5}$ and NO_x (the sum of NO and NO_2). Concentrations have been simulated at nearly 28,000 locations mapped to a 150 m grid over an area that encompasses Detroit and parts of surrounding Wayne County. An extremely high resolution 10 m grid is also tested. Results for the annual average and high pollution days are provided in order to show the contrasting patterns. The latest modeling techniques were used. Emissions are based on the road network, fleet data, and temporal allocation factors for Detroit, used as inputs to the 2010 US Environmental Protection Agency (EPA) Motor Vehicle Emission Simulator (MOVES) model. The US EPA AERMET meteorological processor was used to process Detroit meteorological data. The emissions and meteorological data provide inputs to the 2013 US EPA RLINE dispersion model, designed specifically for road sources. RLINE was extensive modified for this project. The overall modeling system has been developed with support from a Cooperative Agreement between the University of Michigan and the US EPA. Model results have been provided as files for use as layers for GIS mapping and analysis purposes. Some of the maps are reproduced in this report.

The results of the project show the level and spatial distribution of traffic-related air pollutant concentrations in Detroit. The modeling involved a high (and unique) degree of temporal and spatial resolution that allows investigation of both short- and long-term pollutant impacts relevant to both acute and chronic health impacts, as well as other applications. These results are significant given the extent of commuting, the high rate of truck traffic, the international crossing, and the numerous houses, schools, etc., that are located near major roads in Detroit where pollutant concentrations and exposure are highest. In addition, much of the population is medically underserved and disproportionately suffers from diseases linked to environmental factors.

Several suggestions for using project results are made. These include: mapping pollutant concentrations to census and property parcel information; identifying pollutant “hotspots” and especially those containing schools, hospitals, parks, athletic fields, and other areas where children and other susceptible individuals may be highly exposed; estimating exposure and risk from traffic-related pollutants; and using exposure estimates in epidemiology studies to investigate associations between pollutants and adverse health outcomes. The results also can be used in exposure, risk and cost minimization studies aimed at reducing pollutant exposure and risks by using traffic controls, improved emission controls on vehicles, and/or buffers around highways or critical facilities (e.g., schools and playgrounds). Finally, composite “sustainability indicators” can be developed by overlaying air pollutant data with GIS layers representing other environmental, social or physical stressors.

Several policy options for policy makers are suggested. These include requirements or recommendations to consider: buffers around highways to reduce pollutant exposure and adverse health impacts, and for other co-benefits; siting approaches for schools and other critical facilities that minimize pollutant exposure; incorporation of pollution-related impacts of transportation projects in the Environmental Impact Assessment (EIS) process; land use and transit corridor planning that minimizes pollutant exposure; retrofitting older vehicles in bus and truck fleets with control technology to reduce emissions and exposure; reducing traffic-related emissions using transit and incentives for zero-emission vehicles (ZEVs); enhancing health surveillance activities followed by epidemiology analyses to improve the understanding of the risk factors that cause disease; and supporting the development of emission inventories and other analyses for transportation sources that include both conventional and greenhouse pollutants.

The results and analysis has benefited from community engagement, specifically the Detroit-based Community Action Against Asthma (CAAA) partnership, which includes community-based organizations, health and human service organizations, and university researchers. (Please see *Partners and Community Organizations* for a list of the partners involved.)

Overview of Project

This project estimated daily and annual average concentrations of two key air pollutants, $PM_{2.5}$ and NO_x, due to from traffic emissions across the Detroit area. Concentrations for the year 2010 were predicted using RLINE, a steady-state plume dispersion model, and an hourly link-based source inventory for nearly 10,000 links that represents all but the smaller local roads in Detroit and Wayne County. Link-based emissions were calculated using estimates of hourly traffic volume, fleet mix, and speed derived from data from the Michigan Department of Transportation (MDOT) and traffic demand model outputs from the Southeast Council of Michigan Governments (SEMCOG). Traffic flows were adjusted using temporal allocation factors (TAFs) for month, day-of-week, and hour-of-day from SMOKE (Pouliot et al., 2012), e.g., representing morning and evening rush hours. TAFs and fleet mix depended on the road type, which is designated by the National Functional Class (NFC). Emission factors were calculated using MOVES2010 (Wallace et al., 2012), the monthly average temperature, hourly link speed and vehicle class. Hourly emissions for each link and hour were estimated from these factors (Cook et al., 2008). Standard modeling guidance was followed (USEPA, 2004). Meteorological inputs to the models included hourly surface data for 2010 from the Detroit City airport, which was determined to be representative of the area, and upper air data from the same airport. The AERMET pre-processor was used. Missing meteorological data was imputed.

This report provides maps that display concentrations patterns using several concentration statistics. These include annual average concentrations, which provide a more representative indicator that is relevant for effects that depend on long-term or cumulative exposure, and the maximum daily average concentrations, which represents the highest concentration a location is likely to experience over the year and which is relevant for identifying potential “hot-spots” and for evaluating effects that depend on short-term or acute exposure. Day-to-day variation can be considerable, thus the use of both annual average and maximum daily average statistics are complementary indicators.

A number of suggestions are made to use project results, and a number of options for policy makers are provided that can be used to reduce exposure to traffic related air pollutants. The report also summarizes limitations and uncertainties of the results.

Background

This report documents the approach, data and models used in the project entitled “High Resolution Spatial and Temporal Mapping of Air Pollution in Detroit” supported in part by the University of Michigan Graham Environmental Sustainability Institute.

This project focuses on near-road exposures of traffic-related air pollutants, which have been receiving increased attention due to evidence linking emissions from high-traffic roadways to asthma aggravation, impaired lung function, increased cardiovascular mortality, increased all-cause mortality, and other adverse health effects (HEI, 2010; WHO 2005). These exposures are particularly important in Detroit, which contains many neighborhoods bisected by major roads with heavy truck traffic. The development of scientifically-grounded air pollution data within a GIS platform or used in other analyses, as provided by this project, would potentially benefit many researchers and others in a wide range of applications.

The use of geocoded data and geographical information systems (GIS) has rapidly become routine practice in many types of environmental analyses. While surrogates of pollutant exposure, including proximity measures, e.g., the distance from residences or schools to highways or Superfund sites, have been widely used (Batterman and Wu, 2006; Huang and Batterman, 2000), most surrogates have many limitations: they incompletely or improperly account for the nature of emission sources, effects of meteorology, orographic features, small scale variation in pollutant concentrations, time-activity patterns of emissions and the study subjects, and other factors that affect pollutant emissions, transport, fate and exposure. In consequence, results may be biased and exposures may be misclassified. Another important limitation is that quantitative exposure estimates are not obtained, which greatly limits the interpretation of the data (e.g., results cannot be compared to ambient air quality standards) and its use in policy development and management.

Approaches to estimate air pollutant exposures and specifically roadway impacts have been recently reviewed (Jerrett et al. 2005; Lipfert and Wyzga, 2008; HEI, 2010; Batterman et al., 2011). In brief, approaches include "dispersion" models using variety of statistical (e.g., Gaussian plume) and physically-based (e.g., computational fluid dynamic) models that simulate emissions and dispersion; “land use regression” (LUR) models that fit concentrations measured at multiple sites using statistical models and land characteristics, traffic and other data as independent variables, which then are used to predict concentrations elsewhere; and "receptor" models using measured pollutant characteristics as tracers to identify and quantify sources.

The use of dispersion models that simulate pollutant emissions, transport and fate can improve exposure estimates and facilitate new types of analyses. Such models have been used in many applications, including GIS (English et al, 1999; Bellander et al. 2001; Lin and Lin, 2002; Jin and Fu, 2005; Cook et al., 2008; Batterman et al., 2011). These models are data-intensive, with inputs for pollutant emissions, emission source and roadway configurations, meteorological conditions and land use. With appropriate inputs and models, short- and long-term air concentrations can be predicted at desired locations called “receptors,” and multiple receptors can be used to depict spatial and temporal gradients at regional, urban and local scales. This is the approach taken in this project.

The development of the site-specific emission information that “drives” such models is not trivial. Vehicle emissions depend on many factors, including the number, speed, type and age of vehicles, all of which can vary significantly over the course of a day. Emission/dispersion models do not require data from existing pollutant monitoring sites to estimate near-road concentrations and exposures, although such information may be used to estimate the “background” component of concentrations contributed by other “local” and “regional” emission sources, i.e., those not explicitly modeled because they are distant, too numerous, or too difficult to simulate. The drawbacks of dispersion models include, among others, extensive input data requirements, errors due to unmeasured variability in emissions and other parameters, the need for accurate location information, simplified and possibly unrealistic model assumptions; the relevance of the background estimates, and a need for validation.

Another type of process-based modeling uses computational fluid dynamic (CFD) models (Hanna et al., 2004). Based on the Navier-Stokes equations, such models are useful for estimating short-term dispersion of plumes, especially in areas containing obstacles like large buildings and complex terrain, and with calm or very light winds, a situation when other types of models perform poorly. However, CFD models are demanding in terms of data inputs and computational requirements, and they are not immune to most of the drawbacks just discussed for dispersion models.

A final and recent approach for estimating air pollutant exposures, called "land use regression" (LUR) models, fit concentrations measured at multiple sites using statistical models and land characteristics, traffic and other data as independent variables, which then are used to predict pollutant concentrations at other sites (Ryan et al. 2007). The primary advantage of LUR models is their ability to characterize small-scale variations in urban settings without the need for detailed (and accurate) emission information. However, these models are area-specific and cannot be reliably extrapolated to areas with different topography, land uses, emission types, etc. Since monitored pollutant levels are used as the dependent variable in the regression model, they also require a network of air sampling sites and historical data. LUR models have been used to estimate only long-term concentrations.

Description of Methods, Analysis and Findings

Geographic domain

The scope of analysis encompasses the City of Detroit and much of surrounding Wayne County.

Concentrations were calculated at 27,622 "receptors" on 150 m centers over a region 34.5 (E-W) x 23 (N-S) km in dimension, with the SW UTM coordinates of (311,500, 4,680,500). The SE corner of the region, over the Detroit River, Lake St. Clair and Canada is not included. Each receptor represents a discrete point or location, although the prediction for that receptor can reasonably represent concentrations over the 150 x 150 m grid cell it represents. The receptor location represents the center of the cell.

Input data and processing

The following datasets are needed to estimate air pollutant concentrations:

- Meteorology, e.g., hourly measurements of surface and upper air parameters including wind speed, wind direction and mixing height;
- Road network data, e.g., link location, and hourly vehicle speed, traffic flow, and vehicle mix, and;
- Emission source inventory, e.g., hourly emissions of each pollutant for each link

The following sections summarize the input data, processing steps, and modeling approach.

Meteorology

Meteorological data included hourly data from Detroit City airport, which was determined to be representative of the study area. These data were processed by AERMET, which extracted data from data archives, completed quality assessment checks, merged surface, upper air and on-site data, and estimated boundary layer parameters. AERMET produces two files: surface data containing hourly boundary layer parameters; and a profile data with multiple level observations of wind speed, wind direction, temperature and the standard deviation of wind components.

While most meteorological datasets are generally quite complete (typically greater than 95% available and valid data), the lack of complete meteorological data can skew dispersion modeling results, particularly daily and annual averages, and hence it becomes imperative (if possible) to compute predictions based on a full set of meteorological data. Some of the missing parameters (wind speed, wind direction, temperature) were replaced with data from the four surrounding airports (Detroit Wayne, St. Claire, Gross Isle and Windsor) as follows:

- Invalid or missing wind speed (if flagged or were set at 0 or calm conditions) were replaced with Detroit City Airport data if available, or a 4-station average otherwise. Invalid or missing wind direction values were replaced with Detroit City Airport data if available, rotated slightly to improve agreement, or 4-station average, rotated, otherwise.
- The friction velocity parameter $U^*$was re-calculated wherever the wind speed changed from the original meteorological file. U^* values were computed using iterative formula in AERMET. Similarly, the MO-length was calculated using the following equation

  $$L_{MO} = \rho\ C\ TEMP_{ref}\ U^3 / (k\ \ g\ \ H) \qquad (1)$$

  where ρ (density of air) is 1.2041 kg/m^3, C (specific heat capacity of air) is 1 kJ/kg, and $TEMP_{ref}$, is the reference temperature for that particular hour. If the value is missing for that particular hour, the average of the remaining four sites is used. Other parameters were k = 0.4 and g = 9.81 m/s^2, and H (heat flux) new values of U* for the corresponding hour. Finally, the height of mechanically generated boundary layer was computed using new values of $U^{*:}$

  $$H_{BL} = 2300\ \ U^{*1.5} \qquad (2)$$

- Other missing parameters from the AERMET pre-processor were replaced using standard values.

Relatively little replacement was needed to obtain a complete set of meteorological parameters for the year 2010.

Roadway links and traffic activity

Road network data for the Detroit study area, including the locations of individual links, link classifications, annual average daily traffic (AADT) and average speed information, were provided by the Southeast Michigan Council of Governments (SEMCOG) for 9,701 road links and the year 2010. For the larger roads, e.g., major arterials and interstate highways, each road direction is represented by a separate link. These link data do not include local roads, e.g., neighborhood streets and alleys, but these streets generally have very little traffic.

Next, hourly traffic volume, fleet mix, and vehicle speed was estimated for each link, information used to estimate emissions, as described below (Cook 2004). The AADT and speed data for each link were derived using road counts and travel demand modeling (TDM) with link-specific inputs including AADT, number of lanes, roadway type and location, provided by SEMGOG, the Michigan Department of Transportation (MDOT), and the US EPA Office of Transportation and Air Quality (OTAQ). The average speed for each link was estimated for four time periods: morning rush hour peak (7-9 AM), mid-day (9 AM – 3 PM), afternoon rush hour peak (3 PM – 6 PM), and off-peak (6 PM – 7 AM).

Hourly traffic flows were derived for each link and vehicle class. The hourly number of vehicles on link i was calculated as:

$$V_{i,k,t} = FM_{NFC(i),k}\ \ MAF_{MON(t)}\ \ DAF_{k,DAY(t)}\ \ HAF_{NFC(i),t}\ \ AADT_i \qquad (3)$$

where $V_{i,k,t}$ (counts h^{-1}) is the number of vehicles on link i (i = 1 ... 9701) for vehicle class k (k = 1 ... 8) and hour of the year t (t = 1 ... 8760), and $AADT_i$ is the annual average daily flow for link i, as noted above. Eq. (1) uses three temporal allocation factors to account for variation by month of the year, day of the week, and hour of the day, as well as a fleet mixture factor, each described below. The 8 vehicle classes represent aggregations from MOVES emission model and represent motorcycles, light-duty gasoline vehicles, light-duty diesel vehicles, light-duty gasoline trucks with gross vehicle weight (GVW) less than 6001 pounds, light-duty gasoline trucks with GWV>6001 pounds, light-duty diesel trucks, heavy-duty diesel trucks, heavy-duty gas vehicles, and heavy-duty diesel vehicles (MC, LDGV, LDDV, LDGT1, LDGT2, LDDT, HDGV, HDDV). These classes were derived using state-level data from the Federal Highway Administration, and information from the U.S. EPA Emission Inventory Improvement Program.

The fleet mix allocation factor $FM_{NFC(i),k}$ (dimensionless) gives the fraction of vehicles in vehicle class k for link i, which depends on its National Functional Class (NFC) designation. Allocation factors are based on Table VM-4 from the FHWA Highway Statistics Series (http://www.fhwa.dot.gov/policyinformation/statistics/2010/vm4.cfm) in conjunction with information from the U.S. EPA Emission Inventory Improvement Program (USEPA, 1996). Modeled NFCs included interstates, other freeways, other principal arterials, minor arterials, major collectors, minor collectors and bridge (NFC designations 11, 12, 14, 16, 17, 19 and 90). For example, for urban interstates (NFC=11), LDGV and HDDV respectively represent 70.8 and 7.7% of the AADT. This adjustment has the constraint that summed across the 8 vehicle classes, $\Sigma_{k=1 .. 8} FM_{NFC(i),k} = 1$ for each road link. (In Detroit, only 3 links were designated as NFC=90, of which one had AADT=0 and the others were quite short (245 and 163 m in length. No fleet mix allocation factor was available for NFC=90, thus, this we used NFC=11, which had the highest allocation of diesel vehicles.)

The month-of-year allocation factor $MAF_{MON(t)}$ (dimensionless, with month indexed by hour t) had values that ranged from 0.86 (December) to 1.10 (August), reflecting higher summer traffic. This allocation factor has the constraint that summed across the 12 months, $\Sigma_{t=1..12} MAF_t = 12$.

The day-of-week allocation factor $DAF_{k,DAY(t)}$ (dimensionless), where DAY(t) is the day of week (indexed by hour t), has the effect of slightly increasing daily total flows for most vehicle classes on Friday (by 8%), and decreasing flows on Saturday (by 9%) and Sunday (21%), all compared to other weekdays. However, the pattern differs for the HDGV and HDDV classes, which have slightly lower flows on Friday (by 3%) and significantly lower flows on Saturday and Sunday (61 and 71%, respectively). This factor has the constraint that summed across the 7 days in a week, $\Sigma_{t=1..7} DAF_{k,DAY(t)} = 7$ for each vehicle class k.

The hour-of-day allocation factor $HAF_{NFC(i),HR(t),DT(t)}$ (dimensionless) represents the proportion of traffic volume for hour of the day (HR(t) = 1 ... 24, indexed by hour t) and day type DT(t) = 1 ... 3 (indexed by t), respectively representing weekdays, Saturday, and Sunday. This factor was obtained from SMOKE (Pouliot et al., 2012). Separate patterns are used for weekdays, which are typically bimodal with peaks representing morning and afternoon rush hour peaks, and weekends, which are typically unimodal with a broad afternoon peak. However, patterns vary by road type as given by NFC. This factor has the constraint that summed across the 24 hours in a day, $\Sigma_{t=1 ... 24} HAF_{NFC(i),DT(t),HR(t)} = 1$ for each NFC and DT.

For traffic on holidays, a Sunday schedule was assumed, accomplished by setting both the day-of-week and hour-of-day allocation factors $DAF_{k,DAY(t)}$ and $HAF_{NFC(i),HR(t),DT(t)}$ to Sunday values. Holidays in year 2010 considered were New Year's Day (Jan. 1), Memorial Day (May 31), Independence Day (July 5), Thanksgiving (Nov. 25), and Christmas (Dec. 25).

We confirmed that these adjustments obtained the correct AADT by summing link specific-flows over vehicle classes and hours of the year, that is:

$$AADT_i \approx 365^{-1} \Sigma_{k=1..8} \Sigma_{t=1,8760} V_{i,k,t} \qquad (4)$$

Because the AADT does not account for holidays, eq. (2) is not an equality, although the difference between the AADT and the calculated average is very small.

Emissions

A source inventory for $PM_{2.5}$ was compiled for roads in Detroit and surrounding Wayne County for the year 2010. Hourly estimates of emissions were calculated for each of the 9,701 links.

First, emission factors for primary exhaust emissions of each pollutant were calculated using MOVES2010a, a US EPA program (Wallace et al., 2012). MOVES is designed to estimate emissions from vehicle sources using a power-based approach. Emission rates in MOVES vary by vehicle class, vehicle speed, ambient temperature, and fuel properties. Thus, emission factor $EF_{k,\ SPEED,\ TEMP,\ MON}$ (g $mile^{-1}$ $vehicle^{-1}$) were calculated for 8 vehicle class (k=1…8), 16 vehicle speeds (2.5, 5, 10, 15 … 75 mph), 11 ambient temperatures (0, 10, 20 ... 90, 100 ^{o}F), and 12 months (Jan. through Dec.) Monthly average properties for fuels in the modeling domain were used, based on survey information from SEMCOG. MOVES inputs were adjusted for the vehicle age distribution of the 2010 Detroit fleet, based on an analysis of vehicle registration information by the Lake Michigan Air Directors' Consortium (LADCO).

The pollutant-specific emission factors from MOVES were applied to each of the 9701 road links in the study domain to generate an hourly and link-by-link emissions inventory that accounted for traffic activity on each link, including the estimated hourly flows of each vehicle type and the average speed for each link and hour. Link-specific emission rates $E_{i,t}$ (g m^{-1} s^{-1}) for link i and hour t were calculated as follows:

$$E_{i,t} = 1.72604E\text{-}07\ \Sigma_{k=1...8}\ EF_{k,\ SPEED(i,\ t),\ TEMP(t),\ MON(t)}\ V_{i,k,t} \qquad (5)$$

where the first constant converts units of distance (1 mile/1609 m) and time (1 h/3600 s), thus matching the vehicle counts and EFs from MOVES; $EF_{k,SP0EED(i,\ t),\ TEMP(t),Month(h)}$ is the emission factor (g $vehicle^{-1}$ $mile^{-1}$) from MOVES for link i, vehicle class k, link speed SPEED(i, t), hourly average ambient temperature TEMP(t), and month MON(t); and $V_{i,k,t}$ is the number of vehicles per hour for link i, vehicle class k, and hour of the year t, as given in eq. (1). Temperature and vehicle speed were placed into 11 and 16 bins, described earlier, and lookup tables were used to select values. Calculations in eq. (3) were performed for each pollutant.

Temperatures in eq. (5) were calculated as the average of five airport weather stations in the Detroit area. This provided a complete and robust dataset.

In summary, the modeled road network for Detroit contains 9,701 links that total 3,064 km in length. The total $PM_{2.5}$ from all the links (the product of the emission rate and link length summed across individual links is 15.9 g s^{-1} or 501 ton yr^{-1}. The latter number is comparable to values in a recent inventory for southeast Michigan in which primary on-road $PM_{2.5}$ emissions in Wayne County (a slightly larger area than Detroit) were estimated as 1,664 and 613 tons yr^{-1} for years 2008 and 2018, respectively.

Dispersion Modeling

Primary $PM_{2.5}$ from vehicle emissions were predicted using RLINE, a steady-state plume-dispersion model (Snyder et al. 2013; Venkatram et al. 2013) following standard guidance for roadway sources (US EPA, 2004). RLINE incorporates newly developed algorithms for predicting concentrations from road sources, including 'upwind' concentrations that can result from plume meandering. It utilizes a numerical method to integrate multiple point sources along a line source. As a line source model, it integrates multiple point sources along the road link, and automatically determines the number of points needed to represent each link. Meteorological using an error analysis to determine the number of points required. Dispersion parameters are derived from field data and recent wind tunnel experiments for near road sources. The model is capable of predicting concentrations at receptors very close to roads, and includes (upwind) plume meandering.

Currently, RLINE is available as beta test version from US EPA. At present, RLINE is considered to be a "research" model, and not a regulatory model.

Computational considerations

Estimating annual concentrations over the domain is highly computer intensive. Given the 9,701 road links, 27,622 receptors, and 8,760 hours per year, 2.34 trillion source-receptor calculations must be performed for each pollutant. Each source-receptor calculation involves iterative numerical algorithms. For this problem, a standard workstation would require many centuries, and even a large computer cluster can require many months. The following steps were used to speed up calculations:

- An analytical solution was used that provided similar results to the numerical model. This is also incorporated into the beta version of RLINE.
- Only receptor-road distances less 25 km were considered, since roads that are 25 km or more from a receptor provide negligible impacts.
- An adaptive algorithm accounting for distance and road link emissions under worst-case conditions was used to further limit the source-receptor pairs requiring calculation.
- Simulations were first run using a medium resolution receptor grid in order to select key days of interest and to refine the algorithm noted above.
- The spatial resolution and receptor network was adjusted (initially 100 m was considered).
- Annual simulations were based on a subset of meteorology, specifically, every 6th day in 2010 starting 1/3/2010. The selected 61 days were found to provide representative results.
- RLINE was rewritten to allow variable (hourly) emissions without post-processing.
- Portions of the RLINE code were optimized to eliminate repetitive calculations using lookup tables and other methods.
- The emission generator was revised to eliminate the use of enormous files and to use precomputed emission profiles for each NFC and speed class combination.
- Receptors were broken down into several subsets, and calculations were performed using several computers simultaneously by subset.

These steps allow computation of annual averages in approximately 2 days using several workstations simultaneously, with results that were very similar to those that included all source-receptor pairs and the numerical alogorithm. For $PM_{2.5}$, for example, results were about 0.2 µg/m^3 low at all receptors, due to the exclusion of distance sources, and correlation between streamlined and exact models was 0.984. Agreement was nearly perfect for concentrations above 1.0 µg/m^3.

Final format of data

Model outputs are hourly estimates of concentrations at each receptor. From these, daily and annual averages are computed, which is the form of data most useful to users. These data are provided as binary Excel files. A simple rectangular file is provided in which:

- Each file is a particular pollutant and time period, e.g., $PM_{2.5}$ concentration for selected days
- Column 1: an index (or rank)
- Column 2: UTM-X coordinate of receptor
- Column 3: UTM-Y coordinate of receptor
- Column 4: Annual average concentration at receptor in µg/m^3.
- Column 5: Maximum daily average concentration at receptor in µg/m^3.

Results provided to D3 have concentrations increased by 0.2 µg/m^3. The maps in this report do not use this correction.

Data interpretation and mapping

Several maps have been created for this report; Data Driven Detroit (D3) is anticipated to generate several others using ArcGIS and several other geodatabases.

Annual average $PM_{2.5}$ concentrations

Figure 1A displays annual average levels of $PM_{2.5}$ across the Detroit region due to local traffic emissions and the road network, which extends beyond the receptor network (where concentrations are calculated); Figure 1B is similar but zooms in the 10 x 12 km area and shows the detail of the road network and the spatial coverage of each (150 x 150 m) area modeled as a discrete receptor. The X and Y axes use the Universal Transverse Mercator projection, and the scales are in meters. Each map has grouped $PM_{2.5}$ concentrations into five levels (shown on the scale in the figures). Both figures display results from the annual simulation using hourly data, as described earlier.

Figures 1A and B show that that the highest concentrations occur near major roads, e.g., I75, I96, I94, M10 and M39, and particularly at the intersections of these (and other) high traffic roads. Several arterials also have relatively high concentrations, e.g., 8-Mile Road. The highest annual average concentration is 4.22 $\mu g/m^3$. $PM_{2.5}$ emissions arise from each vehicle class considered, but heavy diesel trucks produce a disproportionate share, thus, the highest $PM_{2.5}$ concentrations tend to be near high diesel-traffic roads like I94 and I75.

At first glance, annual average concentrations are roughly symmetrical on either side of major roads. However, a closer examination shows that pollutant levels tend to be higher on the east side of roads, as compared to the west side, an effect of prevailing winds and other meteorological factors. As will be discussed later, daily averages show much greater variation.

Levels of traffic-related air pollutants in Detroit are below the annual average standard for $PM_{2.5}$ which is currently 12 $\mu g/m^3$ (annual mean, averaged over three years). Monitored levels of $PM_{2.5}$ at Detroit area sites currently show levels around 10 $\mu g/m^3$. Again, Figures 1A and B, and all of the results of this project, are limited to only traffic-related air pollutants. (Stationary and regional air pollutant sources are not included.)

The annual average concentration often is considered to be the most representative estimate of pollutant levels. This indicator is relevant for examining effects that depend on long-term exposures, e.g., cancer risk.

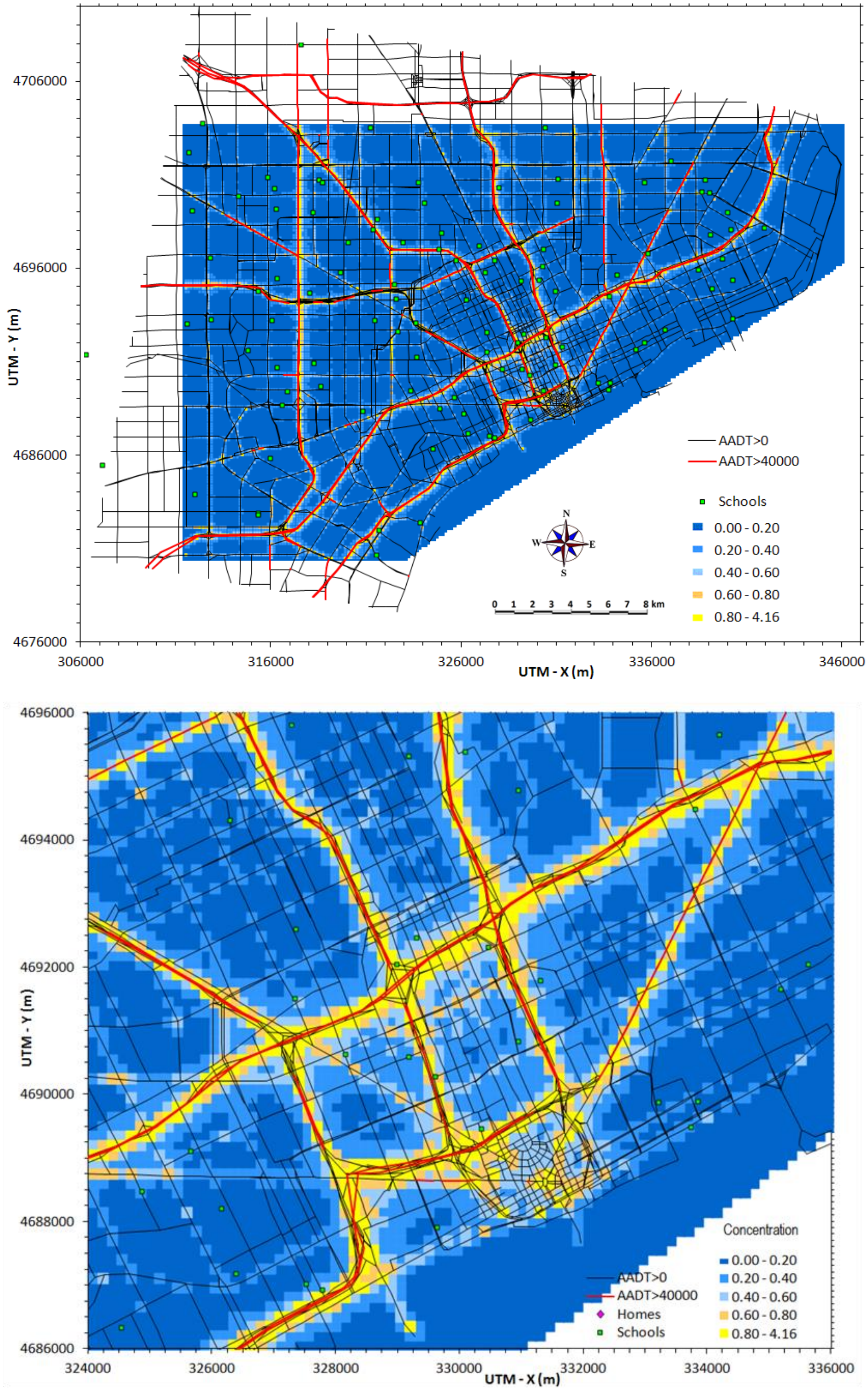
Daily average $PM_{2.5}$ concentrations

Much greater variation is displayed in daily (24-hr) averages, as shown in Figures 2A and B which respectively show 24-hr averages for Feb. 8, 2010 (Monday) and Dec. 29, 2010 (Wednesday), respectively. These days were selected as two of the higher $PM_{2.5}$ days, a result of poor dispersion conditions and higher emissions (due to weekday traffic and higher emissions during cold temperatures). On these days, concentrations reached 11 to 12 $\mu g/m^3$, and greater asymmetry is observed, especially on the Dec. 29th date, where winds were blowing primarily to the north.

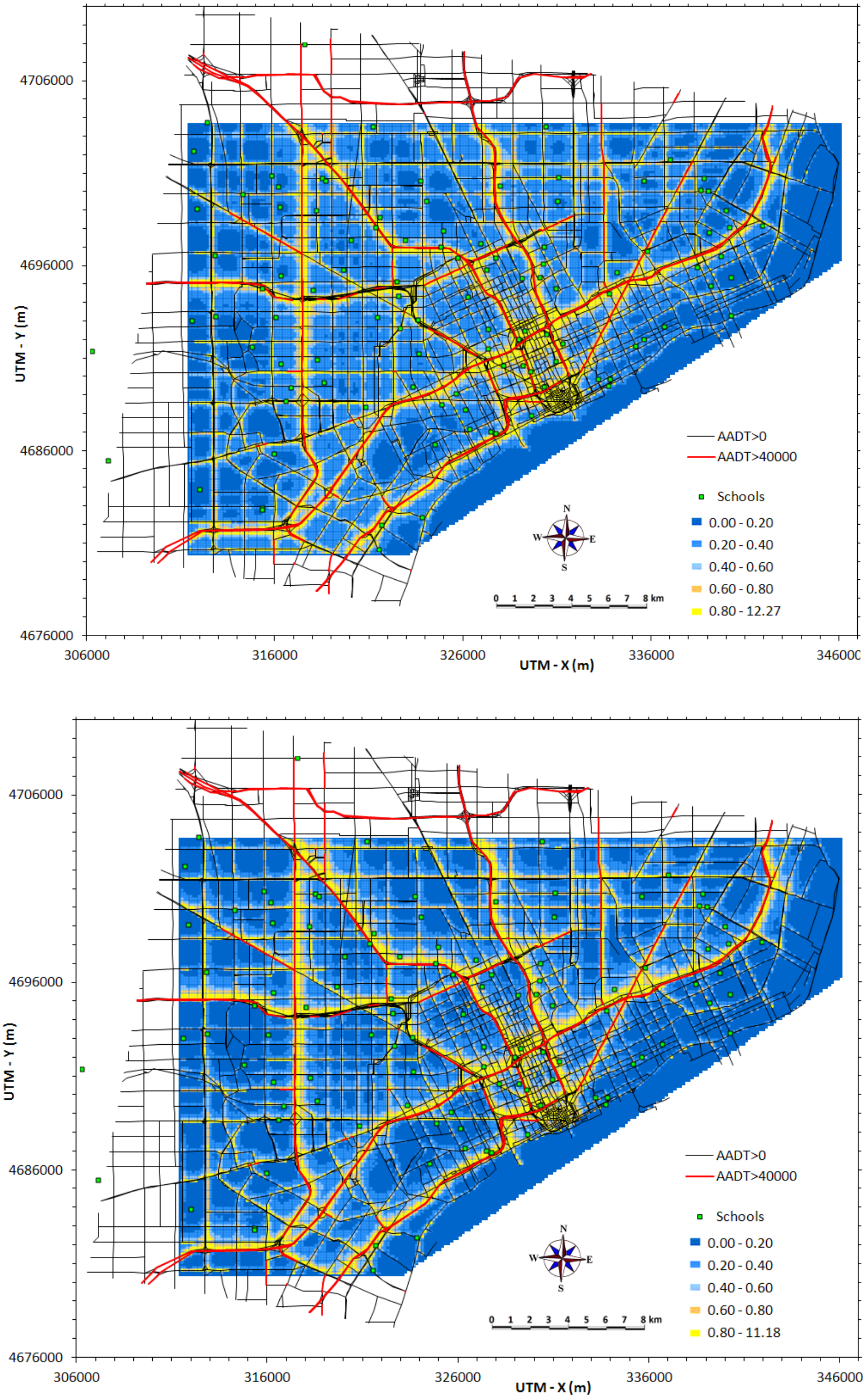
Maximum daily average $PM_{2.5}$ concentrations

A third $PM_{2.5}$ example is provided that uses the maximum daily average concentration occurring over the year. This is determined as the highest 24-hr average occurring at a receptor on any day during the year. As shown in Figure 3A, the portion of Detroit (areal extent) experiencing high concentrations increases with this indicator.

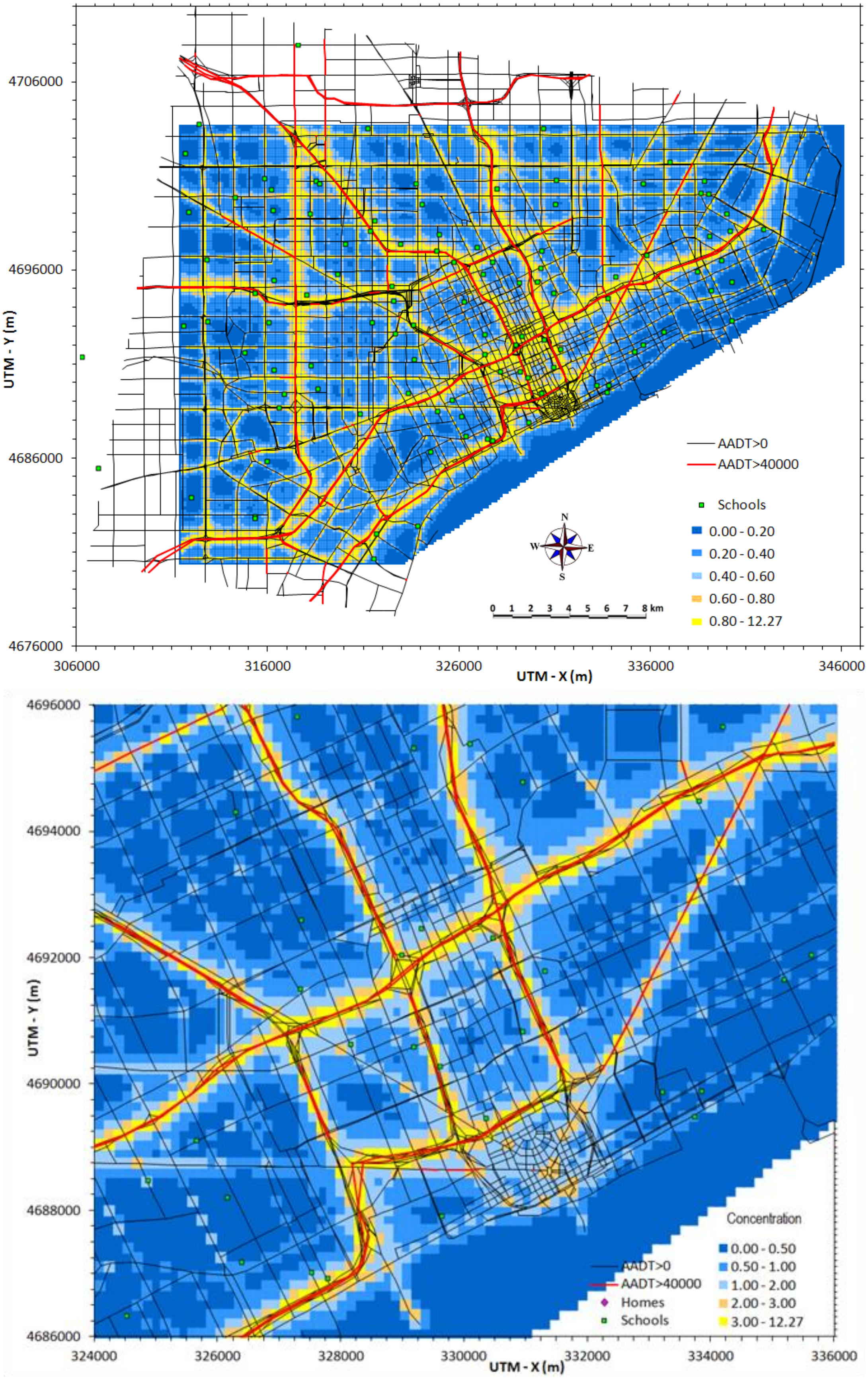
Figures 1A, B. Annual average $PM_{2.5}$ concentrations in $\mu g/m^3$ across Detroit (top) and in central area (10 x 12 km area, bottom). Locations of (some) schools in Detroit are shown as green squares.



Figures 2A, B. Daily (24-hr) $PM_{2.5}$ concentrations in μg/m^3 across Detroit for Feb. 8, 2010 (top) and Dec. 29, 2010 (bottom). Locations of (some) schools in Detroit are shown as green squares.



Figures 3A, B. Maximum daily $PM_{2.5}$ concentrations in µg/m^3 across Detroit (top) and in central area (10 x 12 km area, bottom). Locations of (some) schools in Detroit are shown as green squares.



The maximum daily average can be compared to the short-term National Ambient Air Quality Standard, which for $PM_{2.5}$ is currently 35 µg/m^3 (98th percentile, averaged over 3 years). Figure 3B shows the maximum daily average for the central portion of Detroit. Note that the concentration scale has been changed to show the gradient clearer. This figure illustrates that areas 1 km or more distant from the roadway can experience $PM_{2.5}$ concentrations that are elevated by 1 µg/m^3 or more.

The maximum daily average concentration often is useful to indicate areas potentially affected by high short-term pollutant levels, e.g., it can show potential hotspots. This indicator is relevant for examining effects that depend on acute exposures, e.g., asthma exacerbation and cardiovascular effects.

Annual average NO_x concentrations

Figure 4A displays annual average levels of NO_x across the Detroit region due to local traffic emissions and the road network, which extends beyond the receptor network (where concentrations are calculated); Figure 4B is similar but zooms in the 10 x 12 km area and shows the detail of the road network and the spatial coverage of each (150 x 150 m) area modeled as a discrete receptor. As before, the X and Y axes use the Universal Transverse Mercator projection, and the scales are in meters. Each map has grouped NO_x concentrations into five levels (shown on the scale in the figures). Both figures display results from the annual simulation using hourly data, as described earlier.

Vehicle exhaust emissions include both NO and NO_2, which is summed together as NO_x. Much or most of the NO is rapidly oxidized to form NO_2. Both gasoline- and diesel-powered vehicles can emit substantial levels of NO_x, in contrast to $PM_{2.5}$ emissions which are dominated by diesel-powered vehicles. Thus, estimated NO_x concentrations tend to reflect total traffic (both cars and trucks), and roads such as I96 and M39 which have extensive car traffic and relatively low truck traffic (compared to I75 and I94) can have high NO_x levels. Still, NO_x and $PM_{2.5}$ concentrations are highly correlated, as shown by the similar patterns in Figures 1 and 4.

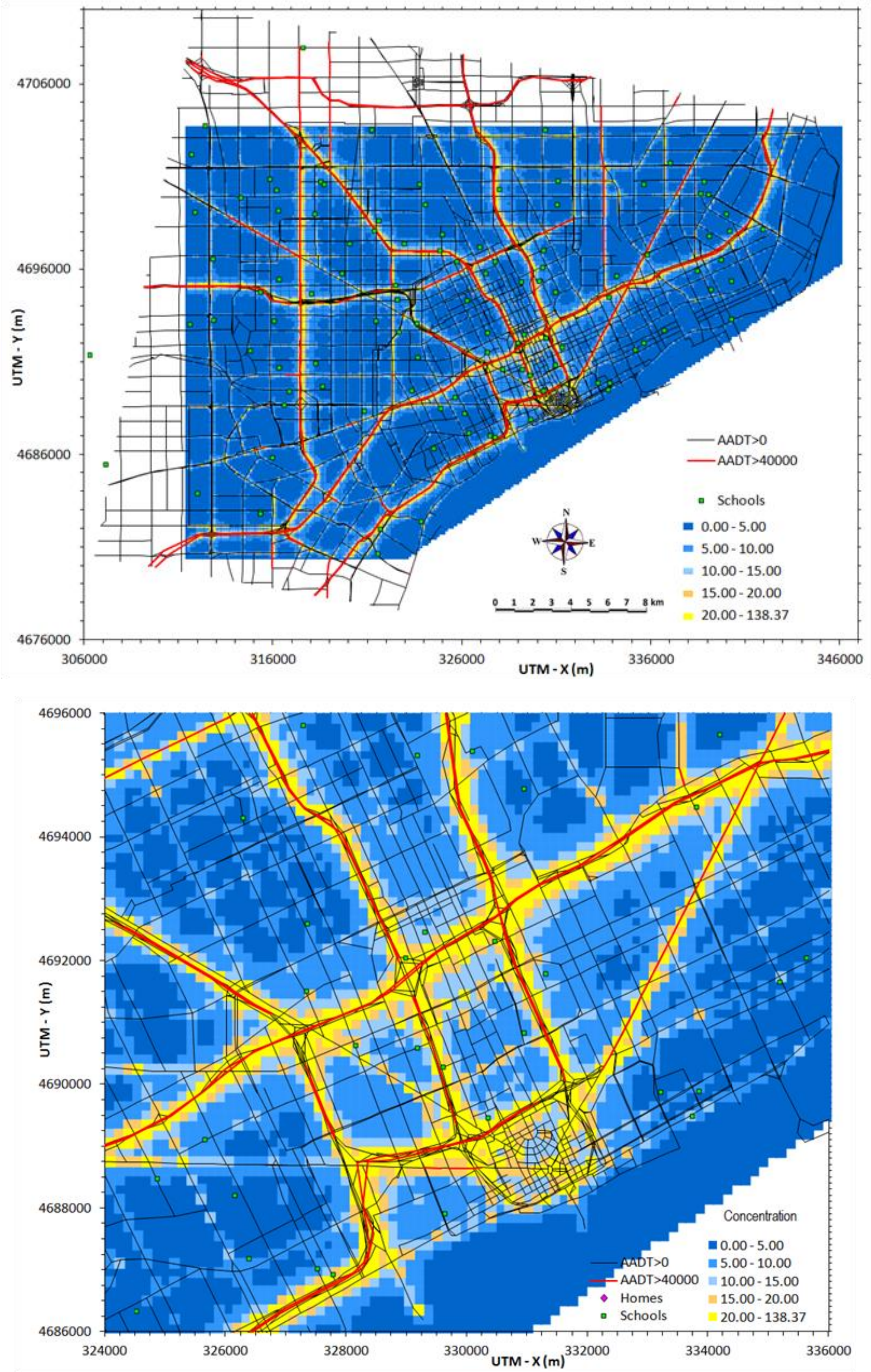
NO_x concentrations that result from traffic constitute a large or potentially the dominant source of NO_x in urban areas. If all NO_x is assumed to form NO_2 immediately, then modeling results approach or exceed the previous NAAQS for NO_2 of 53 ppb or 100 µg/m^3 on an annual average basis. (Recently, the NAAQS primary standard switched to a one hour averaging period.) However, this assumption is not realistic, and observed NO_2 levels in Detroit do not exceed the NAAQS. This comparison is provided only to shows the importance of vehicle emissions.

Hourly NO_x concentrations

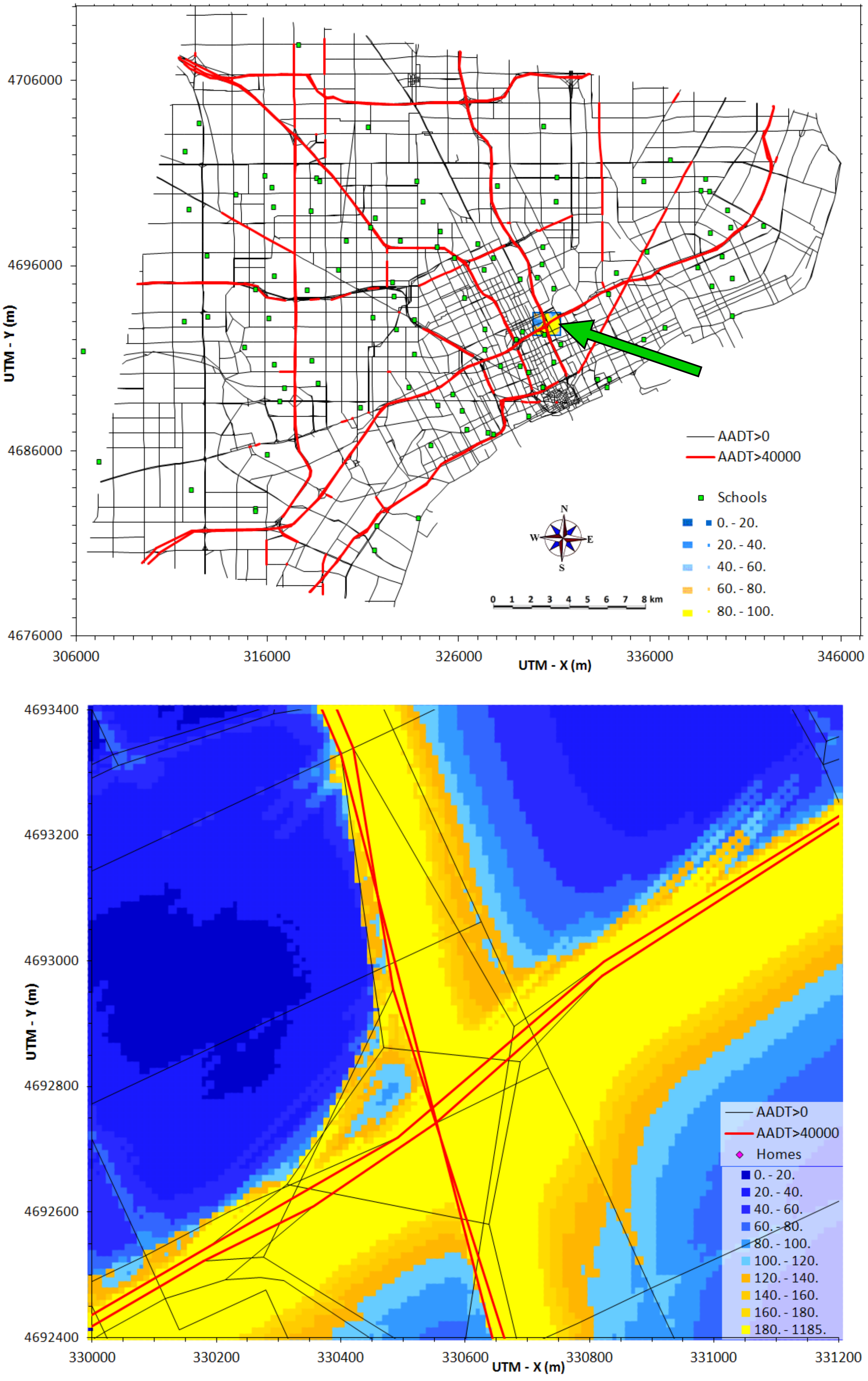
An example of extremely high resolution modeling is presented in Figure 5, which uses receptors on a 10 m grid near a high impact area, the intersection of I75 and I94. A 1.0 x 1.2 km region was simulated for the first 12 days in 2012, and the second-highest hour was selected for display. The prevailing meteorology was cold (267 C or 21 F), low wind speeds (1.1 m/s) from the WNW (314°).
This result shows smooth concentration gradients, large decreases in concentrations by 200 to 300 m of the major roads, and results that generally match those seen in the earlier figures. Such modeling might be used to evaluate compliance with the 1 hour standard for NO_2 NAAQS.

Generally, it is not practical to model large areas with 10 m resolution. Compared to the earlier results using 150 m resolution, the 10 m simulations requires 225 times more receptors (about 7 million for Detroit). The similarly in results obtained at 150 m resolution suggests that earlier results are adequate to estimate exposure in all cases except at locations that are extremely close (within perhaps 50 m) of major roads.

Figures 4A, B. Annual average NO_X concentrations in $\mu g/m^3$ across Detroit (top) and in central area (10 x 12 km area, bottom). Locations of (some) schools in Detroit are shown as green squares.



Figures 5A, B. NO$_X$ concentrations for Jan. 11, 2010 5 pm (in µg/m^3) for I75-I94 area with 10 m resolution. Top: green arrow indicates modeled area; Bottom: 1.0 x 1.2 km area modeled.



Recommendations for data use

Several recommendations are made for utilizing the data produced.

- Pollutant levels can be mapped to census block groups, census blocks and parcels. Preliminary work on this has been completed by D3 and shows that block groups and blocks do not provide the spatial resolution needed to provide accurate results. Specifically, pollutant levels can change dramatically within a few hundred meters and thus the use of small geographic units, like parcels, are recommended.
- To show representative levels, the use of annual average data is preferred. To show potential hotspots, the use of the maximum daily average is preferred.
- Identification of pollutant "hotspots" and especially schools, hospitals, parks, athletic fields, and other "critical locations" where children and other susceptible individuals may be highly exposed to air pollutants. For example, this could improve a previous analysis of Detroit schools that used proximity measures to measure the impact of highways (Batterman and Wu, 2006).
- Epidemiology studies investigating the association of potential exposure to $PM_{2.5}$ and NO_x with adverse health outcomes, e.g., cardiovascular disease, asthma symptoms, and viral infections. This requires that health surveillance data be collected on a spatial scale that is sufficiently resolved, e.g., block or possibly block-group level.
- Exposure and risk assessment studies to quantify exposure and risk to traffic-related air pollutants. This might entail, for instance, use of Census records to identify the numbers of individuals exposed to specific levels or ranges of $PM_{2.5}$, adjustments for indoor exposure, time activity, and dose-response relationships. Such studies might also be useful in (ongoing) environmental impact studies examining the impact of freeway expansion, e.g., to understand the number of households potentially affected by air pollutant emissions.
- Exposure and risk minimization studies aimed at reducing pollutant exposure using, for instance, traffic controls that reduce traffic, improved emission controls on vehicles, and/or buffers around highways or critical facilities (e.g., schools and playgrounds). In particular, vegetated buffers can offer multiple benefits as they can lower concentrations, enhance the removal of pollutants; reduce noise; and provide parkland with opportunities for recreation and physical activity. Furthermore, buffers can form linked corridors for non-motorized transportation (e.g., walking, biking); provide shading and cooling; CO_2 uptake; remediation of contaminated soil (if present); biofiltration of potentially contaminated water run-off; leveling of peak storm water flows and minimization of soil erosion; use as urban gardens; improved aesthetics; and local employment.
- Cost-effectiveness studies, e.g., estimation health and environmental costs of traffic-related pollutants and mitigation strategies.
- Development of composite "sustainability indicators" by overlaying air pollutant data with other GIS layers representing other environmental, social and physical stressors. For instance, additional layers might include household income, access to nearby medical facilities, housing condition, and population density (or number of children in the area). Poor, medically underserved and highly exposed children would be especially vulnerable to both chronic and acute disease.

Potential policy options for decision makers utilizing the data

The previous section already has touched on several policy options. Several specific policy options include:

- Requirements or recommendations for buffers around highways to reduce pollutant exposure and adverse health impacts, and for other co-benefits discussed previously.
- Requirements or recommendations that schools and other critical facilities be sited in a manner to minimize pollutant exposure, e.g., using minimum distances from highways.
- Incorporation of assessment of pollution-related impacts associated with transportation projects (e.g., highway widening, traffic shifting) in the Environmental Impact Assessment (EIS) process.
- Enhanced land use and transit corridor planning to minimize pollutant exposure
- Recommendations that older vehicles in bus and truck fleets be retrofitted with control technology to reduce emissions and exposure.
- Recommendations and policies that reduce traffic-related emissions, including development of transit and incentives for zero-emission vehicles (ZEVs), e.g., electric vehicles.
- Recommendations to enhance health surveillance activities followed by epidemiology analyses using exposure indicators to improve understanding of the risk factors that cause disease.
- Support for enhanced emission inventories for mobile sources that include both conventional air pollutants, e.g., $PM_{2.5}$ and NO_x, as well as greenhouse gases such as CO_2.
- Support and development of infrastructure to maintain emission inventories and modeling capability for concentration and greenhouse gases at both project and regional levels.

Partners and community organizations

This research was conducted with input from several partners including the Community Action Against Asthma (CAAA) Steering Committee. CAAA includes community-based organizations, health and human service organizations, and university researchers including: Arab Community Center for Economic and Social Services (ACCESS); Community Health & Social Services Center (CHASS); Detroit Hispanic Development Corporation (DHDC); Detroiters Working for Environmental Justice (DWEJ); Friends of Parkside (FOP); Latino Family Services (LFS); Warren/Conner Development Coalition; Detroit Institute for Population Health; and the University of Michigan. We also partnered with US EPA. EPA staff in North Carolina provided assistance with modeling inputs, MOVES and RLINE used in the present project.

Limitations

Several limitations of the present work are summarized here.

- Simulation modeling involves a large number of parameters, assumptions and input data. While results are presented as (point) estimates, uncertainties can be considerable. Thus, while predictions use the best available information, actual concentrations will likely differ from predictions. However, the models used are believed to better represent actual data better than previous models. Errors likely decrease as the averaging time increases, e.g., annual average estimates will likely be more reliable than estimates for a particular hour or day.
- While the absolute level of the concentration predictions involves uncertainties, i.e., the model may under- or over-predict by a factor of two (roughly) due to uncertainties in the emission inventory, the spatial patterns are likely to be accurate.
- While a relatively fine grid with 150 m spacing was used to show spatial patterns of pollutant concentrations, the spatial resolution could be further refined, possibly showing very localized “hotspots” of high concentration. This would likely increase the highest concentrations. However, issues of model accuracy, including geocoding of roads, may not significantly improve results.

- Results include only the contributions made by traffic emissions. The estimated concentrations do not include stationary or "point" source emissions (e.g., power plants, boilers), and distant or "background" sources (due to emissions out of the local area). In general, local stationary sources of $PM_{2.5}$ and NO_x are not as important as traffic emissions (although stationary sources can cause localized hotspots). Background levels of $PM_{2.5}$, including secondary sulfate and nitrate, can be very important, however. Much of the background $PM_{2.5}$ arises from coal-fired power plants in the Ohio River Valley and from other distant sources.
- The available monitoring data suggests that the predictions are in a reasonable range; however, no attempt was made to "validate" the model using these data.
- Only primary emissions from traffic-related sources were modeled (chemical reactions that may affect pollutant levels are not modeled.
- Only one year (2010) was evaluated. The results are probably reasonable for the 2008 – 2012 period, but due to changes in emissions and traffic, the results may be less relevant for both earlier (or later periods). In particular, diesel emissions that produce considerable emissions of $PM_{2.5}$ have been greatly reduced in the last few years due to the use of low sulfur fuels and emission controls.
- The selected pollutants, $PM_{2.5}$ and NO_x, are both "criteria" air pollutants regulated by the U.S. Environmental Protection Agency. The Detroit region is presently designated as an attainment area (meaning that federal ambient standards are attained) for these pollutants. However, the region is a non-attainment area for ozone, for which NO_x is a precursor. The modeling results do not include VOCs, which is also an ozone precursor.

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