A Near-Road Modeling System for Community-Scale Assessments of Traffic-Related Air Pollution in the United States

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Highlights

- Developed a near-road modeling system to estimate mobile-source emissions and dispersion
- The modeling system automatically provides nationwide coverage for most major roadways
- Users can manipulate input data on traffic and meteorology to compare differences in resulting air toxics concentrations
- The modeling system is optimized for use in local-scale community-based types of scenarios

Abstract

The Community Line Source (C-LINE) modeling system estimates emissions and dispersion of toxic air pollutants for roadways within the continental United States. It accesses publicly available traffic and meteorological datasets, and is optimized for use on community-sized areas (100-1,000 km^2). The user is not required to provide input data, but can provide their own if desired. C-LINE is a modeling and visualization system that access inputs, performs calculations, visualizes results, provides options to manipulate input variables, and performs basic data analysis. C-LINE was applied to an area in Detroit, Michigan to demonstrate its use in an urban environment. It was developed in ArcGIS, but a prototype web version is in development for wide-scale use. C-LINE is not intended for regulatory applications. Its local-scale focus and ability to quickly (run time < 5 min) compare different roadway pollution scenarios supports community-based applications and help to identify areas for further research.

Keywords: near-road; air toxics; modeling system; emissions; dispersion; air quality

1. Introduction

Living, working, and going to school near roadways has been associated with a number of adverse health effects, including asthma exacerbation, cardiovascular impairment, and respiratory symptoms (see HEI, 2007 for a comprehensive review). In the United States, 30% to

45% of urban populations live or work in the near-road environment, with a greater percentage of blacks, Hispanics, and low-income residents than whites living in areas of highly-trafficked roadways (Tian et al., 2012). Near-road studies typically use surrogates of exposure to evaluate potential causality of health effects (Lipfert, 2008). Surrogates include proximity, traffic counts, or total length of roads within a given radius around the impacted location (HEI, 2010; Ryan et al., 2007).

In the United States, modeling efforts related to a state or federal policy initiative (EPA, 2008) require detailed analyses using specific datasets and highly-structured models to produce the most accurate estimates possible of actual pollutant concentrations. Typical modeling efforts for these applications require the use of separate emissions and dispersion models, with subsequent visualization being performed separately as needed. Applications are often related to specific projects and regions, such as highway expansions or traffic re-routing for an urban area. Therefore, users might require modeling expertise to run the models and collect the local input datasets necessary for their performance, and then to subsequently interpret results (Cook et al., 2006).

Community groups are becoming increasingly active in local initiatives that seek to mitigate potentially harmful environmental conditions. Community-based participatory research is an example where community residents work directly with the scientific community to identify these situations. Studies are typically independent, locally-based, and solution-oriented. As such, they are not required to follow regulatory procedures to collect information and make decisions, but instead utilize information sources relevant to their defined objectives. While these sources may not be adequate to meet regulatory requirements, they can meet the goal of informing local decision making. For example, an integrated modeling system that includes an activity-based transport demand model, a traffic emission model, a dispersion model and a concentration measurement interpolation model has been developed and applied in Europe, in the regions of Flanders and Brussels, Belgium (Lefebre et al, 2013). Another example of using models to inform local decision making is the CARBOTRAF system implemented and evaluated in Graz, Austria and Glasgow, UK with the purpose to reduce BC and CO2 emissions and improve air quality by optimizing the traffic flows (Lefebre et al, 2014). In community-scale modeling in support of local decision making, an accurate assessment of relative conditions (e.g., one area compared to another, or what-if scenarios that elucidate differences in two or more sets of conditions) can be sufficient for the user's needs. In these cases, simplified modeling systems can provide valuable insights to assist with the decision-making process.

Simplified models provide an opportunity to examine how changes in input parameters, such as vehicle counts or speeds, can affect results (Batterman et al., 2010). The structure of these models can vary depending on the developers or application. Typically, they maintain the same or similar algorithms most responsible for characterizing model uncertainty. Components that are not as influential in model performance or the desired outputs, or structured for a specific model function, could be omitted or parameterized (Batterman et al., 2010). Simplified modeling systems like C-LINE allow users to ask what-if questions, such as, "What will happen if diesel traffic doubles on this roadway?" or "How is near-road air quality affected by a traffic jam?" and then to assess the relative changes in near-road air toxics concentrations that could occur (Batterman et al., 2010; Mejia et al., 2011; Vette et al., 2013). For C-LINE, the user is not required to provide any input datasets, and they can manipulate the existing ones or upload their own if desired.

This paper describes the input parameters, analytical procedures, visualization routines, and software considerations for C-LINE, including a discussion of the dispersion algorithm and an example application for an area of Detroit, Michigan. C-LINE is being developed by the United States Environmental Protection Agency (US EPA, or EPA) Office of Research and Development (ORD) as part of the Sustainable and Healthy Communities (SHC) research program, which is designed to empower and inform communities by providing decision support tools, models, and metrics that promote efficient, balanced, and equitable sustainability initiatives (see http://www.epa.gov/research/research-programs.htm for more information).

2. Model Inputs and Outputs

This section describes C-LINE input variables and datasets, and the outputs provided by the modeling system. Potential future additions are described in Section 6 (Discussion). C-LINE automatically accesses publicly available datasets with nationwide coverage and provides results for the user-defined geographic area as both visualized maps and tabular data. Users are also able to upload their own (e.g., locally-derived) datasets on traffic activity and/or meteorology to perform model runs.

2.1 Emissions

C-LINE calculates emissions for each road segment using three inputs: 1) the road network (e.g., roadway types and locations); 2) traffic activity on the network (e.g., traffic counts); and 3) vehicle emission factors (i.e., emitted pollutants based on vehicle type, speed, and outdoor temperature). It currently accesses data from calendar year 2010.

2.1.1 Road Network

The first input variable to consider is the road network for a given area. A road network is the system of interconnected roadways, and a description of their types (e.g., principal arterials such as interstates). The roadway files are cross-referenced with traffic activity data in order to determine the number and types of vehicles on each roadway. Road network is also used in the dispersion component of C-LINE in order to distribute receptor locations across the spatial domain (described below) where concentrations are calculated.

Road networks are downloaded as shape files from the Freight Analysis Framework (FAF), available from the U.S. Department of Transportation Federal Highway Administration (DOT-FHWA). Files provide a GIS-based centerline representation of the roadway network in the United States (see http://faf.ornl.gov/fafweb/Default.aspx for more information). The overall network is divided into approximately 171,000 links (or *segments*) representing nearly 448,000 miles of roads. Each road segment is also designated by type: urban or rural; arterials, collectors, and local. Arterials provide the highest level of mobility and highest speed for long uninterrupted travel, and include highways and interstates. Arterials are further classified as principal or minor. Collectors provide lower mobility than arterials, and are designed for lower speeds and shorter distances; they are generally two lane roads that collect traffic from local roads and distribute it to arterials. Collectors in rural areas are further designated as major or minor. Local roads are all public roads below the collector classification.

2.1.2 Traffic Activity

Traffic activity describes the number, types, and speeds of vehicles on a given roadway and for a given time period. For example, one might expect a higher number of gasoline cars traveling at lower speeds on an urban highway during the morning commute. Therefore, in order to calculate emissions, one needs to determine the total number of vehicles, distribution of vehicle types, and vehicle speeds for a given time period and road segment.

In addition to the road network data, FAF also provides information on annual average daily traffic (AADT), which is then used to calculate vehicle miles traveled (VMT) for each road segment. VMT is AADT multiplied by the length of the road segment. As the name implies, AADT for a given road segment is the average number of vehicles that travel a road segment in a single day, based on the total volume of vehicular traffic for a year divided by 365 days. AADT is a rate that cannot be summed across all roadways, so VMT is a more useful measure of the total amount of traffic in a given area.

FAF does not include detailed fleet mix data (e.g., number of gas and diesel) for each road segment, but it provides distribution tables that describe the typical fleet mix for a given roadway type based on a classification of the roadway segments for each state (see http://www.fhwa.dot.gov/policyinformation/statistics/2010/vm4.cfm for more information). For example, an urban (rural information in parentheses) interstate for Michigan in 2010 had an estimated distribution of 72% (67%) passenger cars, 18% (19%) light trucks, and 7% (11%) combination trucks. Distributions from these tables are applied to the given VMT for a road segment to determine its fleet mix. Vehicle classes from FAF include passenger vehicles (cars, motorcycles, buses, and light trucks (two-axle, four-tire models)); single-unit trucks having six or more tires; and combination trucks, including trailers and semitrailers.

The fleet distribution tables provide a daily estimate of the number and types of vehicles on a given roadway. That total daily traffic count must then be allocated to different time periods throughout the day. For example, a road segment will experience the majority of its daily VMT on weekday rush hour periods during the morning and afternoon commutes. These periods would likely account for correspondingly higher near-road air toxics concentrations. C-LINE distributes VMT by time of day (AM or PM rush; mid-day; and off-peak), week (weekday, weekend), and year (summer, winter) based on temporal allocation factors (TAFs) generated by the Sparse

Matrix Operator Kernel Emissions (SMOKE) modeling system (Houyoux et. al, 2000). TAFs are national and not region-specific.

C-LINE also requires vehicle speed in order to estimate emissions. C-LINE uses FAF 2007 estimated peak period link speed, which includes consideration of the travel demand and road capacity for a given segment. The user is allowed to modify these values to assess variations in conditions, or in case of discrepancies between national and local data.

2.1.3 Emissions Factors

Emission factors (EF) for all pollutants are a function of speed, composition and age of the fleet, ambient temperature and fuel composition. EFs are normalized by an activity basis, such as mass of pollutant per unit time or mile. Combined with EF tables, C-LINE inputs meteorology (outdoor temperature) and traffic distributions to calculate pollutant concentrations at the source of emissions; in this case, traffic type and volume multiplied by the EFs. EF tables were provided by the Multi-scale mOtor Vehicle and equipment Emission System (MOVES, version 2010b; EPA, 2012), an emissions model maintained by the EPA (http://www.epa.gov/otaq/models/moves/). MOVES was run for representative counties across the United States to determine county-specific emissions factors using highly-detailed, locally-derived input datasets. A representative county is the county with the highest VMT among counties in a State with similar fuels and temperature regimes. The representative county approach is used in EPA regulatory analyses (e.g., EPA, 2013). The representative county emissions factors were then assigned to other counties that shared attributes with the representative counties, such as fleet age, mix, and fuel composition, thus providing emissions factor estimates for the entire U.S. on a county-level basis in the form of tables. C-LINE utilizes these tables, supporting its simplified approach and precluding the need to run an emissions model separately for each application (but using results from an established model). C-LINE is intended to incorporate updated EF tables as they become available, which are useful for evaluating changes due to new technologies or stringent control measures.

The FAF vehicle-distribution tables uses a different vehicle classification system than the MOVES emissions factor tables. C-LINE maps the FAF vehicle types to the corresponding MOVES vehicle types, which are labeled as motorcycles, light-duty gas vehicles, light-duty diesel vehicles, two light-duty gas truck sizes, light-duty diesel trucks, heavy duty gas vehicles, and heavy duty diesel vehicles.

C-LINE includes running evaporative emissions in addition to the running exhaust emissions. Given its focus on roadway emissions (i.e., emissions that occur on highways), cold-start emissions are not included.

2.2 Meteorology

Meteorological inputs include wind speed and direction, outdoor temperature, and atmospheric boundary layer conditions such as mixing height, friction velocity (u-star), and Monin-Obukhov length. C-LINE uses hourly weather measurements from the National Weather Service monitoring site is nearest to the study location. Then, in order to calculate additional parameters for the dispersion component (i.e., mixing height, u-star, Monin-Obukhov length), the hourly meteorological data are processed using the EPA meteorological pre-processor, AERMET (http://www.epa.gov/ttn/scram/metobsdata_procaccprogs.htm#aermet).

To preserve the simplified functionality of C-LINE, hourly meteorological measurements are binned into the user-selected time interval, including morning peak (7-9AM), mid-day (9AM-3PM), afternoon peak (3-6PM), and off-peak (6PM-7AM). Season (summer, winter) and time of week (weekday, weekend) are also considered. In order to represent a prevailing wind direction for the area, wind direction is calculated as the median value for daytime hours based on the annual distribution of hourly observations. Like the other input parameters, the user is allowed to change the wind direction or upload their own meteorological datasets for processing, if desired.

Atmospheric conditions can vary significantly during a given day and between seasons. The variations in atmospheric conditions can alter the rate of dispersion of pollutants in the atmosphere, and hence the resulting pollutant concentrations. To account for these variations in atmospheric conditions, C-LINE allows the user to select one of three dispersion conditions that they would like to represent: “typical,” “favorable,” or “unfavorable.” These conditions are related to atmospheric stability.

“Typical” dispersion conditions are based on median values of meteorological parameters (wind speed, friction velocity, and Monin-Obukhov lengths), the user-selected time interval, and season; for example, a selection of Summer Off-Peak represents overnight summer values. Weekday/Weekend has no effect on meteorology. “Favorable” and “unfavorable” are based on the upper and lower 95th percentiles, respectively, of the distribution for the selected time interval. “Favorable” conditions contribute to high dispersion and mixing and relatively lower pollutant concentrations; they are characterized by high wind speeds, higher friction velocity (u-star), and a mid-range negative Monin-Obukhov lengths. “Unfavorable” conditions contribute to low dispersion and mixing, resulting in higher concentration gradients; they are characterized by low wind speeds, low u-star, and small positive Monin-Obukhov lengths.

2.3 Model Outputs

C-LINE calculates air toxic concentrations (in $\mu g/m^3$) at a set of points located perpendicular to the roadway segments; these points are termed, “receptors.” Receptors align with the midpoints of each road segment and are distributed out to 500 m from the road. The model is designed for estimating the impact of traffic emissions in the “near-road” environment. The 500 m buffer is large enough to capture the near-road impacts. Recognizing that the impact of traffic emissions can extend father that 500 m, especially for busy, heavily trafficked highways, the main focus of this project is the “near-road” zone. Karner et al. (2010) found that all pollutants decay to near background levels at distances of 150 – 570m from edge of roadway. Future versions may extend the dispersion profile, but the near-road domain would remain the same.

Receptor concentrations are then spatially joined (described in Section 3.4 Visualization). Thus, C-LINE outputs are air toxic concentrations displayed as continuous, adjacent buffers alongside the roads. Air toxics include both carcinogenic and non-carcinogenic pollutant species (Barzyk, 2012). As stated previously, results represent mean concentrations (calculations described below) for the user-selected time period. We continue to explore the utility and feasibility of storing hourly results for other uses, such as for the calculation of annual averages or for use in health and epidemiological studies.

3. Model Functionality

This section details each step and calculation that C-LINE uses to produce the near-road air toxic concentration gradients. Some aspects were covered in previous sections, but here we elucidate the processing sequence and calculations in more detail. Emissions and dispersion are covered first, and then visualization procedures. Then we discuss the features and inputs that a user can modify to run and analyze variations of a given scenario (i.e., *what-if* scenarios).

3.1 Model Calculations

The three general steps that C-LINE takes to calculate near-road concentrations include: 1) creation of the receptor network, 2) calculation of emissions based on vehicle counts and types, and 3) prediction of dispersion profiles based on meteorological parameters. A user selects the geographic domain within which the near-road concentrations will be produced, and C-LINE automatically downloads the road network for this area. Once the network is downloaded, C-LINE identifies the midpoint of each road segment, and creates the receptor network (at 50 m, 100 m, 200 m, 300 m, 400 m, and 500 m).

VMT is then assigned to each road segment and the fleet mix (e.g., car/truck ratio) is adjusted based on roadway type, time period, and geographic region; this provides total car and truck VMT. Emission factors are multiplied by the number of each corresponding vehicle type, such that total emissions are calculated by, $E_i(s) = EF_i(s) \times A(s)$, where $E_i(s)$ is emission rate (mass per unit time) for pollutant i from a source s (e.g., a given road segment); $EF_i(s)$ is the emissions factor (mass per unit activity) for pollutant i from a source s; and $A(s)$ is the activity level for source s (e.g., vehicle miles traveled) by time-of-day and day-of-week.

The dispersion component then calls the meteorological inputs and calculates the unit value dispersion profiles, which describes the relative concentration at a given distance as a function of the total source emission (e.g., 0.5 x total source emissions at 100 m). This profile is valid for non-chemically-reactive air pollutants. These unit-values are then multiplied by the source emission values to generate concentrations at each receptor. Details of the dispersion algorithm are provided below.

3.2 Dispersion Algorithm

One of the novel features of the C-LINE modeling system is the dispersion algorithm that calculates near-road pollution profiles. The dispersion algorithm is designed to specifically model line sources such as highways; it utilizes scientifically established methods to calculate dispersion; and it is streamlined for use in a simplified modeling system. The dispersion algorithm treats each lane of a highway as a line source that is located along the center of that lane. A set of elemental point sources represents each line source (Figure 1). The contribution of the elemental point source, *dC*, located at $(0,Y_s)$ to the concentration at (X_r, Y_r, Z_r) is given by the Gaussian plume formulation.

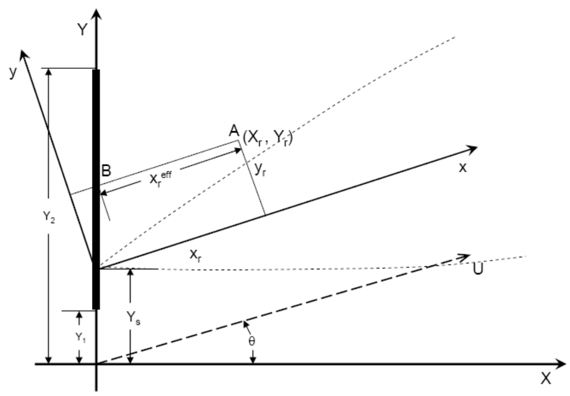

Figure 1: Coordinate system used to calculate contribution of the point source at Y_s to concentrations at (X_r, Y_r). The system x-y has the x-axis along the mean wind direction, which is at an angle θ to the fixed X axis. The dotted lines represent the plume originating from an elemental point source at $(0, Y_s)$.

The contribution of a line source to concentrations at a receptor (X_r, Y_r) is given by the integral of the contributions by the point sources along the line of length (L),

$$C\left(X_r, Y_r\right) = \int_{Y_1}^{Y_1+L} dC \quad . \quad (1)$$

This integral is approximated by the formulation given by Venkatram and Horst (2006), which is strictly accurate when both the release height and the receptor height are zero. The approximate solution is

$$C_p\left(X_r, Y_r\right) \approx \frac{qF(Z_r)}{\sqrt{2\pi}U\sigma_z\left(x_r^{eff}\right)\cos\theta}\left[erf\left(t_1\right) - erf\left(t_2\right)\right] \quad . \quad (2)$$

where

$$x_r^{eff} = X_r / \cos\theta \quad , \quad (3)$$

$$t_i = \frac{(Y_r - Y_i)\cos\theta - X_r \sin\theta}{\sqrt{2}\sigma_y(x_i)}, \quad (4)$$

and q is the emission rate per unit length of the line source. Here σ_y is evaluated at $x_i \equiv x_r$ $(Y_S = Y_i)$. The definitions of t_1 and t_2 correspond to downwind distances, x_r, from the end points Y_1 and Y_2 of the line to the receptor at (X_r, Y_r).

Under low wind speeds, horizontal meandering of the wind spreads the plume over large azimuth angles, which might lead to concentrations upwind relative to the vector-averaged wind direction. A common approach to treat this situation is to assume that when the mean wind speed is close to zero, the horizontal plume spread covers 360° (Cimorelli et al., 2005; Carruthers et al., 1994). In the random spread state, the release is allowed to spread radially in all horizontal directions. Here, we approximate the integral of the contributions from the meandering components of the point sources along the line source using a method by Venkatram et al. (2013a):

$$C_m(X_r, Y_r) \approx \sqrt{\frac{2}{\pi}} \frac{qF(Z_r)}{U\sigma_z(X_r)} \frac{\theta_s}{2\pi} \quad (5)$$

where θ_S is the angle subtended by the line source at the receptor,

$$\theta_s = tan^{-1}\left(\frac{Y_2 - Y_r}{X_r}\right) + tan^{-1}\left(\frac{Y_r - Y_1}{X_r}\right). \quad (6)$$

and σ_v is estimated from other meteorological variables using an approximation given by Cirillo and Poli (1992),

$$\sigma_v^2 = u^2 \sinh\left(\sigma_\theta^2\right), \quad (7)$$

where σ_θ is the measured standard deviation of the horizontal velocity fluctuations.

Then, the concentration at a receptor is taken as a weighted average of concentrations of a random spread, and a plume state:

$$C = C_p\left(1 - f_r\right) + C_m f_r \qquad (8)$$

where the weight for the random component is:

$$f_r = \frac{2\sigma_v^2}{U_e^2}, \qquad (9)$$

This ensures that the weight for the random component goes to unity when the mean wind approaches zero.

For the formulation of vertical and horizontal spreads of the plume, σ_y (Equation 2) and σ_z (Equation 4), C-LINE incorporates a reformulated equation previously developed for RLINE, a new line source dispersion model, described in Snyder et al. (2013) and Venkatram et al. (2013a).

3.3 Dispersion Model Evaluation and Sources of Uncertainty

Prior to its incorporation in the C-LINE modeling system, the dispersion algorithm had been evaluated using measurements from two field studies. The first field study was conducted by CALTRANS in 1982 in which sulfur hexafluoride (SF_6) a tracer gas, was released from the tailpipes of eight specially outfitted automobiles that traveled with traffic on Highway 99 outside of Sacramento, California (Benson, 1989). Details of the evaluation of the dispersion are described in Venkatram et al. (2013a). The results of the evaluation indicate that the dispersion algorithm performs adequately to estimate downwind concentrations with 84% of the estimates within a factor of two of the observations, and an overall bias of 2%. The dispersion estimates do not provide a representative description of the upwind concentrations.

The second field study was conducted during July and August, 2006 in Raleigh, NC along a busy section of Interstate 440, supporting approximately 125,000 vehicles per day (Baldauf et. al, 2008). The study was designed to obtain highly time-resolved measurements of traffic activity, meteorology, and air quality concentrations at varying distances from the road. A unique feature of this field study was the application of optical remote sensing (ORS) to measure NO and other pollutant concentrations along multiple paths near the highway (Thoma et al., 2008). Dispersion estimates were compared with the NO measurements collected at 7m and 17m from the roadway shoulder at a height of 2m and found to be consistent with observations: 87% of the estimates were within a factor of two of the observations, and the under-prediction bias is about 10% (Venkatram et al., 2013b).

Based on these results, the dispersion model represents downwind concentrations with reasonable accuracy (within a factor or two). Therefore, given accurate emissions data as inputs, the model will estimate near-road concentrations with appropriate certainty. However, if the emissions information is not accurate then neither will the resulting air quality concentrations. The publicly-available, national datasets that C-LINE utilizes provide a consistent format, reporting standard, and geographical coverage, but they are provided by state and local government authorities and not subject to subsequent verification or evaluation. C-LINE documentation acknowledges this potential source of uncertainty and users are advised to independently evaluate and cross-check the accuracy of source emissions-related information whenever possible.

3.4 Visualization

Visualization occurs automatically within C-LINE. Receptor concentrations are spatially joined to produce continuous road segment buffers of air quality concentrations. At intersections or other areas where road segments are within 500 meters of each other, buffers will overlap, and the spatial join will sum the concentrations of the overlapping buffers. The buffer concentrations are then mapped to a 50 m grid over the domain. The resulting 50 m grid with concentrations for each of the pollutants is then rasterized for each pollutant to improve display speed. These single-pollutant raster files can subsequently be overlaid upon the road network. Due to the geospatial nature of C-LINE, a user may also wish to overlay additional shapefiles, such as income, demographics, or locations of certain buildings or other pollutant sources. Also, a user may zoom into certain areas of their domain in order to examine them in more detail, or to focus what-if scenarios on a specific location or set of roadways. While a user is not limited in the size of the area that they wish to model, geographic extent does become a limiting factor in model performance due to the density of the receptors. C-LINE is optimized to run for an area on the order of 100-1,000 km^2.

3.5 Scenario Analysis Capabilities

C-LINE's simplified modeling approach facilitates the ability to modify input parameters, re-run the simulation, and compare the modified results with the unaltered ("base-case") scenario. Users have two options to manipulate input variables: 1) they can modify existing values through the system interface, or 2) they can upload their own input datasets. A user can alter any input variable, since they are available as text files. However, C-LINE provides "shortcuts" in the graphical user interface (GUI) to modify certain parameters that are of most use to stakeholders.

A user can choose to alter conditions for the entire geographic domain, or they may select any number of specific road segments to modify individually or as a subset. The variables that are available through the GUI to facilitate manipulation include VMT (total or by vehicle type), vehicle type (e.g., gas cars and heavy duty diesel), vehicle speed, time period (time of day, week, and season), atmospheric stability (i.e., mixing conditions), and wind direction. Once the new conditions are specified, the simulation is re-run; however, C-LINE retains the base case as a stored file. The user can then examine the new conditions independently of the base case, or they may choose an option to produce a spatial map of the concentration differences between the base case and the new scenario.

4. Software Implementation

C-LINE was developed in ArcGIS (ESRI ArcGIS Desktop: Release 10; ArcInfo License; Spatial Analyst Extension). ArcGIS provides all the necessary components to develop C-LINE as a modeling system, including the ability to call various datasets, perform calculations, and visualize geospatial results.

An ArcGIS Toolbox with three Python-based ArcGIS scripts are run sequentially to calculate and visualize C-LINE outputs. The first script creates the receptor network; the resulting network shapefile serves as an input to the second script. The second script incorporates meteorology to calculate unit concentrations at each receptor; this shapefile served as input to the third script. The third script then multiplies unit concentrations by emissions for the dispersion profiles; in this script, the user is allowed to adjust meteorological values (i.e., choose the atmospheric conditions) prior to the calculations. The final outputs from this script are separate raster images for each pollutant representing their concentration gradient along the roadways, which are then overlaid onto the road network.

The ArcGIS platform provided a stable research and development platform, but has a number of challenges for making C-LINE available for wide-scale use. The ArcGIS application requires a user to purchase the software and a license for use. The software can be a challenge for inexperienced users to understand. Model runs took upwards of 10-20 minutes to finish, which is not limiting for research purposes, but can be limiting for general use and assessing community-scale applications, where users prefer a real-time manipulation of model runs. Web-based applications could reduce the run time by an order of magnitude, as mentioned in the Discussion.

5. Illustrative Example of C-LINE Application for an Area of Detroit, Michigan

We applied C-LINE to a portion of Detroit, Michigan to demonstrate its use. Data sources, vehicle distributions, and meteorological inputs are described in previous sections. Those relevant to the study area were extracted and applied to the geographic domain. First, we selected a portion of the greater metropolitan area upon which to focus (Figure 2).

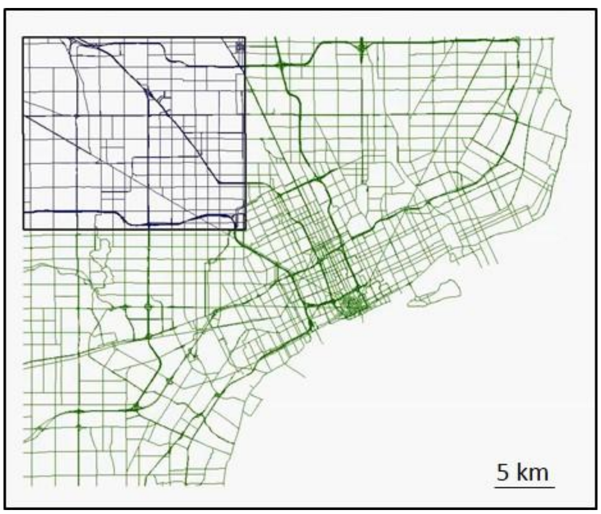

Figure 2. Selecting geographic domain in the Detroit, Michigan metropolitan area. C-LINE then access national datasets for respective roadway and meteorological information.

Then, receptors were distributed at 50 m, 100 m, 200 m, 300 m, 400 m, and 500 m from the midpoint of each road segment (Figure 3). C-LINE stores the attributes for each road segment, so this information can be saved as a separate file for other analyses.

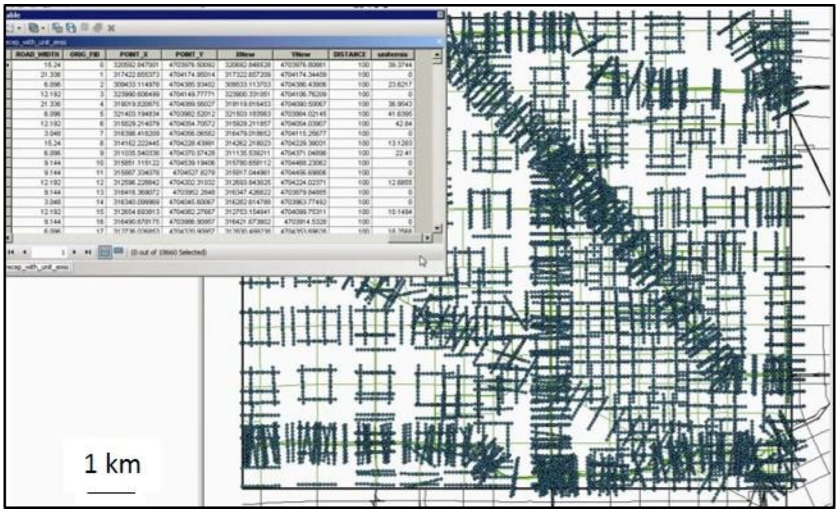

Figure 3. C-LINE assigns near-road receptor points at 50 m, 100 m, 200 m, 300 m, 400 m, and 500 m from the midpoint of each road segment, and accesses road link information (inset).

The next step was to run the dispersion algorithm. The time period for this example was winter, weekday AM peak (morning rush), and the atmospheric conditions were defined as typical. The resulting output was unit-value concentrations at each receptor, which were then combined with emissions profiles in order to calculate the outdoor concentrations. AADT for calendar year 2010 and roadway link lengths for over 9700 road links in the geographic domain were used to calculate VMT. The final fleet distribution for the Detroit application is given in Table 1.

	Rural	Rural	Rural	Urban	Urban	Urban
Vehicle Type	Principal Arterials (Interstates)	Secondary Arterials	Other	Principal Arterials (Interstates)	Secondary Arterials	Other
MC	0.90%	1.10%	1.60%	0.40%	0.20%	2.10%
LDGV	65.99%	65.00%	70.72%	70.82%	75.66%	50.50%
LDGT1	12.04%	14.94%	15.45%	11.59%	11.08%	24.98%
LDGT2	6.13%	7.61%	7.87%	5.90%	5.64%	12.72%
LDDT	0.53%	0.65%	0.68%	0.51%	0.49%	1.09%
LDDV	0.91%	0.90%	0.98%	0.98%	1.04%	0.70%
HDGV	2.40%	2.41%	1.24%	2.21%	2.20%	1.15%
HDDV	11.1%	7.39%	1.46%	7.69%	3.70%	6.75%

Table 1. Distribution of vehicles by roadway type for Detroit application of C-LINE. MC = motorcycles, LDGV = light-duty gasoline vehicles, LDGT1 = light-duty gasoline trucks with gross vehicle weight less than 6001 pounds, LDGT2 = light-duty gasoline trucks with gross vehicle weight 6001 pounds or greater, LDDT = light-duty diesel trucks, LDDV = light-duty diesel vehicles, HDGV = heavy-duty gasoline vehicles, HDDV = heavy-duty diesel vehicles.

Pollutant-specific emissions factors were then assigned to each of the ~9700 road-links in the study domain to generate a link-by-link emissions inventory for the region. These emissions were then multiplied by the unit values at each receptor to calculate near-road concentrations for, in this illustrative case, six different pollutants (benzene, $EC_{2.5}$, $OC_{2.5}$, NO_x, CO, and $PM_{2.5}$; non-air toxics were included for testing). C-LINE benzene concentrations are shown in Figure 4.

Figure 4. Example of C-LINE model results: benzene concentrations (μg/m^3) out to 500 m from each roadway segment**.**

An important feature of C-LINE is the ability to examine how changes in traffic can affect near-road air toxics concentrations. To illustrate this feature, we increased total VMT by 20% and overall speed by 10% for the geographic domain, and compared resulting benzene concentrations with the original scenario. A map of differences between the base case and selected scenario is shown in Figure 5.

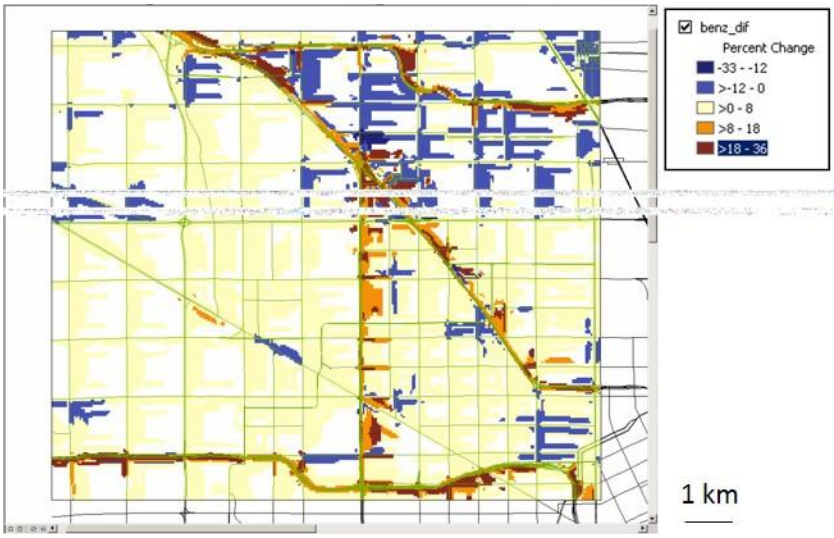

Figure 5. Example of benzene concentration percent differences when VMT is increased by 20% and overall speed by 10%.

EFs are a function of fleet age and composition, ambient temperature, fuel, and speed. The EFs for benzene are highest at low speeds and drop off drastically after about 20 mph. The rate of reduction in EFs from 2.5 mph to 20 mph vary for the different vehicle types. Thus, when VMT and speed are increased in the illustrative example shown, in most cases on primary roads, the increase in total emissions (due to higher VMT) overwhelms the decrease in emissions (due to lower EFs), and hence lead to increases in Benzene concentrations. However, in some secondary roads (with relatively lesser traffic volumes and having vehicle types that exhibit less steep drop-off in EFs with speed, the increase in emissions (due to higher VMT) are not enough to compensate for the decrease in emissions (due to lower EFs), and hence lead to overall decreases in Benzene concentrations in the near-road environment. Also, in the secondary roads (where most decreases are seen), the base case speeds are usually low to begin with, and hence see a steeper drop in EFs, compared to the primary roads where the base case speeds are usually high to begin with, and hence undergo a relatively smaller reduction in EFs due to increased speed.

C-LINE also allows the user to examine changes on specific roads. This situation is illustrated in Figure 6 where we selected specific road segments and modified the fraction of heavy duty traffic. An example of benzene concentrations for a scenario representing a 20% increase in diesel trucks and a 20% increase in gasoline trucks is shown in Figure 7. A map of concentration differences between the base case and selected scenario is shown in Figure 8.

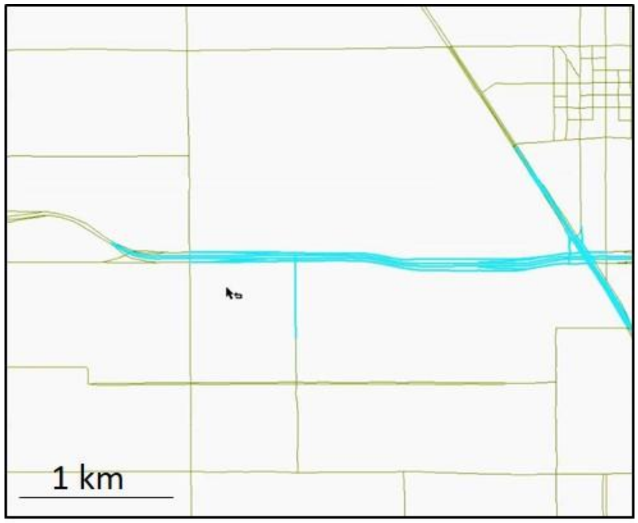

Figure 6. Example of selection of specific road segments in order to modify traffic conditions and examine resulting differences in air toxics concentrations.

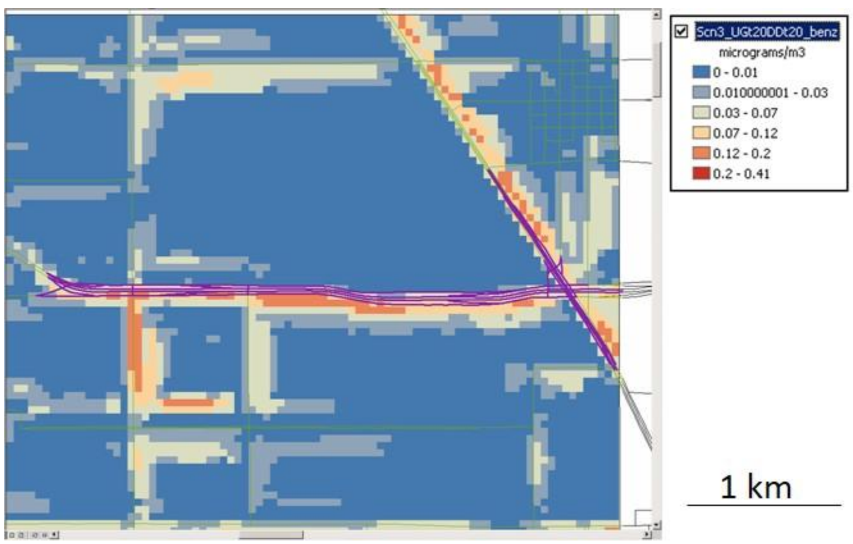

Figure 7. Example of modeled benzene concentrations (μg/m^3) for selected road segments as a base case scenario using unaltered input data.

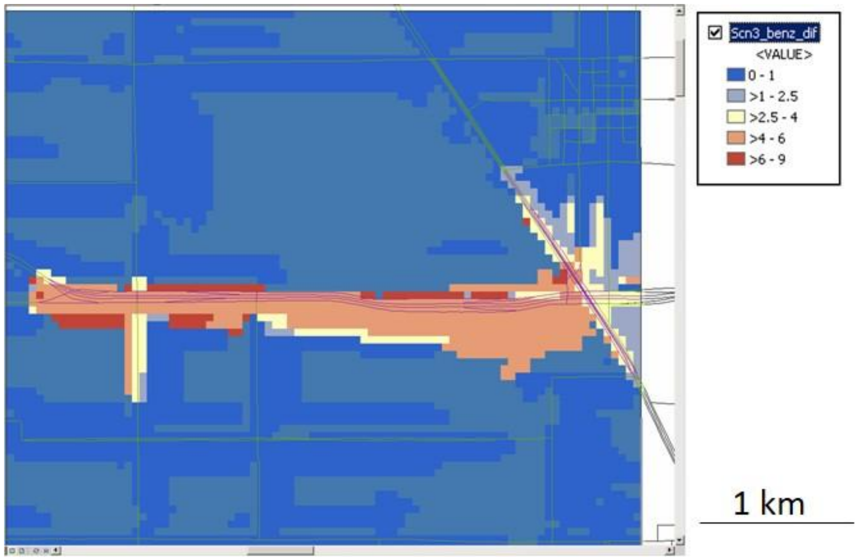

Figure 8. Example of benzene percent differences from the base-case scenario for selected roads, when both gasoline and diesel trucks are increased by 20%.

6. Discussion

6.1 Model Advantages

As mentioned, an important feature of C-LINE is its ability to assess variations of a given scenario (i.e., its *what-if* capabilities), accurately describing relative differences between various roadways within the modeling domain, or relative changes in pollutant levels for a given roadway under different conditions. When initiated, C-LINE uses the available nationwide inputs for a given area to estimate near-road air quality for the user-specified time period and atmospheric conditions. However, users may wish to assess geographic changes in pollution when traffic shifts from one roadway to another; or the implications of an increase in traffic (or decrease in speed) during the morning commute; or how population growth of a given area may impact its near-road air toxics concentrations.

To be clear, C-LINE does not have a button that states, "increase population for this area and assess changes," or "evaluate public transportation options on resulting air quality." If a user knows how population growth (or public transportation options) could influences traffic counts or fleet mix (or other C-LINE parameters) then these activity patterns can be used as C-LINE inputs and results can be compared to the base case. C-LINE inputs that that can be manipulated for individual road segments or a larger set include: 1) traffic counts; 2) vehicle-types (for six different vehicle types); and 3) vehicle speed. Inputs that can be manipulated only for the entire geographic region (i.e., all road segments only), include 1) emission factors; 2) meteorological conditions (wind speed and direction, outdoor temperature); 3) atmospheric conditions (typical, favorable, unfavorable); and 7) timing: time-of-day (a.m. peak: 7-9 a.m.; mid-day: 9 a.m.-3 p.m.; p.m. peak: 3-6 p.m.; and off-peak: 6 p.m.-7 a.m.), time-of-week (weekday, weekend), and season (summer or winter).

C-LINE what-if scenarios can be applied to a number of local, community-scale applications. For example, local groups may be interested in the effects of decreased traffic on air pollution in order to promote exercise campaigns (Whitlow et al., 2011). They may wish to identify areas heavily impacted by diesel truck routes due to commercial activities, and assess potential results of re-routing traffic (Rioux et al., 2010) Community groups may be interested in assessing air quality by schools located near busy roadways, (Wu and Batterman, 2006; Spira-Cohen, et al., 2011; Patel et al., 2009), or demographic distributions associated with low-income or minority populations living near roadways (Tian et al., 2012), and the differential impact on them compared to other areas. C-LINE could also be used to assist researchers with identifying areas in which to focus near-road monitoring or health studies; for example, during the site selection process. C-LINE facilitates these applications because of its nationwide coverage, local focus, and ease of manipulating inputs. Results can be overlaid with other shapefiles, such as for demographics (e.g., race/ethnicity, income), locations of other pollution sources or places of interest (e.g., industrial sites, schools, or parks). To reiterate, it is not intended to replace the models that are required for policy-related statutes and regulations, such as transportation conformity or the National Ambient Air Quality Standards (NAAQS). C-LINE has not been approved for these applications; its use of simplified meteorology and default emission factors, along with the inability to model concentrations through time, prevent its application in these cases.

6.2 Model Limitations

It is important to note that C-LINE is not designed to model conditions through time or outside the near-road environment. It only provides estimates for selected meteorological conditions: “typical” and “favorable/unfavorable”. The next version will include annual averages, therefore the model would be more useful for applications in support of health studies.

While other pollution sources are being considered for incorporation, currently, C-LINE only uses roadways as the pollution source. C-LINE does not take into account background pollutant levels or contributions by other sources, such as industry, ports, or rail yards; however, we continue to evaluate the incorporation of these and they may be included in future versions.

We are currently examining the feasibility of including housing-related information, such as age and square-footage, from national datasets in order to predict indoor concentrations for some areas, which would be a more accurate estimate of personal exposure (Breen et al., 2013; Wu et al., 2011).

Traffic activity is based on a single annual value which is then distributed across roadway types and through time using distributional tables and temporal allocation factors, but traffic conditions in the real-world could easily vary throughout the day and deviate from the conditions based on the national datasets. Even though the user could manipulate these values based on better information, they still provide a source of potential uncertainty.

6.3 Future Development and Availability

Preliminary tests for an online system have proved very promising, and the next version is being developed along these lines. A web-based prototype has been developed with an intuitive, familiar, user-friendly point-and-click interface. It also had a number of technical advantages, including: 1) faster performance than the ArcGIS version (on the order of a minute instead of 5-10 minutes); 2) results visualized on web-based geospatial maps; and 3) increased flexibility in modifying road segment conditions. We are continuing to develop C-LINE as an online, web-based application, with a timeline for completion of a beta version around the latter half of 2014, and subsequent wider-scale distribution by 2015. To-date, the prototype features a Google Earth-based front-end with a Google Web Toolkit (GWT) wrapper hosted on a Tomcat web server that interacts with a PostgreSQL/PostGIS database server. Model updates will be available from the Community Modeling & Analysis System (CMAS; http://www.cmascenter.org) during development and potential users are encouraged to check there for updates.

The C-LINE modeling system lends itself to expansion and customization because of its streamlined geospatially-based approach. Areas of ongoing research include the incorporation of exposure surrogates, additional terrain features, port emissions and dispersion, and including other pollution sources, such as industry, rail yards, and multi-modal distribution facilities. Exposure surrogates could include residential type (e.g., single-family homes) and age, which could then be used to estimate infiltration of outdoor air to the indoors, thus providing a better estimate of personal exposure. Currently, C-LINE dispersion is over a flat terrain, so incorporation of buildings, road configurations, depressed or elevated road sections, and noise barriers are being considered (Finn et al., 2010). We are also exploring the option of drawing or adding hypothetical sources into the modeling domain to examine potential future scenarios, such as the siting of a new facility or other source. These options are a current area of research, yet the primary consideration is to retain the simplified approach of the C-LINE modeling system.

C-LINE models idealized conditions and so a strict measurement-based evaluation of its results would be based more upon consistency and relative differences than absolute predictions of air toxics; for example, the model would accurately predict hot-spot distributions across the domain, but the values of the model (with, e.g., Summer and Weekday chosen) would not mimic any given weekday in the summer when someone went outside with a sensor. However, the model would help locate areas for sensor placement, and relative changes in traffic and meteorological conditions should be reflected in both model and measurements (McAdam, 2011). Efforts are currently underway to include C-LINE in field studies, including citizen-science measurements of near-road pollutants, to inform sensor placement and evaluate the modeling system as a whole.

7. Conclusions

The Community Line Source (C-LINE) modeling system incorporates a novel atmospheric dispersion algorithm, parameterized emission sources, and local meteorology to estimate air toxic concentration gradients in the near-road environment (within 500 m of roadways) for the continental United States. C-LINE uses a number of input parameters based on publicly available datasets to provide nationwide coverage, but it also allows a user to upload and utilize local datasets. C-LINE facilitates relative comparisons between different roadways, or for a given roadway under different sets of input conditions.

The dispersion model used in C-LINE demonstrated good agreement with measurement studies, and accurately predicted resulting air pollutant concentrations under a given set of emissions and meteorological conditions. We presented a case study example for Detroit, Michigan to illustrate potential changes in pollutant concentrations due to changes in traffic and showed that the model performs well in these applications.

This is the first instance where a modeling system has been designed to access readily-available datasets and provide national coverage for near-road air quality modeling. Community-scale and research applications include helping to identify potentially exposed populations, assessing changes in air quality due to roadway conditions, and assisting researchers with site selection for monitoring or health-related near-road studies. The flexible nature of C-LINE helps to inform community stakeholders of the contributing factors to near-road pollution, in order to help develop strategies that could improve community health and the environment.

Disclaimer

The United States Environmental Protection Agency (US EPA) through its Office of Research and Development conducted the research described in this paper. It has been subjected to Agency review and approved for publication. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

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