Modeling Transportation-Related Emissions Using GIS

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Abstract

There are increasing requirements on the efficiency and accuracy of vehicular emission modeling due to significant contribution of the transportation sector to air quality problems. Because the essential component (i.e. transportation activities) of vehicular emission modeling is inherently spatially dependent, this study aims to move the existing old-fashioned Direct Travel Impact Model (DTIM), the California-specific transportation-related emission inventory estimation model, towards a GIS-based model. The strengths of ArcGIS in data management, spatial analysis, and raster modeling are incorporated into three critical steps of emission modeling: disaggregating zonal travel activities (i.e. interzonal trip ends and intrazonal travels), combining travel activities (i.e. speeds and VMT) and emission factors, and gridding emissions into cells. This GIS-based method can promote an integrated transportation and air quality analysis. This proposed method was used to estimate vehicular emissions in the San Joaquin Valley, California.

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Problem Statement

Among various transportation-related issues, traffic congestion and safety often receive the most attention, and energy shortage follows. As the adverse effects of air pollution become more evident, the awareness of reducing emissions from transportation sector is growing. In the U.S., mobile source emissions are currently a major contributor to a variety of atmospheric pollutants, including greenhouse gases, ozone precursors, and particulate matters. In order to improve air quality, various emission-reduction strategies have been implemented through legal requirements and supports. As a means of determining effective emission-reduction policies and control measures, modeling emissions inventories with high resolution and accuracy is particularly important.

Since emissions estimation is the product of travel activities and emission factors, existing studies primarily focus on two sides: either forecasting highly resolved travel activities or providing more accurate emission factors. However, strengthening the linkage between emission factors and travel activities is equally critical for enhancing emissions estimation. Geographic Information System (GIS) is a natural platform to connect them based on several reasons. First, both travel activities and emission factors are intrinsically spatially dependent, and GIS is powerful at performing spatial analysis. Second, GIS is already a common element in transportation models as well as in air quality models. As an intermediate step between transportation and air quality modeling, emissions estimation should also be GIS based in order to streamline an integrated transportation and air quality analysis. Finally, more and more factors, such as land-use patterns and clean vehicle technology dissemination, are being included for a more comprehensive transportation and air quality analysis. This trend requires a platform on which different types of models can be integrated and numerous sources of data can be managed; GIS is the best option. In recognition of the strength of GIS, the National Cooperative Highway Research Program (NCHRP) has encouraged the new generation of transportation-air quality models to incorporate GIS into emissions modeling (Cambridge Systematics, Inc., 2001).

However, literature review has found that existing efforts at using GIS for transportation-related emissions are insufficient. Most previous attempts are pilot studies focusing on incomplete sets of pollutants (e.g., CO or NOx only) and sources of vehicular emissions (e.g., running emissions only). None of the existing methods is qualified to provide inputs to both transportation conformity analysis and air quality modeling, which require more comprehensive pollutant types and emission sources. In addition, current studies in the related fields are mostly limited to using old-fashioned GIS techniques, such as data manipulation and visualization. Recent advances of GIS technology, such as geostatistics, spatial analysis and object-oriented programming, are rarely used, although they could provide innovative solutions for improving the performance of mobile source emissions estimation. Therefore, there is a great need to move transportation-related emissions modeling towards to be a GIS based system.

Study Objective

This research was motivated by the desire to improve mobile-source emissions estimation by incorporating GIS. The goal of this research was to develop a GIS-based on-road mobile-source estimation method that can provide better emission estimates. This study expected that integrating GIS into emissions estimation would achieve the research goal by offering added value to present data sources, such as local vehicle population data, land uses, and detailed travel activities.

Literature Review

This section provides a review of efforts focused on advancing GIS technologies in transportation and air quality analysis. A typical transportation and air quality analysis usually involves three phases: forecasting transportation activities, estimating emission factors and inventories, and modeling the photochemical process. This section reviews the applications of GIS in the first two phases. The involvement of GIS in transportation is first reviewed. The emphasis of the review is placed on efforts incorporating GIS in vehicular emissions estimation.

GIS in Transportation

Transportation communities have long been interested in exploring the benefits of GIS in research and practices. Currently, the applications of GIS in transportation reach almost every aspect of transportation ranging from planning and design to operation and management (Perkins, 1999). In particular, GIS has been extensively used for transportation planning, where the management of data from various sources, spatial analysis and visualization are frequently needed. Existing prevalent transportation planning tools are either fully GIS-integrated or connected to a GIS at some degree. For instance, TransCAD and VISUM are entirely built in a GIS environment (Caliper Corp., 2000; PTV, 2003). An interface between EMME/2 and ARC/INFO was also developed to facilitate data exchanges (Lussier and Wu, 1997). Another collection of software packages widely used for transportation planning, including TP+, TRIPS, MINUTP and TRANPLAN, used to seamlessly interface with VIPER. VIPER mainly performs various GIS functions in order to effectively manage modeling inputs and outputs. As an outcome of a combined effort between Citilabs and ESRI, these travel forecasting packages (e.g., TP+, TRIPS, and TRANPLAN) have been upgraded to CUBE, in which ArcGIS has been integrated to replace VIPER (Citilabs, 2004). Moreover, including GIS capabilities in an integrated land use and transportation analysis is particularly important since more comprehensive spatial analyses and more complicated data exchanges between different types of models are involved. The GIS benefits in integrated urban models were also reflected in a study by Johnston and Barra (2000), linking TRANUS and GIS.

GIS Applications in Transportation-Related Emission and Air Quality Analysis

GIS has also been widely used in the areas of air quality management and modeling. But when it comes to transportation related air quality analysis, GIS applications in this context are not extensive.

Hallmark and O'Neill (1996) integrated transportation analysis tools and air quality models for analyzing localized pollutants (e.g., CO) by taking advantage of a GIS-based travel demand forecasting package, TRANSCAD. Two types of air quality models, CALINE3 and CAL3QHC, were used to calculate pollutant concentrations due to line and intersection source emissions, respectively. Pollutant concentrations were then imported to TRANSCAD to generate pollutant concentration contours since TRANSCAD is capable of performing many visualization and spatial analysis features of a GIS. Combining pollutant concentration contours and land use layers in TRANSCAD can analyze air quality impacts on some sensitive areas, such as schools and hospitals. Transportation planners and traffic engineers can also use this integrated method to develop planning countermeasures and traffic control strategies. The method proposed by Hallmark and O'Neill demonstrated that GIS is effective in supporting an integrated analysis involving land uses, transportation and air quality models. However, the air quality models in the method are only for small scale analysis (e.g., intersection or corridor analysis), and only one type of pollutant, CO, is included.

GIS was used to link travel demand models and air quality analysis by another group of researchers (Jensen and Sathisan, 1996; Souleyrette and Sathisan, 1992). In this effort to use GIS to improve transportation and air quality analysis, TRANPLAN was a travel demand forecasting tool to provide transportation inputs, and the Urban Airshed Model (UAM) was used to model the photochemical and dispersion process and to calculate pollutants concentrations. Emission rates were given by MOBLIE 4.0. ARC/INFO was selected as the GIS tool to build the linkage between TRANPLAN and UAM. Specifically, a program developed in ARC/INFO read VMT and speeds from TRANPLAN and emission rates from MOBILE 4.0 outputs, and then combined them to obtain gridded emissions. In addition to preparing gridded emissions for UAM, ARC/INFO also graphically displayed pollutants concentrations based on the outputs of UAM. The method was applied to a transportation conformity analysis in the Las Vegas valley, and proved that the method could help local authorities analyze the effectiveness of potential travel demand management (TDM) strategies or transportation control measures (TCMs) in improving air quality. But the method also needs further significant enhancements in three respects. First, the connections among TRANPLAN, ARC/INFO, and UAM were performed manually rather than through an automated process. The primary reason is that the old version of these packages was running on different operating systems, for example, TRANPLAN on DOS, ARC/INFO on UNIX, and UAM on VMS. The difference made developing an automated data exchange process difficult. Second, the system was only able to analyze one pollutant, CO. Some other critical pollutants, such as PM, NOx and HC, were not considered. Finally, the method was not able to account for emissions resulting from vehicle stops and starts.

Summary of Literature Review

This literature review has presented the major applications of GIS in transportation, emissions estimation, and integrated transportation and air quality analysis. It is evident that transportation communities have been sophisticated and passionate GIS users. Particularly, travel demand forecasting models continue strengthening the role of GIS in their modeling procedure. Since travel demand models are the primary travel activity data provider to emissions estimation, it is logical to estimate vehicular emissions within the same environment, GIS, in order to develop a seamless interface between travel demand models and emissions estimation models.

As to transportation-related air quality analysis, several efforts involving GIS have also been found. But most of them were small-scale pilot studies, only focusing on one type of pollutant (e.g., CO or NOx) or one type of emissions sources (e.g., intersections or running emissions). There were also several studies using GIS in integrated land use, transportation and air quality analysis, and they shared some similarities. For example, the comprehensiveness of these studies made them less likely to be focused on obtaining accurate emissions inventories. Both emission factors and the spatial allocation of emissions were coarse in these integrated analyses. Nonetheless, the benefits of GIS in connecting different submodels (i.e. land use and travel demand models, emissions estimation and air quality models) and spatially analyzing emissions have been well demonstrated in these studies.

In conclusion, the needs to develop a new GIS-based vehicular emissions estimation method can be reflected from several facts based on the literature review. First, although several relevant attempts appeared in some integrated transportation and air quality studies, the efforts to use GIS in vehicular emissions estimation have been relatively limited. Second, GIS should play a more important role in modeling vehicular emissions not only due to the natural spatial dependence of emissions modeling but also because the two ends of emissions modeling (travel forecasting and air quality modeling) are often GIS-based. Third, previous studies on using GIS for emissions estimation frequently applied basic capabilities of GIS, such as data processing and mapping; however, recent advances of GIS technology have rarely been found in the applications of modeling mobile source emissions. Finally, the growing attention to reducing mobile source emissions requires that emissions estimation models should not only be limited to obtaining emissions totals for the transportation conformity analysis purpose but also need to serve for identifying effective emissions-reduction measures as well as air quality modeling. The enhanced requirements need emissions inventory models to further improve their accuracy and resolution. Integrating GIS in emissions estimation could fulfill these requirements by offering added value to present data sources, such as local vehicle population data, land uses, and detailed travel activities.

Methodology

This section presents the proposed GIS-based methodology. Two major components of the proposed methodology are discussed: disaggregating travel activities and calculating gridded emissions inventories.

<u>Data Preparation</u>

The proposed modeling method requires the following transportation data: transportation network, TAZs, link-based volumes and speeds, intrazonal travel activities, and interzonal trip ends, all of which can be provided by Travel Demand Models (TDMs). A detailed description of those data is given below.

Table 1 GIS Data Needs

GIS Coverage	Coverage types	Attributes
Road links	Polyline	Facility Type[1] Link length Number of lanes Link free-flow speed Link capacity Link volumes by periods[2] Link speeds by periods
Node	Point	Node ID Node type[3] Node coordinates (x,y) Node type
TAZ	Polygon	TAZ ID Number of trip productions Number of trip attractions

1: Freeway, Expressway, Divided Arterial, Undivided Arterial, Collector, Centroid Connector, Diamond Ramp, Loop Ramp, Cordon Connector
2: Periods: AM Peak, PM Peak, Mid-Day, Offpeak
3: Centroids, Link Ends

Disaggregating Travel Activities

There are two types of travel data – zonal-based data and link-based data – involved in emissions estimation, both of which are usually from travel demand models. Zonal data include interzonal trip ends and intrazonal trip ends, volumes and speeds. Link travel activities consist of traffic volumes and speeds. Since air quality models require gridded emissions, both zonal and link travel data have to be disaggregated into grid cells in order to obtain emissions at the grid cell level. As for distributing link travel activities, both DTIM and UCDrive construct grid meshes to obtain the portions of roadway links within each grid cell as shown in Figure 1. The grid mesh method involves complex vector calculations. For a large network and fine grids, the method needs to consume a considerable amount of computer memory and computing time. As to disaggregating zonal activities, DTIM ignores the spatial heterogeneity of zonal activities and assigns the entire TAZ emissions to the grid cell that contains the TAZ (Zheng, 2004). GIS raster modeling method provides opportunities to overcome these shortcomings when modeling gridded emissions within a GIS environment.

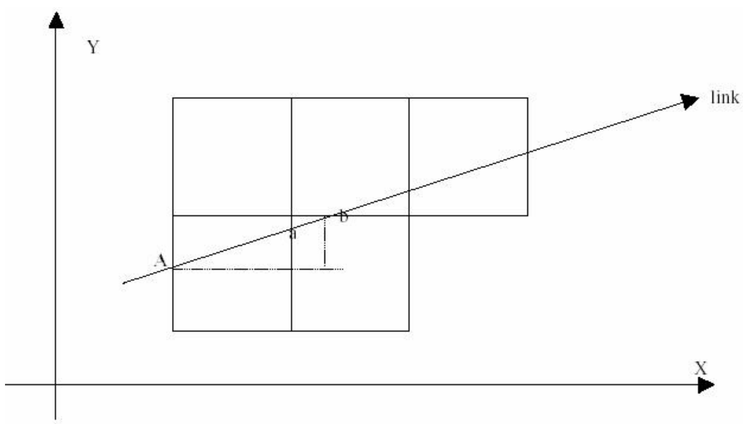


Figure 1 DTIM and UCDrive Mesh Construction Method

Adapted from (Zheng, 2001)

As shown in Figure 2, zonal travel activities can be represented in the form of rasters. Each raster represents both the geographic location and the specific characteristics of a subarea within a TAZ. If there is no information on the internal distribution of zonal travel activities, travel activities can be uniformly allocated to each grid cell. There are increasing requirements on the spatial disaggregation and accuracy of modeling vehicular emissions inventory at the grid cell level. UCDrive proposes a new approach that can disaggregate TAZ activities into grid cells based on activity density using the bicubic Spline interpolation method (Zheng, 2004). Since the Spline interpolation is a built-in function of raster models in ArcGIS, implementing UCDrive's new gridding algorithm based on the Spline interpolation is greatly convenient in GIS. In addition, UCDrive distributes zonal travel activities within a TAZ into a matrix of grid cells covering the TAZ. Therefore, some portion of travel activities in a TAZ may be assigned to grid cells that are actually outside of the TAZ. This problem does not occur in a GIS approach. Thus, this research can be considered as a further improvement to the new grid-based emissions inventory model –UCDrive. Considering the importance of start and hot soak emissions, this part of research specifically dealing with zonal travel activities becomes particularly important. As an example, Figure 2 also shows the rasters with different dot sizes, describing the unequally distributed zonal activities.

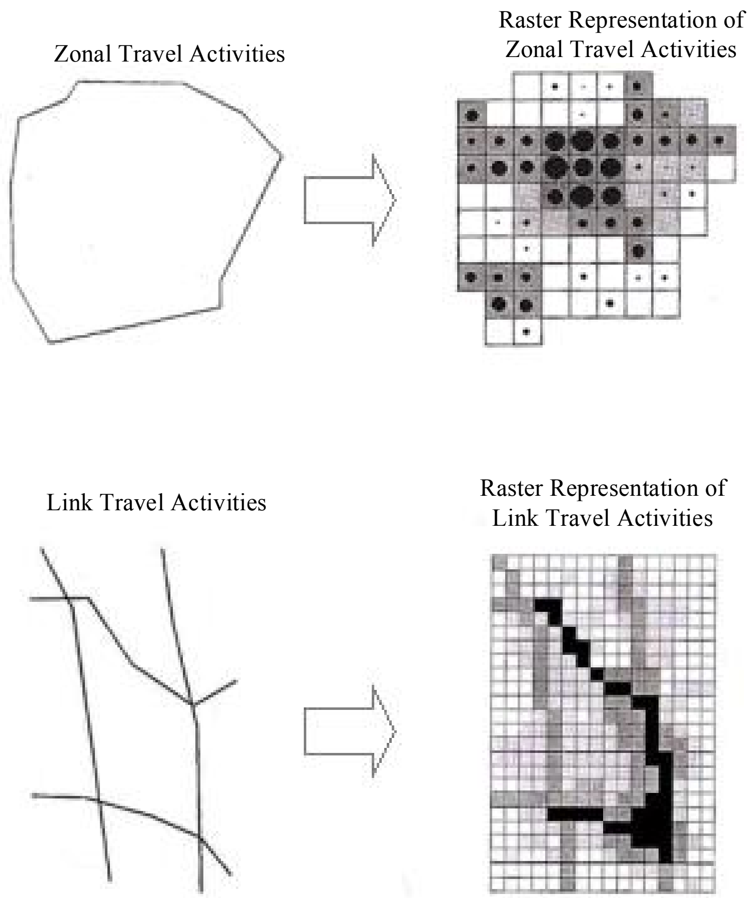


Figure 2   Disaggregation of Zonal and Link-based Data to Grid Cell Level

Modified from (Spiekermann and Wegener, 2000)

Transportation network is composed of a number of links. In raster models, those links are represented by a series of connected cells laid over the transportation network. Each cell can be considered as a tiny portion of a link and receives traffic information associated with this link, such as traffic volume and speed. The accuracy of the representation varies with the resolution of raster dataset: the finer the cell resolution, the more accurate the representation. After transforming links into rasters, we only need to deal with rasters in the following step of calculating running emissions and avoid the complexity due to constructing grid meshes as a means of obtaining gridded emissions. Theoretically, computing based on raster data is always much faster than computing based on vector data (e.g., roadway links). Moreover, since new gridded emissions are raster based, we can easily apply cell statistics functions in GIS to aggregate gridded emissions into any desired grid sizes. However, traditional models such as DTIM have to repeat the whole computing process in order to modify a grid size.

Calculating Grid-Based Emissions Inventories

We have now known two fundamental measures: travel activities and emission factors. The product of them at a grid level can produce a gridded emissions inventory. The primary types of pollutants that will be calculated include: running exhaust emissions, diurnal and resting loss emissions, and trip-end emissions (i.e. start emissions and hot soak emissions). The emissions calculation functions are similar to the methods used by DTIM, a model developed by Caltrans for producing gridded emissions. The difference lies in that this study takes disaggregated travel activities based on raster models.

Case Study

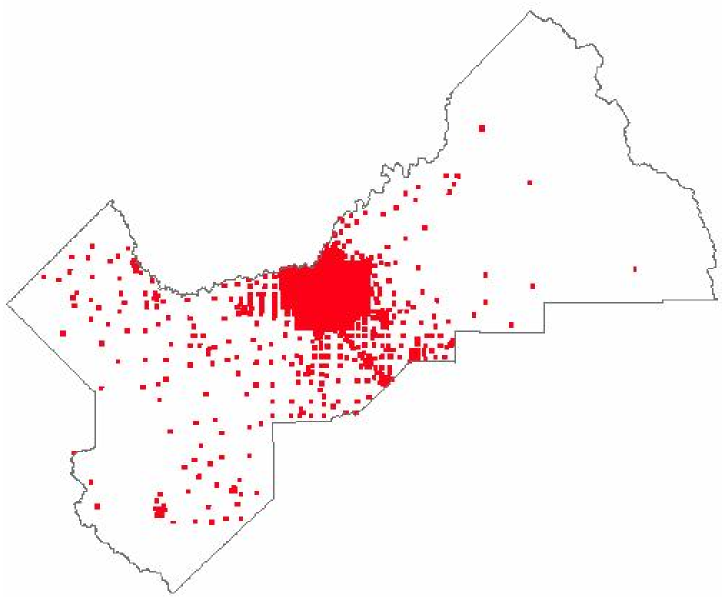
We selected the 8-county San Joaquin Valley (SJV) in California to conduct a case study. The San Joaquin Valley air basin consists of eight counties: Fresno, Kern, Kings, Madera, Merced, San Joaquin, Stanislaus, and Tulare, which cover Caltrans Districts 6 and 10. The SJV is facing serious air quality problems and is currently designated as in "severe nonattainment" for the state 1-hour ozone standard, "extreme nonattainment" for the federal 1-hour ozone standard, and "serious nonattainment" for the federal fine Particulate Matter (PM10) standard (SJVAPCD, 2004).

Non-GIS Method vs. GIS Method in Presenting Intrazonal Emissions

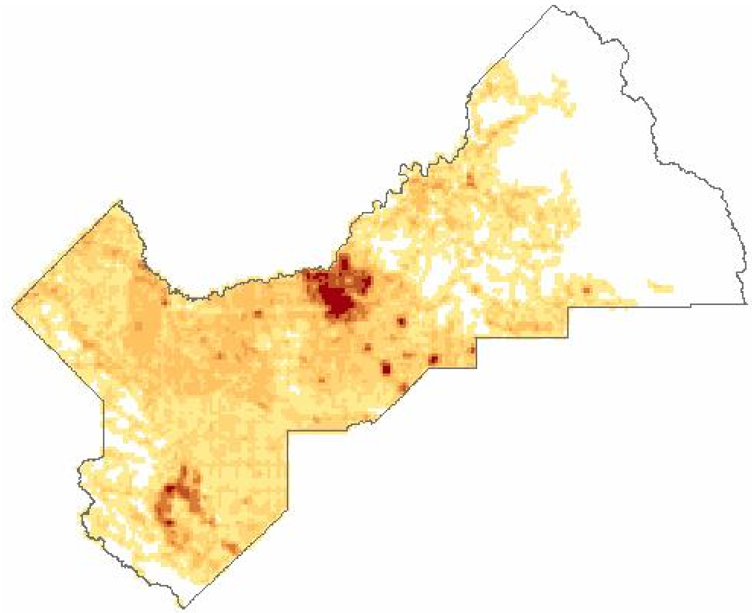
Using Fresno County as an example, Figure 3 compares the difference between a non-GIS method (i.e. DTIM) and the proposed GIS study in presenting intrazonal emissions. We can see that the current non-GIS based method, DTIM, ignores the spatial heterogeneity of intrazonal activities (i.e. trip ends and volumes) and assigns emissions from an entire TAZ to the grid cell that contains the TAZ centroid. Modeling gridded emissions within a GIS environment provides opportunities to overcome this shortcoming. By using detailed road networks to disaggregated intrazonal travel activities, the GIS method provides a much better representation of the spatial distribution of travel activities within a TAZ. Therefore, this results in a more realistic allocation of emissions at the grid cell level.

Integrating Emissions with Socio-demographics Information

The GIS method allows us to conduct an integrated analysis by incorporating various spatial information, such as land use, socio-demographics, etc. For example, Figure 4 shows the concentration of PM2.5 (particulate matter that is 2.5 microns in diameter and less) for the San Joaquin Valley. By combining with population census data, we can use GIS to locate the population that is exposed to the area which exceeds the PM2.5 federal standard. The pink area in Figure 5 shows the affected population. We can further obtain that the total number of affected people is 770,574. Those analyses cannot be done with a non-GIS emission model.



Non-GIS Method



GIS Method

Figure 3 Non-GIS Method vs. GIS Method in Presenting Intrazonal Emissions

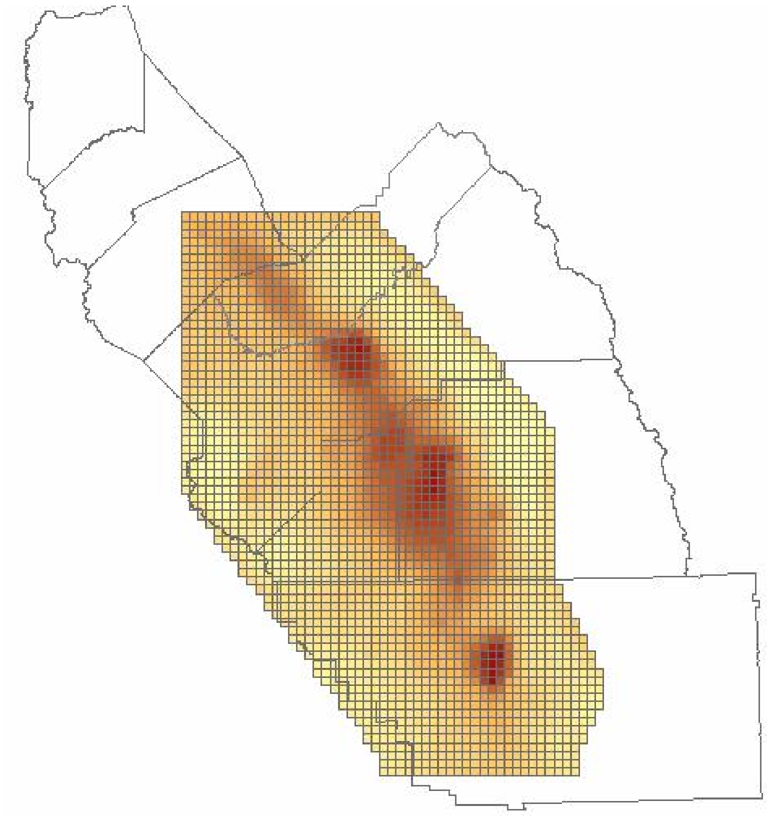


Figure 4 PM 2.5 Concentration of the San Joaquin Valley

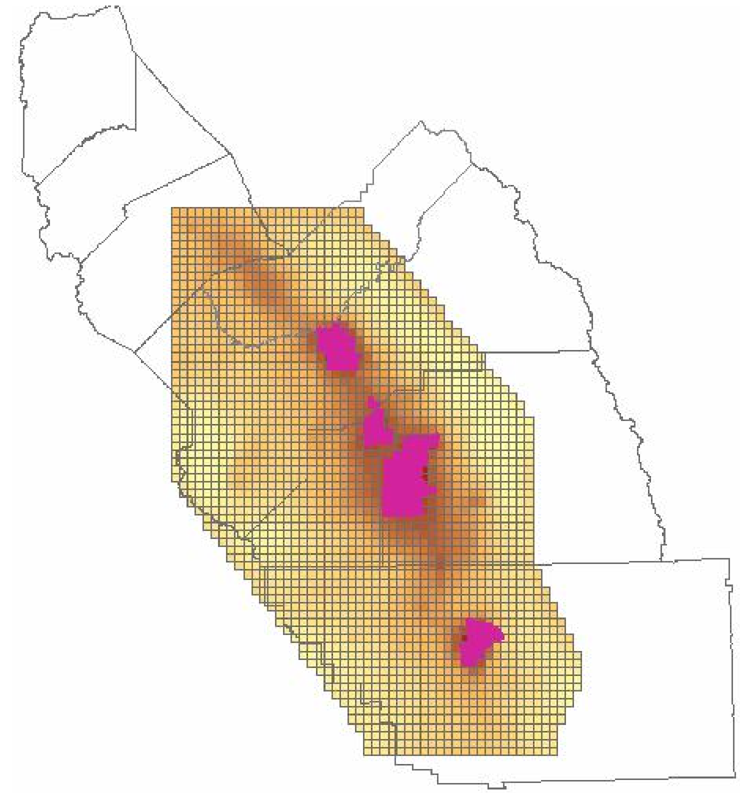


Figure 5 Affected Population under Federal current PM2.5 Standard

Summary

The proposed study is a response to the recommendation by the EPA and NCHRP who claim that the new generation of transportation and air quality models should take advantage of the use of GIS in emissions modeling. This study represents one of the first several efforts in modeling on-road mobile-source emissions inventories based on GIS. Transportation and air quality analyses are inherently spatially dependent. With the continuing technology advancements of GIS in spatial modeling, geostatistics and data integration, GIS plays an increasing role in every aspect of transportation and air quality modeling. However, most previous studies involving GIS and vehicular emissions modeling are only limited to input data preparation, post processing (e.g., visualization), or dealing with a single source of mobile emissions, such as running emissions. This study aims to incorporate GIS capabilities into several critical steps of emissions modeling: quantifying highly resolved emission factors, calculating gridded emissions inventories, and analyzing spatial variation of emission factors.

This study can help interface transportation models and air quality models and could serve as an intermediate step towards an integrated transportation and air quality analysis. Existing commonly used travel demand modeling packages (e.g., TRANSCAD, EMME/2, VISUM, TRIPS, TRANPLAN, and TP+) are mostly built on a GIS platform or are evolving to be GIS-based. On the other hand, air quality models also use GIS to manage various emissions sources, terrain, and ambient conditions. This study simplifies the process of frequently exchanging data on both sides of travel demand models and air quality models. Therefore, this study can work as an interface that helps create a more streamlined transportation and air quality analysis.

In addition, this GIS based method found its applications in California. CARB (California Air Resource Board) is planning to develop a GIS-based statewide emission inventory system that will include various emission sources contributing to air quality problems. The potential benefits of GIS in improving the accuracy and efficiency of managing emissions are the primary motivations of this initiative. California's new system is expected to enhance the ability of government agencies to develop effective measures to meet air quality objectives. Since transportation-related emissions are a major source of ambient pollutants, this proposed study represents a concrete step towards developing a GIS-based emission inventory system in California

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