Development of a Fine-Scale On-Road Mobile Source Emissions Inventory for the San Francisco Bay Area

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ABSTRACT

Several communities in the Bay Area Air Quality Management District (the District) are developing Community Risk Reduction Plans (CRRPs) as a proactive step toward reducing exposures to toxic air contaminants and fine particulate matter. To support the development of CRRPs, Sonoma Technology, Inc. worked with the District to develop fine-scale on-road mobile source emissions inventories for six communities in the San Francisco Bay Area.

STI developed link-level inventories in a geographic information system (GIS) environment for state highways and major arterials in each community of interest for the years 2012 through 2040. The inventories were based on annual average daily traffic count data for state highways from the California Department of Transportation, traffic count data for major arterials from local transportation departments, and emission factors for each calendar year derived from the California Air Resources Board's EMFAC model. The resulting traffic activity data (which were held constant across all years) and emissions estimates (which vary by calendar year) were provided to the District as a GIS roadway network shapefile linked to a Microsoft Access database. The District incorporated this information into Rcaline dispersion modeling runs to develop their Highway Screening Analysis Tool for Risk and Hazards.

The District conducted dispersion modeling for each segment of the GIS roadway network, using separate hourly emission profiles for light-duty and heavy-duty vehicles. For each roadway segment, observed winds and other meteorological modeling inputs were selected from the nearest appropriate meteorological station. Modeled $PM_{2.5}$ concentrations, cancer risk, and chronic non-cancer hazard indices for near-roadway receptor locations were compiled into an online Google Earth screening tool that allows users to estimate concentrations and risks along all major Bay Area roadways.

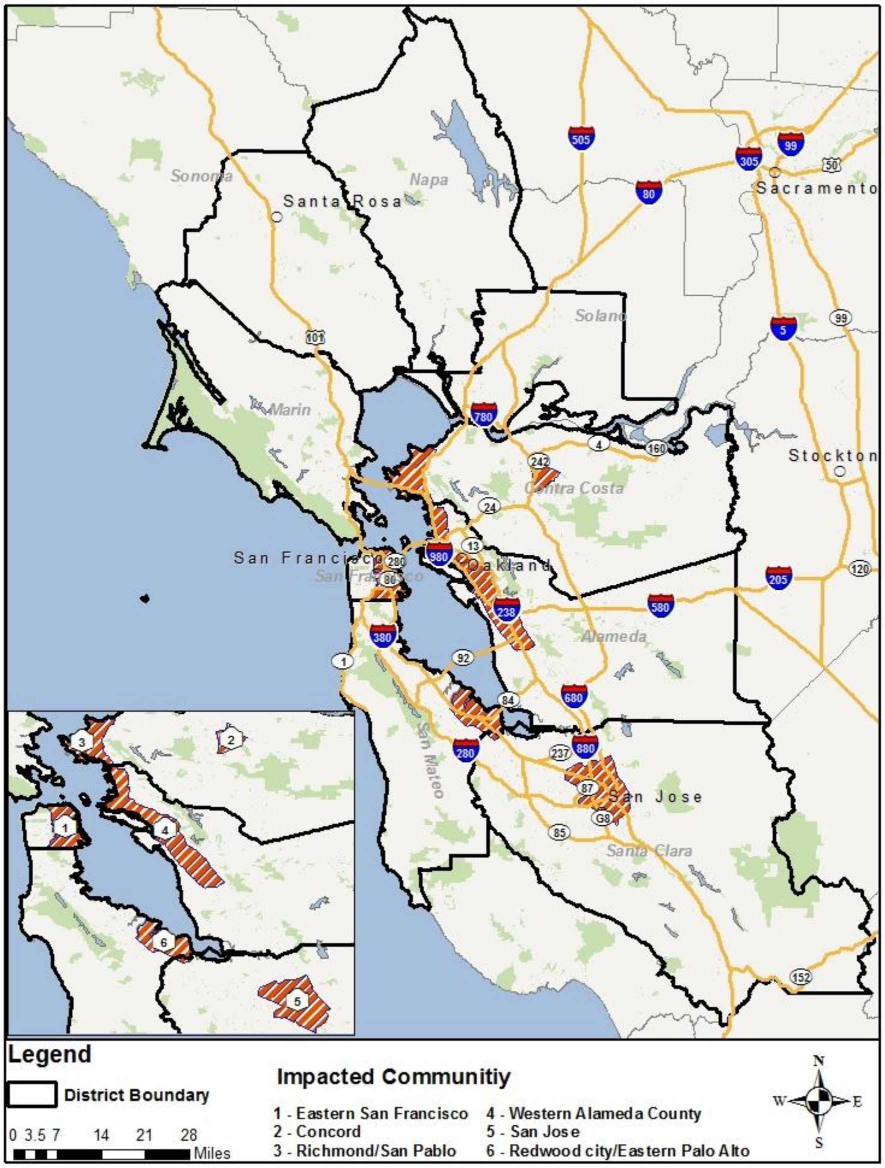
INTRODUCTION

The Bay Area Air Quality Management District (the District) has begun to develop guidance for a plan-based approach to address community risks and hazards associated with pollution sources. Cities or counties within the Bay Area that are seeking a proactive approach for reducing exposure to toxic air contaminants (TACs) and particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) can use this guidance to prepare Community Risk Reduction Plans (CRRPs). These plans will allow for a comprehensive, community-wide approach for reducing local air pollution emissions and exposures.[1]

To support the development of CRRPs, the District is working with Sonoma Technology, Inc. (STI) to generate the detailed emissions inventories needed for the plans. As part of this process, the District and STI have developed fine-scale on-road mobile source emissions inventories for six communities in the San Francisco Bay Area: Concord, Richmond/San Pablo, western Alameda County, San Jose, Redwood City/East Palo Alto, and eastern San Francisco (see **Figure 1**). The District's

Community Air Risk Evaluation (CARE) Program has identified these areas as “impacted” communities that are significantly affected by local sources of TAC and $PM_{2.5}$.

Figure 1. BAAQMD jurisdiction boundary and six impacted communities.



The District’s CRRP guidance calls for the development of base year emissions inventories that are representative of near-term, “typical” conditions and target year inventories that provide an estimate of future year emission levels. Therefore, the link-level mobile source inventories developed for the six impacted communities include emission estimates for all years from 2012 through 2082. The data sets and methods used to develop these inventories are described in the sections that follow.

EMISSIONS INVENTORY DEVELOPMENT

To develop the fine-scale on-road mobile source emissions inventories for the six communities of interest, the latest traffic activity data for these areas were acquired and composite emission factors for passenger vehicles and trucks were derived from ARB’s EMFAC2007 model. This section describes the data sources and technical approach used for combining vehicle activity data and emission factors to develop on-road emissions inventories for state highways and major arterials in the six Bay Area communities.

Data Acquisition and Processing

Estimating emissions from on-road motor vehicles at a fine scale requires a variety of data, including link-level road network information, traffic volumes, fleet mix data (e.g., passenger cars vs. trucks), vehicle travel speeds, and emission factors (i.e., pollutant emission rates per mile traveled). Sources of data used to estimate emissions are discussed below.

Roadway Networks

A roadway network in Esri shapefile format for state highways and major arterials was established as the geographic foundation of the link-level emissions inventories (see **Figure 2**). The state highway network was developed by reconciling a National Highway Planning Network (NHPN) shapefile with a 2008 Topographically Integrated Geographic Encoding and Referencing (TIGER) Line shapefile. The NHPN shapefile was adopted as the primary data source, and the TIGER data were used to fill in any missing roadway links. For major arterials, which were defined as roads with an average daily traffic (ADT) count of 10,000 or more vehicles, the TIGER Line shapefile was used as the data source for defining roadway networks in the six communities of interest. For roads for which recent ADT data were unavailable, traffic volume outputs from the Metropolitan Transportation Commission's (MTC) BAYCAST-90 Travel Demand Model (TDM) were used to determine whether the roadway would be defined as a major arterial. A unique link ID was then assigned to each road segment in the two-road network shapefiles, and attributes associated with each link included road name, road type, and link length in miles. To support the District's dispersion modeling, the total number of lanes for each link was counted in Google Earth and added to the attributes tables of the two network shapefiles. The link ID was also used to associate the traffic and emissions data developed through the project.

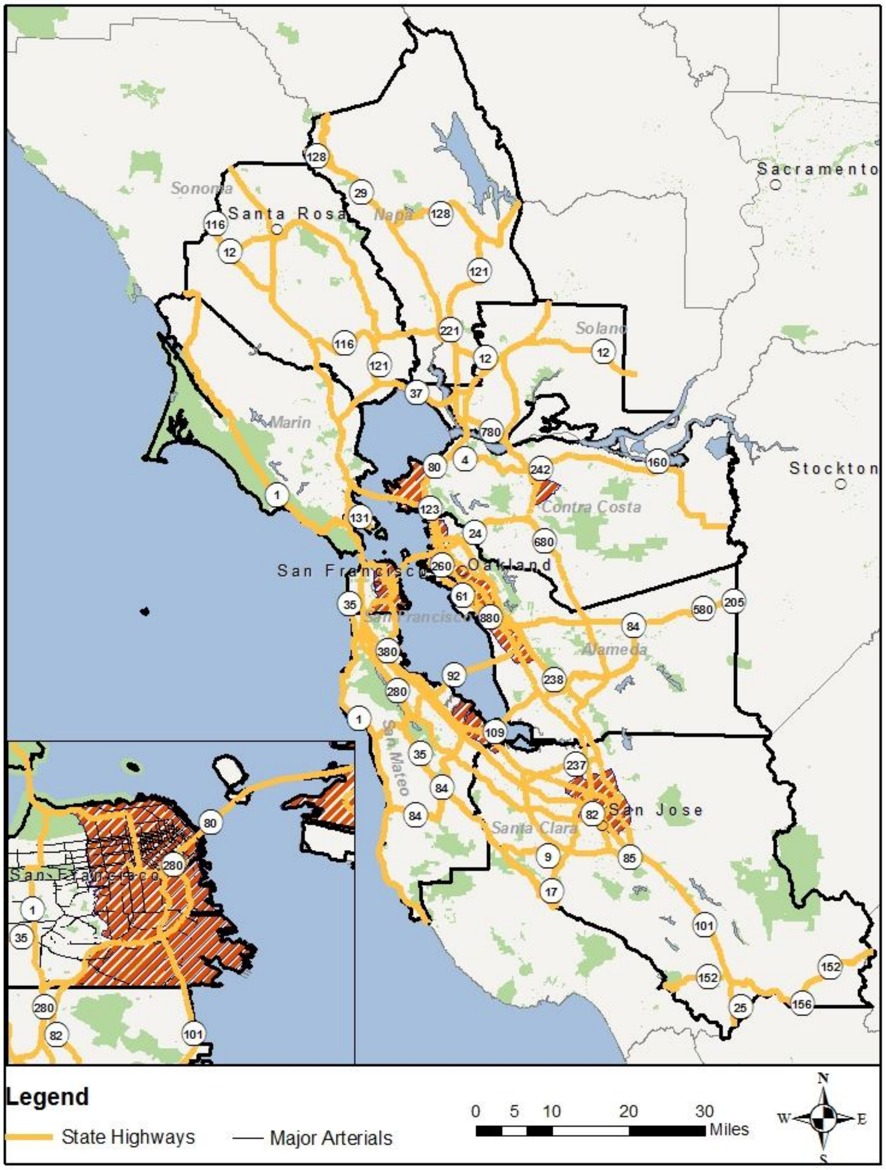
Traffic Volumes

The best available traffic volume/count data were acquired from state and local transportation departments, public works departments, and congestion management agencies (CMAs). For the state highway network, 2009 annual average daily traffic (AADT) counts from the California Department of Transportation (Caltrans) were used to represent traffic volumes for emissions estimation (see **Figure 3**). The AADT values represent total traffic counts for the year divided by 365 days. These counts are reported for individual state highway segments that are designated with milepost values. In cases where a road link of our state highway network covers more than one Caltrans highway segment (or milepost), the average AADT value of all segments covered was used as the traffic volume for that link. For major arterials, link-level traffic count data were obtained from local agencies where possible. For roadways for which traffic count data was unavailable or out of date, traffic volume outputs from MTC's BAYCAST-90 TDM or the San Francisco County Transportation Authority's (SFCTA) SF-CHAMP model were used as a surrogate.

Vehicle Speeds

Vehicle speeds are important for emissions estimation, as emission rates vary by speed. For state highways, vehicle speeds by highway segment were based on 2010 and 2015 outputs from the BAYCAST-90 TDM. Link-level vehicle speeds for 2010 and 2015 were averaged to develop speed data for 2012. In addition, speed data from BAYCAST-90 and from the SFCTA's SF-CHAMP model were used for major arterials for which speed data were not provided by local agencies. Because both models provided speed data for the five time periods shown in **Table 1**, period-specific speeds were weighted by corresponding traffic volumes to derive a daily average speed for each roadway link.

Figure 2. Base map of state highways across the Bay Area and major arterials in eastern San Francisco (inset).



Growth Factors

The traffic volume data for state highways and major arterials were collected or modeled for various calendar years, mostly ranging from 2000 to 2010. To reconcile these data, year 2012 was selected as the base year for all activity data, and 2012 traffic volumes were held constant for all future years through 2040. To develop county-level growth factors for projecting the historical traffic volume data to 2012, ARB's EMFAC2007 model was run for all Bay Area counties for each year from 2000 through 2012. The vehicle miles traveled (VMT) output data from EMFAC were used to calculate growth factors for projecting historical traffic volumes to 2012.

Figure 3. Map of 2009 AADT data for state highways in the Bay Area.

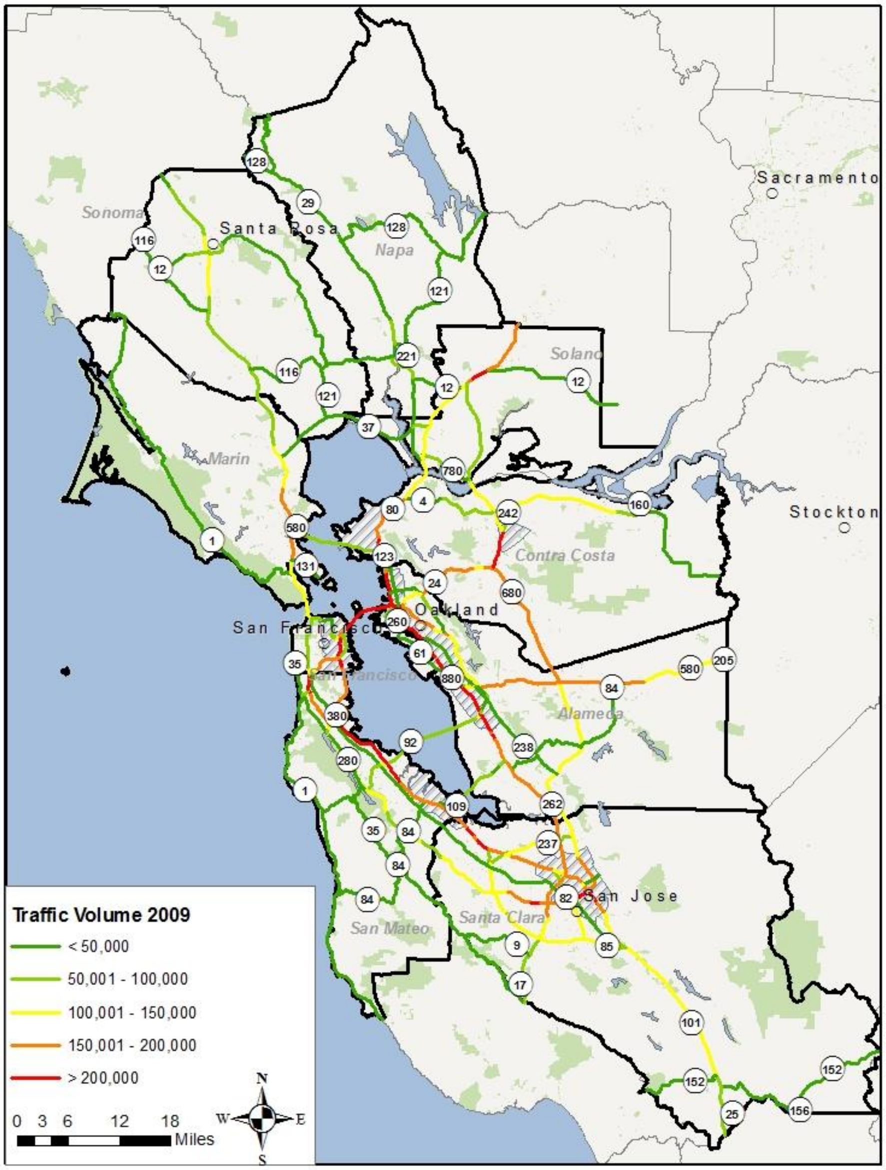


Table 1. Time periods for which speed data are reported by the BAYCAST-90 and SF-CHAMP models.

Period #	MTC		SF-CHAMP	
	Abbreviation	Description	Abbreviation	Description
1	6MOR	Early Morning (0000-0600)	EA	Early Morning (0300-0600)
2	4AMPK	AM Peak (0600-1000)	AM	AM Peak (0600-0900)
3	5MID	Midday (1000-1500)	MD	Midday (0900-1530)
4	4PMPK	PM Peak (1500-1900)	PM	PM Peak (1530-1830)
5	5EVE	Evening (1900-2400)	EV	Late (1830-0300)

Truck Volumes and Restrictions

Composite emission factors for each roadway were based on link-level vehicle speeds and truck traffic percentages. For the state highway system, Caltrans provides both all-vehicle and truck-only AADT counts. As was the case for the all-vehicle traffic volume, a weighted average method was used to determine the truck volume for links including more than one Caltrans highway segments. For major arterials in the six communities of interest, truck traffic volumes were obtained from local agencies where available. In addition, major arterials that restrict truck traffic were identified using information from local agencies (these roadways are typically in high-density residential areas). For major arterial links for which local data were unavailable, the county-level truck percentage data derived from the California Motor Vehicle Stock Travel and Fuel Forecast (MVSTAFF) report were used as a surrogate.

Geospatial Processing

Once the 2012 traffic volumes, truck percentages, vehicle speeds, and other attributes were prepared, these data were joined to individual roadway links in the road networks based on the road name, description of the start and end nodes of the link, and geographic proximity. For state highways, the traffic volume and truck percentages for each highway segment were joined to the state highway network shapefile based on milepost values and descriptions. The average daily speeds were joined to the network shapefile based on the proximity of highway links to segments defined in the shapefile of BAYCAST-90 model outputs. For major arterials, similar methods were applied except for San Francisco, where the proximity to links in the shapefile of SF-CHAMP model outputs was used.

Composite Emission Factor Development

The EMFAC2007 model, the on-road mobile source emissions model for California developed and maintained by ARB, was used to develop composite emission factors for all roadways of interest. Link-level composite emission factors for trucks and all vehicles were derived from EMFAC2007's Impact Rate Detail output (*.rtl files) for EMFAC2007 runs performed for the years 2012 to 2040. (Note that because EMFAC2007 only estimates emissions out to the year 2040, emission factors for 2040 were used for remaining years out to 2082.)

The composite emission factors developed for each roadway link were based on the truck percentage and average speed associated with that road segment. Emission factors were generated for running exhaust and running losses only, as emissions for other modes (e.g., vehicle starts) are not relevant or negligible compared to exhaust and running loss emissions for the state highways and major arterials of interest. Composite emission factors were developed for oxides of nitrogen (NO_x), carbon monoxide (CO), total organic gases (TOG), sulfur dioxide (SO_2), carbon dioxide (CO_2), PM, PM_{10}, and $PM_{2.5}$.

Truck Emission Factors

Composite emission factors for trucks greater than 8,500 lb were calculated for each highway link as follows:

Equation (1) $$EF_{Truck} = \sum_{vec=5}^{vec=8} EF_{vec} \times vmtTF_{vec}$$

$$vmtTF_{vec} = relativeVMT_{vec} \Big/ \sum_{vec=5}^{vec=8} relativeVMT_{vec}$$

where

EF_{Truck}	=	composite truck emission factor for the link average speed
EF_{vec}	=	emission factor by vehicle class
$vmtTF_{vec}$	=	vehicle class travel fraction relative to all trucks
$relativeVMT_{vec}$	=	vehicle class travel fraction relative to the whole fleet
vec	=	vehicle class ID, with trucks defined as classes 5-8 from **Table 2**

Table 2. Truck/non-truck designations based on vehicle classes in the EMFAC2007 model.

Vehicle Class ID	Vehicle Class	Abbr.	Truck Designation
1	Passenger Car	LDA	Non-truck
2	Light-Duty Trucks (0-3750 lb)	LDT1	
3	Light-Duty Trucks (3751-5750 lb)	LDT2	
4	Medium-Duty Trucks	MDV	
5	Light-Heavy-Duty Trucks (8501-10,000 lb)	LHDT1	Truck
6	Light-Heavy-Duty Trucks (10,000-14,000 lb)	LHDT2	
7	Medium-Heavy-Duty Trucks	MHDT	
8	Heavy-Heavy-Duty Trucks	HHDT	
9	Other Buses	OBUS	Non-truck
10	Urban Buses	UBUS	
11	Motorcycles	MCY	
12	School Buses	SBUS	
13	Motor Homes	MH	

In addition, separate emission factors were prepared for diesel trucks so that diesel particulate matter (DPM) and diesel organic gas (DEOG) emissions could be estimated. Composite emission factors for diesel trucks were calculated for each highway link as follows:

Equation (2) $$EF_{DSLTruck} = \sum_{vec=5}^{vec=8} EF_{vec,DSL} \times vmtTF_{vec,DSL}$$

$$vmtTF_{vec,DSL} = relativeVMT_{vec,DSL} \Big/ \sum_{vec=5}^{vec=8} relativeVMT_{vec,DSL}$$

where

$EF_{DSLTruck}$	=	composite diesel truck emission factor for the link average speed
$EF_{vec,DSL}$	=	emission factor by diesel vehicle class
$vmtTF_{vec,DSL}$	=	vehicle class travel fraction relative to all diesel trucks
$relativeVMT_{vec,DSL}$	=	vehicle class travel fraction relative to the whole fleet
$\boldsymbol{vec}$	=	vehicle class ID, with trucks defined as the diesel-fueled portion of classes 5 to 8

<u>All-Vehicle Emission Factors</u>

To prepare for estimates of total emissions on each roadway link, composite emission factors for all vehicles combined were calculated as follows:

Equation (3) $$EF_{fleet} = EF_{Truck} \times TruckPect + EF_{NonTruck} \times NonTruckPect$$

where

EF_{fleet}	=	fleet-average composite emission factor for the link average speed
$TruckPect$	=	link-specific truck percentage
$NonTruckPect$	=	link-specific non-truck percentage
EF_{Truck}	=	composite truck emission factor for the link average speed
$EF_{NonTruck}$	=	composite non-truck emission factor for the link average speed (calculated using the same process as for the composite truck emission factor, but excluding vehicle classes 5-8)

In addition, separate emission factors were once again prepared for diesel vehicles so that DPM and DEOG emissions could be estimated.

Emissions Calculations

Once link-specific composite emission factors for running exhaust and loss emissions were prepared for all years from 2012 through 2040, these data were applied to link-specific travel data in a Microsoft Access database to estimate emissions. Running exhaust emissions were calculated as follows:

Equation (4)
$$Emis = EF_{fleet} \times VMT$$
$$TREmis = EF_{truck} \times VMT \times TruckPect$$

where

$Emis$ = emissions in grams per day from all vehicles traveling on the road link;

$TREmis$ = emissions in grams per day from all trucks traveling on the road link;

VMT = daily vehicle miles traveled on the road link, the product of traffic volume and length of the link.

The methods used to calculate running loss emissions are similar; however, exhaust emissions are based on distance traveled (i.e., grams per mile), while running losses are based on travel time (grams per hour). Running loss emission factors vary by travel time as the vehicle warms up. To simplify computations, we used emission factors that represent a fully warmed travel time of 60 minutes, assuming that vehicles have been operated long enough to fully warm before entering the state highway or major arterial. The travel time for each road link was estimated by dividing VMT by travel speed, and running loss emission factors were applied to these time estimates.

DISPERSION MODELING

Concentrations of pollutants emitted by cars and trucks on state highways were estimated using Rcaline (v0.95).[2] The Rcaline model was developed to run under the statistical programming language R as an interface for the roadway dispersion model CALINE3. Rcaline removes some of the limitations present in CALINE3 by allowing a large number of roadway segments and receptor combinations to simulate concentrations along each geographic information system (GIS) roadway segment for which emissions were generated. Meteorological data from the closest of 55 available meteorological stations for each roadway segment were input to Rcaline. Rcaline and associated R packages are able to receive and process Esri shapefiles as input and output KML files that can be read by Google Earth. Modeling was completed for each of the nine Bay Area counties and posted online.[1]

Additional dispersion modeling was conducted to support the CRRP development for San Francisco in a joint project with the San Francisco Department of Public Health (SFDPH). Roadway modeling was conducted using the aforementioned methods for developing roadway emissions estimates. For the San Francisco CRRP, the AERMOD dispersion model[3] was applied for volume elements using dimensions and heights for San Francisco roadways that were developed by SFDPH.

RESULTS

Emissions

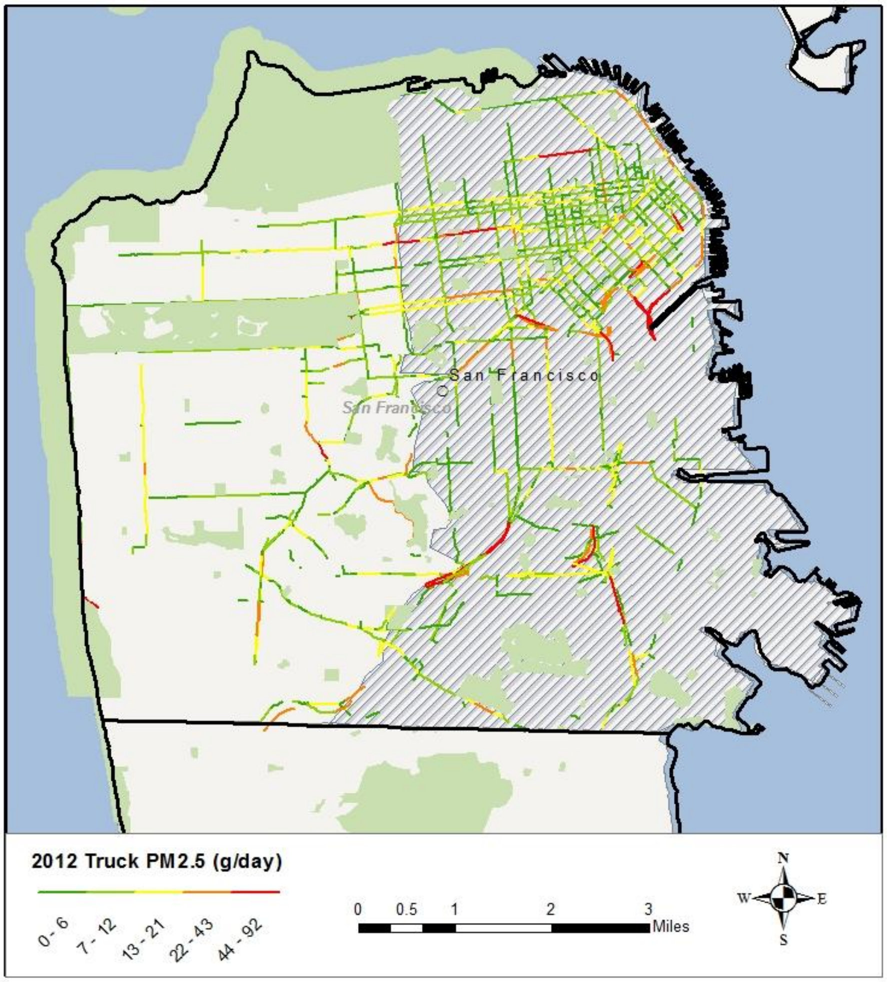
Emissions for each link in the state highway and major arterials system were calculated using Microsoft Access, and the emissions data were joined to the road network by unique link ID. As a quality assurance check, STI worked with District staff to compare emission estimates with other on-road mobile source emissions inventories for the Bay Area (e.g., EMFAC2007 outputs and a fuel-based emissions inventory for the state highway system developed at UC Berkeley). **Table 3** provides a summary of total 2012 emissions by pollutant for the entire state highway system in the Bay Area. **Figures 4 and 5** show ArcGIS plots of the average daily on-road mobile emissions inventory delivered to the District for their dispersion modeling.

Table 3. 2012 emissions for the state highway system by pollutant (units: tons per day).

Pollutant	All Vehicles	Trucks	Percentage
CO	252.52	13.30	5%
CO2	44,006.00	5,737.72	13%
DEOG	1.74	1.51	87%
DPM_{10}	1.13	1.01	89%
$DPM_{2.5}$	1.04	0.93	89%
NO_X	70.59	33.28	47%
PM_{10}	2.29	1.02	45%
$PM_{2.5}$	2.11	0.94	45%
SO_2	0.43	0.05	13%
TOG	19.15	1.94	10%

Figure 4. 2012 $PM_{2.5}$ emissions of all vehicles (normalized to road link length).

Figure 5. 2012 $PM_{2.5}$ emissions from trucks on major arterials in San Francisco.



Dispersion Modeling

Using Rcaline, dispersion modeling was conducted for state highways for nine counties in the San Francisco Bay Area. For each county, KML files were developed and made available online[4] to be viewed using the freely available Google Earth mapping software (**Figure 6**). On both sides of each roadway segment, near-roadway $PM_{2.5}$ concentrations, cancer risk, chronic hazard index, and acute hazard index are displayed at distances of 10, 25, 50, 75, 100, 200, 300, 400, 500, 750, and 1,000 ft.

Using AERMOD and emission estimates for San Francisco roadway segments, we estimated the direct contribution of on-road traffic (exhaust and running evaporation) to $PM_{2.5}$ concentration (**Figure 7**) and cancer risk on a dense network of receptor locations. Roadway contributions were added to those from other sources to map areas with high PM and high cancer risks.

Figure 6. Google Earth-based tool with selectable links displaying modeled $PM_{2.5}$ concentrations and risk from state highways in the Bay Area; Alameda County links are in red.

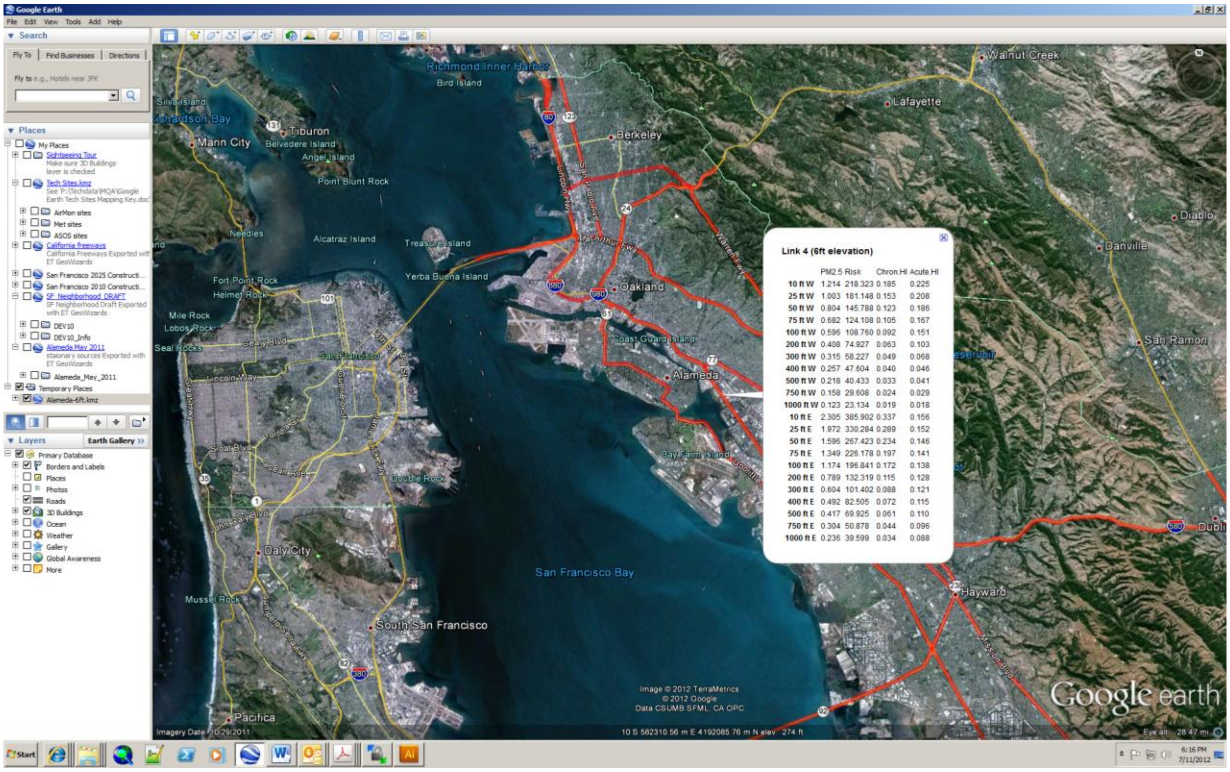
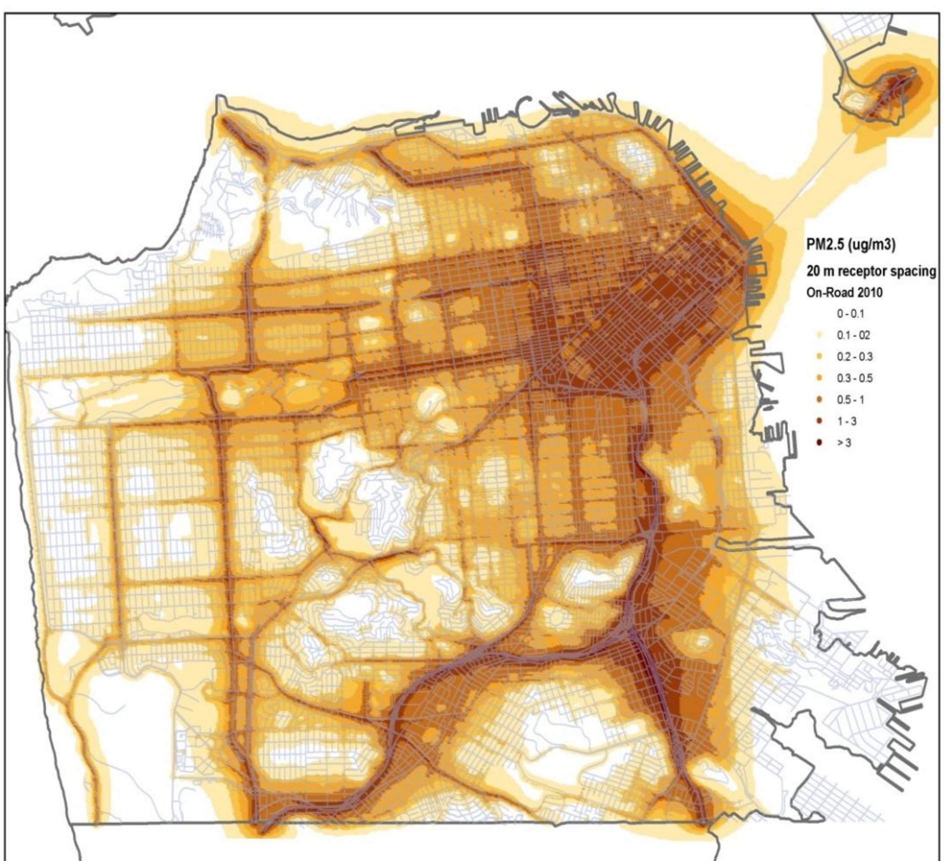


Figure 7. Dispersion modeling results of $PM_{2.5}$ concentrations from state highways and major roadways in San Francisco.



CONCLUSIONS

Fine-scale emission inventories, such as the on-road mobile source inventory developed for this study, have become increasingly important at the District. The methods described herein—fine-scale spatial mapping, detailed activity data for light- and heavy-duty traffic, emission factors for both light- and heavy-duty vehicles, and compilation into modern database structures accessible to automated programming tools—are key to generating detailed maps of air quality risk over a city scale. San Francisco Bay Area health and planning agencies are seeking such maps as they work to balance increasing urban density with the need to protect public health from exposure to local air pollution sources, such as busy roadways. Truly smart infill development can preserve urban greenbelts and reduce greenhouse gas emissions but local air pollution risks and hazards must be taken into account. Detailed air pollution maps help inform city planning efforts and identify areas with high risk and the sources that contribute to them.

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KEY WORDS

Fine-scale emissions inventory

Fine particular matter ($PM_{2.5}$)

Toxic Air Contaminants (TACs)

On-road mobile sources

Dispersion modeling