Modeling regional mobile source emissions in a geographic information system framework

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Abstract

Suburban sprawl, population growth, and automobile dependency contribute directly to air pollution problems in US metropolitan areas. As metropolitan regions attempt to mitigate these problems, they are faced with the difficult task of balancing the mobility needs of a growing population and economy, while simultaneously lowering or maintaining levels of ambient pollutants. Although ambient air quality can be directly monitored, predicting the amount and fraction of the mobile source components presents special challenges. A modeling framework that can correlate spatial and temporal emission-specific vehicle activities is required for the complex photochemical models used to predict pollutant concentrations. This paper discusses the GIS-based modeling approach called the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). MEASURE provides researchers and planners with a means of assessing motor vehicle emission reduction strategies. Estimates of spatially resolved fleet composition and activity are combined with activity-specific emission rates to predict engine start and running exhaust emissions. Engine start emissions are estimated using aggregate zonal information. Running exhaust emissions are predicted using road segment specific information and aggregate zonal information. The paper discusses the benefits and challenges related to mobile source emissions modeling in a GIS framework and identifies future GIS mobile emissions modeling research needs. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The Clean Air Act, as amended in 1990, and other federal legislation and regulations require metropolitan areas with unacceptable air quality to develop strategies for reducing air pollution. In planning for attainment of these standards, metropolitan areas establish emissions 'budgets' that provide benchmarks for gauging attainment progress. Meeting emissions budget limits in target years often becomes difficult. Metropolitan areas must accommodate the needs of a growing population and economy, while simultaneously lowering or maintaining levels of ambient pollutants. Therefore, growing urban areas must continually develop creative strategies to curb increased pollutant production. Transportation systems contribute significantly to carbon monoxide (CO), nitrogen oxides (NOx), and hydrocarbon (HC) emissions in urban areas. Estimates for the amount of pollutants produced by motor vehicles vary from 33% to 50% of NOx, 33% to 97% of CO, 40% to 50% of HC, 50% of ozone precursors, and at least one-fourth of volatile organic compounds (VOC) (Chatterjee et al., 1997; SCAQMD, 1996; USEPA, 1995; CARB, 1994; USDOT, 1993). Developing measures of effectiveness and subsequent predictions of the overall impact of control strategies requires an ability to model the relationships between observable transportation system characteristics and their resulting emissions. In addition, models that incorporate these relationships must balance input data availability and quality with predictive power.

Motor vehicle emission rates correlate with a variety of vehicle and engine characteristics (weight, engine size, transmission type, emission control equipment, etc.), operating modes (idle, cruise, acceleration and deceleration), and transportation system conditions (road grade, pavement condition, etc.) (Barth et al., 1996; Guensler, 1994). Emission rates used in models are estimates of the rate at which different pollutants are emitted in grams per activity unit, such as grams of CO/s or CO/mile. Different vehicle activities (starting an engine, accelerating, cruising, etc.) result in different emission rates. Exhaust pollutants produced from starting a vehicle are correlated to the vehicle's engine characteristics and duration of the engine cool down time between starts. Running exhaust emissions require additional estimates of dynamic engine conditions that vary with the way the vehicle is driven. Estimating motor vehicle emissions requires the ability to predict or measure these activity parameters for an entire region at a level of spatial and temporal aggregation fitting the scope of anticipated control strategies.

Traditional motor vehicle emissions modeling involves four separate modeling regimes: travel demand forecasting models, mobile source emissions rate models, photochemical models (for emission inventories and resulting regional air quality), and microscale models. Travel demand forecasting models use characteristics of the transportation system and socioeconomic data to estimate road-specific traffic volumes. Emission rate models employ fleet characteristic data, operating environment characteristics, and assumptions related to emission control programs to predict emission rates for the on-road fleet. The travel demand estimates are linked with the outputs of the emission rate models to predict mobile source mass emissions. Analysts spatially allocate the mobile source emissions estimates along with stationary source estimates, to a regional grid as input to photochemical models. The photochemical models employ emissions estimates (from all sources) and meteorological data to predict ambient pollutant levels in space and time. Microscale models such as CALINE or FLINT employ mobile source emissions estimates and ambient estimates to predict pollutant levels near specific transportation facilities such as
signalized intersections. CO is usually analyzed on a microscale because of the immediate localized health effects, whereas HC and NOx are most often analyzed on a regional scale since they are precursors to ozone formation.

Several problems inherent in the four-model system limit effective evaluation of motor vehicle emission control strategies. First, the estimates of vehicle activity (vehicle-miles traveled and average speed) lack the accuracy and spatial resolution needed to evaluate control measures (Chatterjee et al., 1997; Stopher, 1993). Second, the mobile source emission rate modeling process uses highly aggregate fleet estimates and biased emission rates, which more recent research has shown to be inaccurate (Barth et al., 1996; Guensler, 1994; LeBlanc et al., 1995). Third, the modeling process is not oriented to the needs of the transportation planners and engineers who design and implement emissions control strategies. These users require more feedback from typical transportation system improvement strategies (e.g., lane additions, optimized signal timing, signal-coordination, and peak-hour smoothing) than is provided in the four-model system.

A modeling approach that provides significant improvements to these three issues would be desirable. This paper focuses on using GIS as a platform for modeling mobile source emissions and the potential improvements it offers over the current regulatory approach. While GIS does not implicitly improve the ability to forecast travel, nor improve the accuracy of existing spatial data, it does provide a mechanism for storing and maintaining complex socio-economic and infrastructure data. Using GIS, these data, as well as a variety of other types and resolutions of spatial data required for emissions modeling, can be brought together into an integrated modeling environment. Furthermore, many transportation agencies already use GIS to maintain the inputs into landuse and travel demand forecasting models (Vonderohe et al., 1993). Intrinsically, GIS fits the character of emission science as well as the technical environment of the expected end users.

One drawback to the integrated GIS modeling approach is that it requires the development and integration of new data that takes a great deal of time and effort to produce. Thus, the costs associated with implementing a comprehensive GIS-based emissions model are large because of the resources needed for model development, standardization, and integration of new data sources. However, since a metropolitan area’s ability to demonstrate conformity depends on accurate emissions modeling, the disadvantages of current emissions modeling methods significantly overshadow the benefits of simplicity and lower modeling cost.

2. Establishing a foundation for modeling emissions in a GIS environment

Mobile emissions are intrinsically spatial. Among other things, emission rates vary by location and engine activity. Fig. 1 shows conceptually how emissions vary as a vehicle operates in space and time. Each ‘block’ of elevated or reduced emissions has different predictor variables. When the engine is off, emissions continue but at a reduced level (evaporative mode). When a vehicle starts (engine start mode), emissions are high due to the nature of catalysts (they need to reach an elevated temperature before operating efficiently). After a few minutes, emissions are low unless interrupted by a sharp power demand from hard acceleration or grade-induced engine load (running exhaust mode). All of these conditions vary in spatial terms as a vehicle moves along its path. This relationship between emission rates and location is a primary argument for using GIS in mobile emissions model development.
2.1. Considering the spatial variability of mobile emissions related data

Mobile emissions model inputs can be divided into three general categories: fleet activity, fleet characteristics, and operating conditions. Most regions model emissions using regional aggregations of all these inputs, and then use estimates of vehicle miles traveled (VMT) calculated for each grid cell to disaggregate each of the totals. Unfortunately this practice does not account for the spatial variability of each of the inputs. For example, current regulatory emissions models assume a uniform distribution of the vehicle fleet across a region in calculating their emission estimates. This is not a reasonable assumption in most areas. Fig. 2 shows the census block group distribution of average vehicle model years in the Atlanta metropolitan area. Clearly, significant spatial variability of automobile ownership exists across this region. Improving the spatial scale of emissions modeling would be a major advance that could benefit from the many geoprocessing capabilities of a robust GIS modeling platform.

2.2. Literature review of GIS activities in air quality modeling

Many research efforts have taken advantage of the spatial environment of a GIS to perform various aspects of transportation-related air quality modeling. Bruckman et al. (1992) identified many benefits of using GIS in the preparation of mobile emissions model input data including fleet activity, fleet characteristics, and operating characteristics. Souleyrette et al. (1992) acknowledged the potential of a GIS to manage the complex spatial data often required to address transportation and air quality analysis problems. They developed a model that investigated the relationship between CO concentrations and traffic characteristics such as vehicle miles traveled, location of refueling stations, and wind patterns. Another research effort created an activity-based model for travel demand forecasting that integrated household activities, landuse patterns, traffic flow, and regional demographics in a GIS. Although not directly developed as an emissions model, the model was able to provide output for analyzing issues related to the Clean Air Act Amendments (Stopher et al., 1996). Hallmark and O’Neill (1996) capitalized on the use of a GIS for localized air quality modeling. They describe development of a model that combines the microscale air quality model (CAL3QHC) with a GIS. Medina et al. (1994) presented the framework for an air quality analysis model that integrates CADD, GIS, transportation, and air
quality models linking traffic information with a GIS to produce synthesized databases for use in vehicle emission and air dispersion models. Barros et al. (1998) developed a methodology to develop a GIS-based traffic emission inventory for Portugal, useful for estimating both area and line sources. Briggs et al. (1997) described the use of a GIS combined with least squares regression analysis for mapping traffic-related air pollution to generate predictive models of pollution surfaces based on monitored pollution data and exogenous information. Anderson et al. (1996) also described the use of a GIS as a tool to illustrate the spatial patterns of emissions and to visualize the impact congestion has on emissions. The model consisted of an integrated urban landuse model that interfaced with the emissions rate model MOBILE 5C. The integrated model allowed the impact of transportation and landuse policy changes to be simulated in terms of their air quality impact.
One common theme of all of these efforts is the use of GIS as a tool to prepare or process data related to emissions modeling. None of these earlier efforts used GIS as an integrated modeling environment capable of estimating emission rates at a user-defined grid cell level.

A research effort that does not involve a commercial GIS platform but has focused on improving the spatial scale of data inputs into emissions photochemical models is the development of the TRansportation Analysis and SIMulation System (TRANSIMS) microsimulation travel forecasting model (Williams et al., 1999). TRANSIMS processes, stores, and manipulates spatial data through the use of a powerful spatial database engine with explicit network topology. It uses an advanced approach of vehicle microsimulation using synthetic populations. The TRANSIMS approach dramatically improves the spatial scale issue by modeling individual synthetic vehicles on a second-by-second basis. Unfortunately, TRANSIMS model inputs far exceed even the most detailed regional models. Further, the TRANSIMS model is still under development with many of its components undergoing calibration and validation. Until TRANSIMS becomes widely accepted and implemented, there will be continual reliance on existing modeling frameworks. A GIS-based macroscopic modeling approach that does not rely heavily on regional aggregations for inputs provides a robust alternative to the current modeling regime as well as future regional microscopic model such as TRANSIMS. In Section 2.3, we introduce a conceptual framework for a GIS-based macroscopic modeling approach.

2.3. Conceptual framework for a GIS-based emissions model

Elements of any emissions model should include data important to accurately predict emission rates, data that are available to the expected user, and data that fit the mitigation tools available to transportation professionals. GIS, computing power, and data storage capabilities allow this model design to expand from historical ones focused on simplicity, to one focused on comprehensiveness, usefulness, and flexibility. By removing the concern of processing time and disk storage, a robust emissions model conceptual framework can be conceived without fear that it cannot be implemented.

Research suggests that the conceptual framework for a robust model should be modal in nature. A GIS framework is ideally suited for implementing a modal modeling approach, where emission rates are a function of specific modes of vehicle operation (engine starts, running exhaust, enrichment, etc.). Modal models hold the most significant promise for improving model accuracy and eliminating the various shortcomings of the current highly aggregated approach (Washington, 1995; Barth et al., 1996). Conceptually, a GIS can be used to estimate mobile source emissions for different operating modes and store these results on individual layers. The layered information could then be aggregated to grid cell layers that are compatible with photochemical models. Once aggregated, total estimates can be calculated by summing across layers. The summing process in itself would not contribute to the error of the individual layer estimates because the cell polygons whose attributes are summed across corresponding layers would be identical in shape, size, and location. Thus the main contributor to error from a spatial processing standpoint is in the disaggregation (and to some extent the aggregation) of data to grid cells.

In 1995, Bachman et al. (1996a) developed a conceptual framework for a modal GIS-based emissions modeling regime. The conceptual framework benefited from lessons learned in earlier attempts using a GIS to assist in modeling mobile source emissions. Fig. 3 illustrates this original
conceptual model. The framework attempted to improve on the spatial resolution of inputs, while adding additional elements that had been shown to have significant impact on emissions but were not currently considered in regulatory emissions models. For example, several research efforts have shown that roadway grades are directly related to elevated emissions because they have significant impacts on engine loads (Cicero-Fernandez et al., 1997; Pierson et al., 1996). Unfortunately, grades have been largely ignored in current regulatory models.

Portions of the original conceptual framework were implemented into a working prototype model that included experimental emission rates designed to identify the impacts of changes in acceleration and engine load. While the prototype was limited (e.g., it did not consider fleet distribution) it did illustrate several benefits of using a GIS platform for modeling emissions estimates:

- efficiently manages spatially referenced parameters that affect emissions,
- provides manipulation tools to calculate emissions from the modal parameters,
- allows a 'layered' approach to individual vehicle activity estimation,
- can efficiently aggregate emission estimates into grid cells for input to photochemical models using topologic overlay capabilities,
• includes a robust set of geocoding tools, such as address matching and global positioning system linkages to facilitate creation of new and modified databases.
• provides visualization and map-making tools, and
• contains useful links to other software packages such as statistical analysis software, that allow analysis and manipulation of data beyond the capabilities of a stand-alone GIS.

3. Introducing MEASURE

The GIS conceptual framework and associated prototype has evolved into the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). While MEASURE model development and evaluation are ongoing, a discussion of its specific approach and design provides insights into how the production GIS-based model for public release is being developed. Early validation and testing have shown promising results. The details of MEASURE model design and architecture can be found in the USEPA report entitled “A GIS-Based Modal Model of Automobile Exhaust Emissions” (USEPA, 1998).

MEASURE includes automobile exhaust-related modal vehicle activity measures for different vehicle conditions including starts, idle, cruise, acceleration, and deceleration. Vehicle technology characteristics (model year, engine size, etc.) and operating conditions (road grade, traffic flow, etc.) are included as data inputs. The model outputs emissions by facility type, grid cell, operating mode, and pollutant type (VOCs, NOx, and CO). Fig. 4 depicts general model processes and the flow of information. The model is currently undergoing a variety of validation studies to demonstrate that MEASURE exceeds the predictive capabilities of current models (see Section 3.6 for additional discussion on validation efforts). A recent study conducted in Atlanta compared MEASURE and MOBILE emission rate models to predict the results of 16 different running exhaust emission test cycles (bag tests). MEASURE proved to be substantially better than MOBILE in predicting the cycles (which varied in cycle speeds and accelerations) (Fomunung et al., 2000).

This description focuses on the model components and procedures that demonstrate innovative uses of GIS and spatial analysis. Other crucial elements, such as new modal emissions rates, are discussed briefly; in depth discussions have been published elsewhere (Washington, 1995; Washington et al., 1997; Fomunung et al., 2000). While not all the indirect relationships are modeled (e.g., land use change), an effort was made to include these parameters in anticipation of future research findings.

Required data necessary to develop a MEASURE model can be divided into five categories: spatial character, temporal character, vehicle technology, modal activity, and trip generation. These data are identified as follows:

Spatial character:
• landuse boundaries,
• US census block boundaries,
• traffic analysis zone boundaries,
• roads,
• travel demand forecasting network.
• output grid cell boundaries (user-defined).
Temporal character:
- hour of the day.

Vehicle technology:
- model year,
- engine displacement,
• transmission type,
• fuel delivery technology,
• supplemental air injection system,
• catalyst configuration,
• exhaust gas recirculation.

Modal activity:
• idle,
• cruise,
• acceleration,
• deceleration,
• starts,
• engine off.

Trip generation:
• landuse,
• housing units,
• socioeconomic characteristics (for spatial allocation only),
• home-based work trips,
• home-based shopping trips,
• home-based university trips,
• home-based grade school trips,
• home-based other trips,
• non-home-based trips.

3.1. Organizing the spatial environment

The organization of the MEASURE spatial environment is a function of the format of input data provided from other sources. Historically, emissions modeling regimes have divided exhaust emissions into start and non-start (running exhaust) emissions. Most prognostic travel models provide a traffic analysis zone (TAZ) estimate of the number of trip origins and a link (link) estimate of road volume and average speed. By defining an engine start as being synonymous with a trip origin, TAZs become the base spatial entity used for estimating engine start emissions within MEASURE. Running exhaust emissions occur on the road network, suggesting the network ‘link’ as the base spatial entity. Improvements in the spatial resolution of the zonal estimates can be made outside the travel model by disaggregating trips to smaller zones. In MEASURE, trip origins are disaggregated by census landuse data and by US census block group household data. Census blocks can be used to disaggregate trips even further. For example, TAZ trips leaving from home are spatially allocated to the portions of the TAZ that contain residential land uses and further weighted by household density determined from census blocks. This process does not affect the total TAZ home-based origins; the origins are simply allocated to smaller zones within the TAZ based on those factors. The final ‘zone’ used for emissions modeling is created through a series of GIS polygon overlays that intersects TAZs, census block and census block group boundaries, and US postal code (ZIP code) boundaries.
The spatial accuracy of the line estimate is improved by conflating the travel demand forecasting network 'links' to a comprehensive and accurate road database. Travel demand forecasting model networks are frequently abstract stick networks without intermediate shape points. Conflating improves the spatial resolution of roadway links and helps to clearly identify the network access points from each TAZ. Bachman et al. (1996b) describe a GIS conflation procedure for improving the spatial accuracy of travel forecasting networks. This procedure uses the GIS's built-in rubber sheeting tools as well as a series of heuristics (rules of thumb) to guide the automated conflation. A one-to-one correspondence table is also necessary to accurately conflate complicated road configurations, such as interchanges and closely spaced roads. The Bachman paper also discusses the potential impacts which conflating a travel demand forecasting network would have on hot stabilized emissions when the final estimates are aggregated to 1- and 5-km grid cells suitable for photochemical modeling.

3.2. Estimating vehicle fleet characteristics

Although many different emissions modeling approaches are being developed around the country, all indicate that identifying the emission-significant components of the operating fleet is important to emission rate accuracy (Siwek, 1997). Current regulatory emission models use model year distributions to describe the fleet, taking these data from registration or inspection and maintenance databases. However, many other vehicle characteristics hold significant explanatory capability for predicting emission rates, such as type of emission control equipment, engine size, vehicle weight, and transmission type (Fomunung et al., 1999; Barth et al., 1996; Stopher, 1993). Furthermore, to improve on the highly aggregate approach currently used, spatially resolved sub-fleet characterization is important.

In MEASURE, regional vehicle registration data are used to define emission-related vehicle characteristics. MEASURE's fleet module develops estimates of vehicle technology distributions for each of the zone and line representations. Every ZIP code has a 'technology group' distribution. Technology groups are combinations of vehicle characteristics and operating conditions that have been identified in regression tree analysis and linear regression analysis as being the most predictive. Regression models were developed for each of the three pollutants of interest (CO, HC, and NOx) by analyzing a data set of more than 13,000 hot-stabilized laboratory treadmill tests on 19 driving cycles (specific speed versus time testing conditions) and 114 variables describing vehicle, engine, and test cycle characteristics. A total of 44 such technology classes were defined out of 2560 technology rules (Fomunung et al., 1999). Engine start technology groups only include vehicle characteristics. For each emission-significant combination of vehicle characteristics, an associated gram per start emission rate is identified. Running exhaust technology groups include vehicle characteristics and/or modal operating parameters (idle, cruise, acceleration, etc.). Unlike engine start groups, running exhaust technology groups can have different emission rates based on modal operating conditions.

The technology group distributions by ZIP code are assigned to every zone directly using a simple relational database procedure. Attaching distributions to roadway links is a little more difficult. Tomeh (1996) conducted a study of on-road vehicle distributions. In the study, vehicle registration data were used to define vehicle distributions by census block. Vehicle license tags at several interstate ramp locations were observed, and when distributions of the regional fleet and
distributions of a local fleet (census blocks within a 3-mile radius of the ramp) were combined, the fleet distribution at each ramp location could be predicted. While Tomeh's approach to predicting on-road vehicles proved valid, his research results also indicated that a more accurate prediction would result if the local fleet could be better defined. Instead of a 3-mile radius, the actual spatial pattern of observed vehicle home locations was skewed based on the network configuration and the time of day. If the ramp was an 'off-ramp', there was an upstream concentration of local vehicles in the afternoon and a regional distribution in the morning (the opposite held true for on-ramps). In its current form, MEASURE relies on Tomeh's original strategy (3-mile search radius), but future efforts may include a more advanced approach based on his observations. In addition, MEASURE adjusts the weightings of regional versus local vehicle distributions based on road classification. Interstates are assigned a higher regional fraction (assuming that interstates serve more of a regional set of vehicles), while local roads are assigned a higher local fraction (Bachman et al., 1998; Tomeh, 1996).

3.3. Estimating emission-specific vehicle activity

The core prognostic capability of the model rests on the ability of travel demand forecasting models to accurately predict regional travel. The emission related vehicle activity estimates provided by regional travel models are the number and location of peak hour (or daily) trip origins, the road segment volumes, and the volume-to-capacity-based average speeds (later post-processed in estimating speed/acceleration distributions). Important activities not provided by most current models are temporal travel behavior and modal (idle, cruise, acceleration, and deceleration) operations. In MEASURE, the usable travel model information is translated into the emissions modeling environment and any missing emission-related parameters are estimated based on data available.

3.3.1. Engine start activity

Engine starts are equivalent to trip origins determined at the TAZ level by the trip generation component of travel demand forecasting models. These TAZs represent a spatial unit for aggregating socioeconomic data and the resulting trip generation (trip production and trip attraction) estimates. This is typically done by the developers of the travel demand forecasting models by aggregating data from smaller census blocks and block groups. Census information that falls across two TAZs is typically divided by examining landuse density within the census block or block groups. Estimates of trip generation are made for each TAZ for a variety of trip purposes. Trip purposes usually include home-based work (to and from the workplace), home-based shopping, home-based school, home-based other, and non-home-based trips. While these trips are estimated to begin or end in certain TAZs, the trip type definitions imply that they are home (residential) going to work (non-residential) or a trip originating from work going home. Likewise, home-based shopping trips are to or from a commercial landuse. For the engine start component, external trips that originate outside the study area are not included. However, any trip that has an origin in the study area is included. A table of temporal distributions of trip origins for the region is used to estimate the time of day that the engine start occurred.

The US Census Bureau maintains zonal databases developed for the decennial census. The smallest zonal designation is a block, usually an area bounded by roads or other line features
(cadastral, hydrologic, etc.). Census blocks typically include 50–200 dwelling units. The 1990 estimates of the number of households are available at the census block level. Although these estimates are dated, they can provide clues to housing density within the TAZ and landuse designations. This information is used to further spatially disaggregate trips originating from residential areas. With good landuse and socioeconomic data, various trips can be disaggregated to smaller zones. Even if the landuse designations are as broad as “residential” and “non-residential”, the spatial resolution of trip generation estimates is improved. This allows for an improved spatial resolution for engine start estimates.

3.3.2. Intra-zonal running exhaust activity

Travel time is a key variable in predicting running exhaust emissions (preferably broken down by operating mode) because emissions are directly related to hours of vehicle operation. Other than evaluating the size of the zone, travel times for intra-zonal trips (and inter-zonal travel off the major roads) are often unaccounted for in the travel demand modeling process. However, disaggregate trip generation estimates allow the development of travel time estimates using the digital road network and spatial analysis tools provided by the GIS.

Many GIs provide tools that allow the determination of the optimal network path between two points based on a shortest path algorithm. The disaggregated trip generation estimates provide a trip origin location. The closest intersection of an aggregately modeled local road with an explicitly modeled major road provides a destination location where the trip becomes on-network. The shortest network path between the two points provides an estimate of the travel distance. Averaging all these travel distances within a TAZ provides an estimate of the typical intra-zonal travel distance that occurs before vehicles reach the modeled network for a particular TAZ. Using this intra-zonal travel distance along with a typical average speed for local road travel provides an estimate of the average intra-zonal travel time. Although the strategy described above is somewhat crude, the method is more palatable than the alternatives of leaving the estimates out or assuming travel times based on TAZ area. The intra-zonal travel times can be improved if the average of actual spot speeds is used rather than relying on speeds based purely on roadway functional classes.

3.3.3. Modal activity

Modal vehicle activity is characterized by cruise, idle, acceleration, and deceleration operations. Research has clearly identified that modal activity is a better indicator of emission rates than average speed. Determining regional modal operation is not possible using current travel demand forecasting models alone. Travel models can forecast traffic volume (±15%) and average speed (±30%) (USDOT and USEPA, 1993). Because average speed estimates from travel models are relatively inaccurate, they should be used with caution. However, the average speed could be accurate enough to determine differences in levels of service (LOS) E and F, where forecast volume to capacity (v/c) ratios approach or surpass 1.0.

Research by Grant et al. (1996) and Hallmark and Guensler (1999) has identified methodologies to relate speed and acceleration distributions for vehicle activity as a function of road classification, level of service, and other Highway Capacity Manual parameters. Given a roadway's volume and capacity (and signal timing if evaluating an intersection), an estimate of congestion can be developed. Subsequently, speed and acceleration distribution tables that contain
accurate fractions of vehicle activity in the high power demand areas are selected to estimate the fraction of emission-specific modal behavior occurring in those instances. Modal profiles have been developed for interstates, ramps (suspected as high power demand areas), arterials, and signalized intersections. Sample profiles are shown in Fig. 5. Because vehicle emissions for most speed and acceleration conditions are relatively constant, it is only important that the assigned

Fig. 5. Sample speed-acceleration profiles for different road segments along a major interchange in Atlanta.
profiles accurately reflect the fraction of vehicle activity under crucial high-emission modes. Hence, although these speed acceleration profiles do not perfectly reflect the entire range of speed and acceleration operations, they do accurately predict the fraction of activity occurring under high acceleration and high power demand conditions for different levels of congestion (Hallmark and Guensler, 1999). When this process is conducted for every road segment section, the distribution of modal behavior can be estimated in space and time.

3.4. Predicting facility-level emissions

Roadway facilities are divided into zones and lines corresponding to the previously mentioned emission modes of engine starts and running exhaust (respectively). Facility activity estimates are used to allocate emission production to those vector spatial data structures currently used by transportation planners. By typing emission production estimates to facilities, tasks associated with research, reporting, validation, or control strategy development are easier. Emission rates for each portion were developed by reanalysis vehicle emission tests from a variety of sources (Wolf et al., 1998; Fomunung, et al., 1999).

3.4.1. Engine start zonal facility estimates

Elevated emissions at engine start occur over a period of one to three minutes while the catalytic converter warms up. These elevated exhaust emissions are modeled as a "puff" (all engine start emissions allocated to the trip origin zone). While start emissions are actually dispersed through the local network as a vehicle travels, research has not identified a practical strategy for spatial allocation to local roads. Furthermore, it is more useful for planners and/or researchers to have engine start emissions tied to the point of origin, allowing linkages to zonal characteristics that may be crucial in identifying mitigation strategies.

The calculation of emissions for a single zone is

\[
E = \sum_{n=1}^{N} (TG_n \times ER_n) \times O,
\]

where \(E\) is the emissions for single facility in grams (CO, HC, or NO\(_x\)), \(N\) the number of technology groups for pollutant of interest, \(TG\) the fraction of registered vehicles in the zone in the specified technology group, \(ER\) the gram per start emission rate for the specified technology group and pollutant, and \(O\) is the number of vehicle trip origins.

The resulting emissions of CO, HC, and NO\(_x\) are usually reported for a typical weekday (Tuesday–Thursday) on an hourly basis. The typical weekday limitation is a result of the travel demand modeling process, as few models are currently setup to predict weekend or Friday travel. MEASURE allows other time aggregations to occur since vehicle activity is a direct input into the model.

3.4.2. Minor road zonal facility estimates

Minor road zones are used to spatially represent the portion of running exhaust emissions that occur between the trip origin and the major roads modeled by the travel demand forecasting
network. For these zones, the total travel time, the typical local road speed and acceleration profile, and the zonal technology characteristics are used as inputs to the emission rate algorithm (discussed in Section 3.4.3).

3.4.3. Line facility estimates

Line facilities are the major roads that are modeled in the travel demand forecasting model. On-road fleet distributions and predicted traffic flow parameters are used to generate road segment specific estimates of CO, HC, and NOx. For each road segment and each hour, modal variables are determined based on the speed and acceleration characteristics identified in the situation-specific profiles. Road segment technology group fractions and modal variables are combined to develop the fraction of activity occurring with each specific emission rate (grams per second). Total hourly travel time is calculated and segmented by the fraction of the vehicles with each emission rate. Combined running exhaust emissions estimates from minor and major roads provide total on-road running exhaust emissions.

The calculation of emissions for a single road segment is

\[ E = \sum_{n=1}^{N} (TG_n \times B_n \times I_n) \times F_p \times T, \]

where \( E \) is the emissions for single facility in grams (CO, HC, or NOx), \( N \) the number of technology groups for the pollutant of interest, \( TG \) the fraction of registered vehicles on the road in the specified technology group, \( B \) the mean FTP Bag2 emission rate in g/s for the specified technology group, \( I \) the interaction factor for specific technology combination and estimated modal conditions, \( F \) the constant for each of the three pollutant, and \( T \) is the total seconds of travel time for that road segment.

More details on the equations and their validation can be found in Fomunung et al. (1999, 2000).

3.5. Generating the mobile emissions inventory

The role of the emissions inventory module is to convert the facility-based emission estimates into gridded estimates. Procedurally, the user selects a grid cell size; the software creates a polygon database of grid cell boundaries, allocates each zone or line (or parts of zones or lines) to its corresponding grid, sums all emissions for each cell, and finally converts the results to raster data structures.

Grid cell size is optional for the user but usually is dictated by the subsequent photochemical model. The gridded results from MEASURE are inputs into other models that predict ambient pollutant concentrations. Most photochemical models use grid cell sizes of 4-5-km; however, new designs plan to use 1-km grid cells. MEASURE creates a grid cell boundary database (polygons, not raster cells) for the study area. Emissions at each facility (zone or line) are converted to a rate based on the area (zones) or length (roads). Resulting values are therefore in g/square km, or g/km. The grid cell boundaries are used as 'cookie cutters' to identify which facilities or parts of
facilities fall in each grid cell. The facility emissions are then converted back to grams by multiplying the rates by the new areas or lengths.

The polygon grid cells are then converted to raster data structures with raster cells equivalent to the size and position of the original polygon. This conversion does not contribute to model error because each raster cell has the exact same shape and location of the corresponding polygon grid cell. The conversion is conducted because the raster database is more efficient at storing gridded information. The final raster datasets are individual ‘layers’ of each pollutant emission ‘mode’ (totals, engine starts, etc.). MEASURE includes a customized user interface for querying and visualizing two- and three-dimensional images of the various input and output databases.

3.6. Sample model run for Atlanta

MEASURE was written using ‘C’ code and ARC/INFO AML. Each of the modules described previously is controlled by a ‘Makefile’. The model requires ARC/INFO software to be resident on the system, but handles all software access and syntax. A sample model was developed that predicts grams of CO, HC, and NOx, for all zones, lines, 100-m cells, 250-m cells, 500-m cells, and 1-km cells. The study area was the 13 county, non-attainment area in Atlanta, Georgia. The following input datasets were used:

- 1995 Atlanta Regional Commission (ARC) LandUse Data,
- 1990 US Census Summary Tape File (STF) 3a,
- 1994 US Census Topologically Integrated Geographic Encoding and Referencing (TIGER) File,
- 1995 Updated TIGER Road Database,
- 1996 ARC ARCMAP Road Database,
- 1995 ARC Traffic Analysis Zones,
- 1995 ARC Travel Demand Forecasting Network,
- 1995 ARC Temporal distributions by trip type,
- 1996 Georgia Department of Motor Vehicles Registration Dataset, and
- 1996–97 Georgia Tech Speed and Acceleration Profiles.

The following output files were created by the model:

- Zonal Vehicle Characteristics,
- Road Segment Technology Group Distributions,
- Zonal Vehicle Activity,
- Road Segment Vehicle Activity,
- Zonal Start Emissions (Fig. 6),
- Zonal Running Exhaust Emissions (Fig. 6),
- Road Segment Running Exhaust Emissions, and
- Gridded Emissions (Fig. 7).

Sample model run outputs for Atlanta are demonstrated in Figs. 6 and 7. Spatial input data for the model run were organized under a single datum and projection system. Major data preparation steps that were conducted outside the MEASURE domain include geocoding of the vehicle registration database to ZIP codes, vehicle identification number (VIN) decoding of
the vehicle registration database, generating block group polygons from TIGER, and adding US Census STF3a housing unit data to the block groups. The travel demand forecasting network was converted using a software utility developed specifically for that purpose. Some “clean-up” of this network was necessary using some of the automated techniques described previously.

The model code (‘C’ and ARC/INFO AML) is organized in a ‘make’ routine that verifies code updates, cleans temporary files, and initiates the modules in the appropriate sequence. The shortest path routines that allocate each engine start zone to the closest major intersection took the longest to process. The entire run, which took approximately 25 h of continuous processing,
was conducted on a Dell dual-processor 400 MHz Pentium II operating Windows NT with ARC/INFO resident.

This initial run for Atlanta did not include modal activity for intersections since signalized intersection data were not available. Instead, a speed/acceleration profile for a typical signalized arterial road was used. This 'typical' arterial speed/acceleration profile included observed data aggregated from several signalized and unsignalized arterial roads. All of the sites observed were multi-lane facilities. In the model run, all non-interstate, non-ramp multi-lane roads were assigned this profile as an estimate of modal activity.
The Atlanta model is being used as a basis for validating MEASURE components. One effort currently underway is a vertical pollutant flux study that involves detailed monitoring of a metered ramp system on I-75, north of downtown Atlanta. The research team collected traffic flow data, vehicle classification, fleet technology characteristics (by monitored license plate data and later decoding the registration VINs), and speed acceleration profiles with laser guns on the four ramps and the adjacent freeway links. The research team is currently analyzing the 18 days of vehicle activity data and will use the vertical pollutant flux results to compare predicted and measured emission rates.

Initial comparisons have already been conducted between MEASURE and MOBILE5a to explore and identify differences in their emission rates. Fig. 8 shows the NOx g/s emission rates for MOBILE5a and MEASURE by speed and acceleration bin (using an Atlanta regional fleet). The charts indicate that MEASURE is much more sensitive to changes in acceleration, particularly at high operating speeds. This is not unexpected because MOBILE emission rates are primarily a function of average speed, while MEASURE rates are directly influenced by the relationship between speed and acceleration. In this comparison, the regional fleet distribution was used to estimate emissions for interstate LOS A–F. Mean emission rates in g/s were within 20% of each method for LOS A. MEASURE emission rates were 50% higher than MOBILE for LOS B and C, and twice as high for LOS D and E. Emission rates were back to within 20% for LOS F. Because MEASURE is sensitive to accelerations at high speed, its emission rates were much higher for moderate congestion levels where high speeds and variable acceleration resulting from increased vehicle interaction is typical. Once there is a break down, a traffic flow resulting in low speeds with variable acceleration, MEASURE emission rates drop to levels comparable to MOBILE.

The significant differences in emission rates between MEASURE and MOBILE, especially at moderate LOSs, magnify the need for further validation studies.

Fig. 8. Comparison of average NOx g/s emission rates for an Atlanta regional fleet.
3.7. Potential policy impacts

If EPA approves a GIS-based modal emissions model, such as MEASURE, for regulatory use, the types of mitigation strategies available to local and state governments will change dramatically. Under the current modeling system, transportation planners and engineers have only three ways to reduce mobile emissions: depend upon EPA to pass new vehicle certification standards, reduce vehicle miles of travel, or optimize average speeds to ranges where emissions based on average speed estimates are reduced. The choices usually result in reducing the mobility and accessibility desired by the transportation system users.

If spatially resolved modal models are developed, much more diverse and creative strategies become assessable. Any strategy that reduces the number of high-emitting vehicles or reduces the occurrence of hard accelerations and decelerations is expected to reduce mobile emissions. However, current modeling regimes cannot accurately assess the impact of those changes to regional air quality. A model framework, such as MEASURE’s, makes two significant improvements in this area: spatial variability becomes an important component of any mitigation strategy and the modal characteristics allow the assessment of variability in traffic flow, not just average speed. Reducing traffic volumes may be less important than improving traffic flow through ITS strategies, signal timing, or even lane additions. The new modal approaches may show that (at least in the short term) mobility and accessibility can increase as mobile emissions decrease (Hallmark et al., 2000).

Spatially resolved emissions estimates allow planners to prioritize certain locations for mitigation strategies because of their disproportional contribution to regional ozone formation. This is the real value of improved spatial variability. The disproportional contribution may be the result of topography, landuse, or climatic factors. Regardless, a dollar spent mitigating mobile emissions in one part of the region may not result in the same reduction if spent in another part. The spatially resolved estimates at proper resolutions also allow local transportation planners and traffic engineers to develop sub-regional strategies that help to improve regional air quality.

4. Future research

Some specific GIS-oriented model design and implementation research projects could improve the accuracy of MEASURE estimates. While model validation is important in confirming current capabilities, addressing these theoretical issues could provide significant modeling benefits over the short term.

- **Fraction of total vehicle operation by vehicle type**: The registration dataset represents all light-duty vehicles that are licensed to operate on the road. The actual operating fleet may look quite different. Older third and fourth vehicles in a household are not expected to be used to the same extent.

- **On-road vehicle distribution search pattern**: Additional studies have indicated that the radial search pattern used in the model could be significantly improved for determining a local operating fleet. Research into the size and shape of the search pattern will significantly improve the capability of predicting the on-road fleet distribution.
While the conceptual design of MEASURE is comprehensive, the actual working model is not. The current model scope is limited to automobile exhaust emissions. Moving to a complete mobile emissions model involves adding much more information and data. Some of the major items are listed below.

- **On- and off-network grade distributions and impacts:** Because road grade has spatial variability and has significant impact on the load on an engine, it should be included in the research design. This may mean moving to more detailed modal emission rates that model emissions as a direct function of engine load rather than as a function of load surrogates.

- **More speed/acceleration matrices:** Currently, the model is limited to approximately 20 different profiles. Further refining the subroutines that define speed and acceleration profiles for all road types and configurations (accounting for influences of weaving sections and other physical parameters) will provide a more comprehensive view of modal activity.

- **Other motor vehicle types:** A comprehensive mobile source model must include all vehicle classifications. Currently, all light-duty vehicles are modeled as automobiles because there are few vehicle emission tests for sports-utility vehicles and light-duty trucks under a wide variety of operating conditions. Heavy-duty truck modeling components (load-based) are currently being added.

- **Load-based approach:** A new engine load-based modeling approach to predicting emissions will allow enrichment emissions to be separately identified, an original model design objective.

- **Non-exhaust mobile emissions:** Exhaust emissions only make up a portion of the overall mobile emission modes. Evaporative emissions are currently being adapted directly from the MOBILE5a model and will be upgraded in future models.

- **External/internal trips:** Currently, external/internal trips are excluded from the models’ predictions of start activity and evaporative emissions.

At the time MEASURE development first began, a number of GIS platforms were evaluated. ARC/INFO was chosen because of its robust set of spatial analysis tools as well as its widespread use at Metropolitan Planning Organizations (MPOs) throughout the US. The emergence and evolution of Arc View and related components, Geomedia, and MapObjects offers attractive and more affordable GIS platforms for a future version of MEASURE once the ongoing validation phase is complete. A thorough evaluation of these and other GIS software will need to be conducted to determine if they are suitably equipped to accommodate the complex spatial modeling requirements of MEASURE.

5. **Conclusion**

Traditional transportation emission models have been shown to suffer from problems, such as highly aggregated datasets, non-representative emission factors, and lack of spatial resolution. Consequently, there is a desire to move towards a modal approach which relates activity-specific emission production with corresponding vehicle activity. The special capabilities of a GIS can greatly simplify the procedures associated with creating, combining, and manipulating the spatial databases necessary for implementing a modal approach. Further, the GIS can be used to establish emissions estimates as a function of a number of variables associated with points and areas (off-network activities) or roadway links (on-network activities). Once established, these improved
spatial estimates can be aggregated to grid cells that are compatible for input into regional photochemical models. The major modeling deficiencies that exist in current models are addressed with the implementation of the MEASURE model. The limitations of MEASURE revolve mostly around the intensity of data required. MEASURE was designed and developed as a research model that considers all relevant data at the best resolution possible. As research and validation continue, relationships between variables may be identified which would reduce the quantity and variety of data. This is critical if MEASURE is to be widely accepted and implemented on a large scale.

While tailpipe emission reductions for the fleet-at-large will continue to be an important control strategy for years to come, there is an increasing interest in other methods of controlling mobile sources. Future mobile-source emission models must be equipped to predict the impact of such methods as improved traffic flow, improved inspection and maintenance programs, targeted enforcement of super-emitters, traffic restrictions, and use of alternative fuels. MEASURE has already been shown to be capable of analyzing these types of policies. For example, MEASURE is currently being used in Atlanta by the Georgia Department of Transportation to evaluate the emission impacts of proposed ITS projects. Even with great strides in mobile emission reductions, there will always be a need to gather comprehensive spatial and temporal distributions of emissions for urban areas. A GIS-based emissions modeling framework makes this more practical than ever before.

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