Overview of the MEASURE Modeling Framework

Randall Guensler[1]
Simon Washington[1]
William Bachman[2]

Abstract

This paper presents an overview of the mobile emissions model that has been developed by the Georgia Tech Research Partnership. The model estimates the mobile source production of carbon monoxide, volatile organic compounds, and oxides of nitrogen in space and time. The modeling approach provides a number of distinct modeling advantages: 1) the model is modal in nature, whereby emissions are estimated as a function of vehicle operating modes rather than average vehicle speeds; 2) the model is GIS-based and compatible with the analytical and decision-making frameworks currently employed by the majority of state departments of transportation and metropolitan planning organizations; 3) the model components are based upon medium term improvements in vehicle activity and emissions rate relationships; and

---

[1] Assistant Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, 690 Atlantic Drive, Atlanta, Georgia, 30332

[2] Research Scientist II, Center for Geographic Information System Research, Georgia Institute of Technology, Atlanta, Georgia, 30332

4) model components, assumptions, algorithms, and predictions are being falsified through the collection of real-world data to the greatest extent possible.

Introduction

For the past four years, the Georgia Tech Research Partnership has been developing a motor vehicle emissions model within a geographic information system (GIS) framework. The model is called the Mobile Emission Assessment System for Urban and Regional Evaluation (MEASURE). The model development research has been conducted under a cooperative agreement with the US Environmental Protection Agency and Federal Highway Administration, and has received direct funding and in-kind contributions from a variety of public and private research partners. The Georgia Tech model currently predicts emissions as a function of vehicle operating mode (including cruise, acceleration, deceleration, idle, and the power demand conditions that lead to fuel enrichment, or high fuel:air ratios). MEASURE predicts on-road emissions as a function of specific vehicle characteristics (model year, engine size, etc.) and speed/acceleration profiles. The GIS modeling framework allows for facility-level aggregations of microscopic traffic simulation, or disaggregation of traditional macroscopic four-step travel demand forecasting models to develop emission-specific vehicle activity data.

MEASURE is divided into several modules; the vehicle technology modules, the vehicle activity modules, the vehicle emissions modules, and the reporting module. The vehicle technology module takes regional vehicle registration data and outputs location and time specific emission technology group distributions. The vehicle activity module takes regional planning model results and joins them with appropriate speed and acceleration lookup tables to produce location and time specific estimates of emission-specific modes of vehicle activity. The emission components of the model are weighted, least squares, regression models developed from large databases of vehicle emission tests (an iterative, heuristic, linear approach). The reporting module combines estimates into a gridded, hourly, format that is used for input into regional photochemical models (i.e., UAM, Models3, EMS95).

The existing emission test databases from which the model was derived do not necessarily represent the true diversity of fleet technologies nor the extremes in speed/acceleration profiles. The model is therefore limited to predictions that can be derived from the existing emissions testing databases. A great deal of unexplained variability exists even within these enhanced analyses. Nevertheless, the model framework is capable of providing significant enhancements over the current average speed models.

Modeling Goals and Objectives

The development of an emission inventory first necessitates spatial and temporal tracking (or estimation) of those activities that result in emissions. Of course, this requires laboratory and field work to identify those activities that cause emissions. Once these activities are identified, the emission rate per unit of activity are predicted. The magnitude of the emissions rates associated with each of these activities depends upon the causal relationships. Four basic groups of variables affect emissions: vehicle, operating, and fuel parameters, and environmental conditions.

A modal emissions model is based on the premise that modeling emissions from specific modes of vehicle operation will more accurately reflect on-road emissions than will models based on average speeds. Mobile source emissions are associated with specific vehicle and engine operating modes (cruise, acceleration, deceleration, idle, power demand, etc.). Because activity data are likely to include a wide variety of measures and attributes, not simply vehicle miles traveled as is commonly used today, a new modal modeling regime will be much more complex than the current models. The fundamental goal of the research project has been to develop a modal model within a GIS framework to provide significant improvements to predicted emissions on a spatial and temporal basis. The objectives of the overall research program include:

- The development of emissions relationships that improve emission inventory modeling techniques and include explicit effects of vehicle fleet characteristics and vehicle operating conditions.
- The development of emission factors appropriate to each modal emission-producing activity and measures of uncertainty.
- Incorporate speed and acceleration factors in the vehicle activity estimation process.
- Explicitly incorporate the effects of various policy initiatives and programs on fleet emissions (e.g., effects of inspection and maintenance and repair programs). Ensure that the new model is sensitive to changes in vehicle technologies, fuels, and traffic flow.
- Estimate gridded hourly activity and activity attribute data (with specified uncertainty).
- Conduct field studies to validate mathematical models.
- Develop cost-effective strategies for obtaining and processing the intensive data needed for enhance emission models.
- Publish a modal model development handbook.

It is important to note that as research unfolds and new modeling issues are identified, the final work program will reflect collective thoughts on important modeling issues. In essence, work plans and research plans remain dynamic, so that new data and analyses can influence the direction of the modeling research efforts.

CONCEPTUAL MODEL

A research program that will result in improved methodologies for estimating emission inventories must begin with a concept of how the various (relevant) variables fit into an overall modeling approach. Such a conceptual model not only needs to identify key variables, but also their interrelationship and their likely importance in the emissions estimates that result. A number of premises adopted by the research team inherently focus the model research process in certain areas that are believed to be most productive in terms of long term model development:

- *GIS-Based* - The model will be GIS-based in order to take full advantage of the generation of spatial database management tools being employed by state and metropolitan areas for the management of municipal assets, resources, and activities. The focus on a GIS approach allows emissions estimates to be properly allocated spatially. The capability to overlay spatially resolved vehicle activity data and local subfleet characteristics and then link these activity and fleet characteristic estimates with emission rate algorithms that all lie within the same modeling tool makes the GIS framework extremely versatile.
- *Modular* - A modular approach to the model allows individual model components to be independently assessed and validated. The modules are based around important concepts (i.e., engine start activity, on-road fleet distribution) and produce outputs in a manner that can be field validated (i.e., engine starts by US Census Block, fleet distributions by specific road segment).
- *Stochastic* - The modeling approach will be stochastic in nature, given the high degree of variability in emission rate response to vehicle operating conditions noted across vehicles. In first generation approaches, rather than developing predictive enrichment emission rates for all vehicles within the subfleet, the probability of enrichment given vehicle operating conditions will be estimated from the vehicle activity and emission rate data collected. Then, these distributions will be coupled with the normal and enriched (and enleaned) emission rates for the fleet derived from analyses of a number of data sources. The modeling approach will seek to develop statistical models that minimize prediction bias and maximize explanation of emission rate variance.
- *Fleet Characteristics* - Vehicle fleets are characterized by identifying the distributions of emission-specific technology groups across space and time. The important vehicle characteristics were determined by analyzing large sets of vehicle emission test data. Normal and high emitting vehicles are separately assessed for emission production.
- *Vehicle Activity* - Model development subdivides vehicle activities into two regimes: 1) on-network activities, and off-network activities. The model relies on the transportation network and prognostic models that are already in use by metropolitan areas. Although the accuracy of current model outputs leaves a great deal to be desired, until long term simulation models (TRANSIMS) are available, improved sources of network activity data will still rely upon existing models. Furthermore, until simulation models that include local street networks are available for a metropolitan area, off-network activity (local roads) must be handled on a zonal basis.

- *Modal Activity* - Modal emissions rates are modeled as a function of the variables that affect emission rate magnitude. The model currently incorporates onroad speed/acceleration distribution and grade into an aggregate modal modeling approach. A second modal approach, a load-based model, is near completion and will be integrated by the end of winter.
- *Hot-stabilized and Enrichment* - Running exhaust emission rates are divided into two regimes: normal stoichiometric (or near stoichiometric) operations represented by the hot stabilized emissions found under non-enrichment conditions, and enrichment operations (high CO and HC emissions due to excess fuel). A third regime for enleanment operations (high NOx emissions due to excess air and high temperatures) may be implemented in the future.
- *Uncertainty Assessment* - It is essential that model development include assessment of the uncertainty associated with using the final derived model(s). Given the inherent uncertainty associated with using the existing modeling approaches, and, given the fact that additional modal models are likely to be developed over the years an assessment of model algorithm confidence bounds is essential if the relative merit of the model is to be compared with previous and future modeling efforts.

Current State of the Model

As mentioned earlier, the first version of MEASURE is currently operational. The modal algorithms are based upon preliminary data analysis of the FTP and other emissions testing databases. The algorithms are currently based upon incomplete and non-representative data for the fleet. In addition, a limited number of vehicle subfleets and speed/acceleration profiles are currently being employed as analyses of activity data continue and these relationships are refined. Nevertheless, the modeling framework is in place and emissions calculation routines are being reviewed and solidified. By the end of winter all detailed data analyses will be completed and three user options will be included in the model for estimating running exhaust emissions: 1) the standard MOBILE5a modeling approach employing baseline exhaust factors by model year and speed correction factors, 2) an aggregate modal modeling approach in which influential modes of operation for vehicle technology groups are identified through statistical analysis of standard bag emissions testing, and 3) a load based emissions model in which vehicle enrichment operations are predicted as a function of vehicle load. Currently, only options 1 and 2 are functional The actual model structure to date is best described in the Figure 1 schematic below:

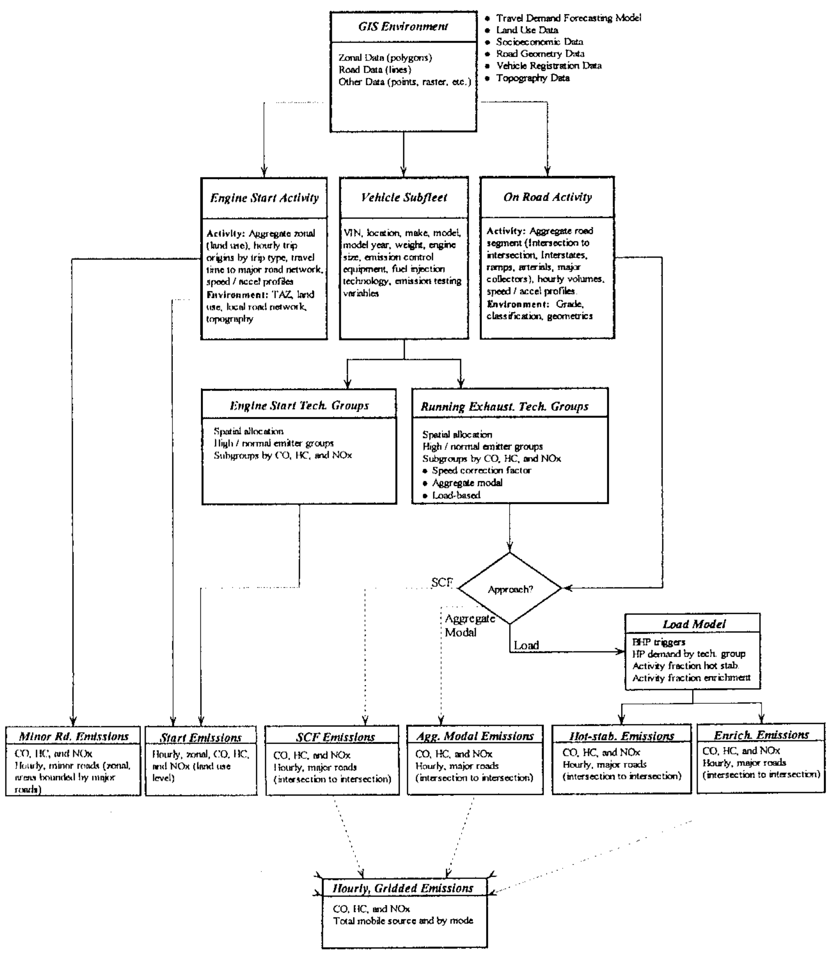

Figure 1 - MEASURE Conceptual Flow Diagram

The modular format outlined in Figure 1 contains autonomous ARC/INFO AML, FORTRAN, and C routines linked by a UNIX program management utility called Make. Vehicle subfleet characterization serves as the cornerstone for emissions rate development. Emission rate modeling routines are developed for different vehicle technology groups. Different technology groups are developed for each emissions component or modeling approach because subfleet characterization is developed as a result of the statistical analysis used to develop engine start and hot stabilized emission rates. Engine start emissions, off-network running exhaust emissions, and on-network running exhaust emissions are developed for each technology group by coupling vehicle activity with operating and environmental characteristics and then with appropriate emissions rates for those conditions. Activity estimates can be provided through standard or enhanced 4-step travel demand models or from activity monitoring systems. Similarly, speed/acceleration profiles and environmental conditions can be modeled or monitored. After each emissions component is estimated and allocated to GIS lines and polygons, gridded emissions inventories are developed by summing the emissions contributions to each physical grid cell.

Model Design and Operation

Vehicle Activity

Location and emission-specific vehicle activities are estimated using travel demand model outputs, speed and acceleration profiles (based on road classification, level of congestion, vehicle type, and road grade), and in-house network path routines.

Fleet Characteristics

Location-specific subfleet distributions are estimated and employed in the subsequent emissions estimation process. Statewide motor vehicle registration databases are geocoded to the study area, and decoded using commercial vehicle identification number routines. The resulting dataset is location-specific (US Census Blocks) of vehicle characteristics (model year, engine size, emission control equipment, fuel injection type, and curb weight). These technology characteristics are used to assign vehicles to emission-specific technology groups (see next paragraph), resulting in technology distributions by zone. The on-road fleet characteristics are estimated by combining the regional technology distributions, and the local technology distributions (based on proximity to the road segment being analyzed).

The emission rate modeling routines are developed for different vehicle technology groups, but these technology groups are not pre-determined by analytical staff. Rather, the results of statistical analyses are used to identify groups of vehicles that behave similarly within the group both in terms of mean emissions under standard testing conditions and in terms of mean response to changes in operating or environmental characteristics. Different technology groups are developed for each emissions component or modeling approach because subfleet characterization is an inherent analytical component. For example, different vehicle technology groups are developed for engine start emissions, the aggregate modal model, and the load based modeling routines. This is because the technology interactions associated with engine start emissions are significantly different than those for hot stabilized emissions. Furthermore, the technology interactions associated with an aggregate modal model are expected to differ from a load-based model because the variability explained by the more refined model (which was previously lumped into error terms in the less refined model) should yield more refined vehicle technology groups and response variables.

A small fraction of motor vehicles on the roadway are responsible for a large fraction of fleet emissions. Identifying these vehicles in an urban area (both spatially and temporally) and quantifying their emissions will lead to improved emissions modeling and will provide a potential basis for improved emission reduction policies that target subsets of the vehicle fleet.

High emitters (i.e. malfunctioning and tampered vehicles) are usually defined relative to the emissions of other vehicles in their technology group (representing model year groups with emission control technology combinations that behave similarly with respect to emissions production). Thus, when a new vehicle and an old vehicle both exhibit a large gram/mile emissions rate, the new vehicle might be considered a high emitter while the older vehicle might be considered a normal emitter.

Four emitter groups were first developed by analyzing the emissions test results for more than 700 vehicles obtained on Bag 2 of the FTP, where emission rates are known to be hot and stabilized and where bag emissions contain little to no enrichment contributions. Regression tree modeling was employed first to allow the variability in emissions under the FTP Bag 2 to naturally group vehicles together into emitter classes (Washington, et al, 1997). Four emitter classes are currently employed in the model for each pollutant. These emitter classes were defined through regression tree analysis in which the gram/second emission rate was the dependent variable and a wide variety of technology characteristics were allowed to serve as potential explanatory variables. The model selects the technology variable that can split the data into two groups with the greatest net reduction in emissions variance. Then, the model makes continued splits until the desired reduction in variability is achieved or a desired number of groups are created.

While the regression tree modeling methods seem a bit arbitrary at first glance, there are a number of tremendous advantages. First, the vehicle groups that are formed through the analytical technique behave similarly to each other in terms of technology response to the FTP Bag 2 test. Second, the groups that are formed ensure that modern and old technology vehicles exhibiting similar emissions rates will not be lumped into the same technology categories, because the split between older and

newer vehicle technology characteristics will explain the vast majority in emission variation despite the presence of a few high emitting modern vehicles. The technique separates first and second order modeling effects and allows technology interactions to be directly modeled. A wide variety of statistical issues such as correlation are more readily addressed through regression tree modeling than through OLS regression. Finally, it is important to note that model results are not simply adopted without examining the predictions to determine if the technology groupings make sense in terms of causal relationships noted in the laboratory.

Engine Start Emissions

Motor vehicle emission rates are elevated during the first few minutes of vehicle operation. The magnitude of the elevation is a function of: duration and magnitude of commanded enrichment, engine temperature and combustion efficiency, and catalyst temperature. Once combustion stabilizes, commanded enrichment ceases and the catalytic converters reaches "light-off" temperatures (not necessarily in that order), dramatically reducing emission rates. This preliminary stage of high emission rates is modeled differently than running exhaust rates due to the differences in important cause and effect relationships, and the generalized locations of vehicles operating under start conditions.

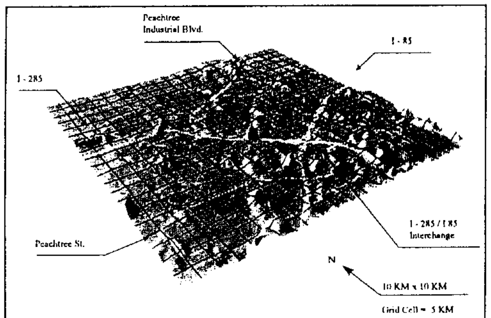

Figure 2 - Engine Start Emissions in Northeast Atlanta, 7-8 AM

In the first phase of model development, the emission rates associated with engine start activity were estimated as emissions "puffs" and spatially allocated to engine start zones (zones of similar land use and socioeconomic characteristics). The gram per start emission rates were developed from a reanalysis of the Federal Test Procedure (FTP) database. Cold start increments (grams/start) for CO and HC were defined as the difference between the emissions that occurred under FTP Bag 1 and the emissions that would have occurred under Bag 1 if the average grams/second emission rate observed under FTP Bag 2 had been maintained. Cold start increments (grams/start) for NOx were defined as the difference between the emissions that occurred under FTP Bag 1 and the emissions that would have occurred under Bag 1 if the average grams/second emission rate observed under FTP Bag 3 had been maintained. The reasons behind the selection of the baseline emissions rates is discussed in a forthcoming paper on engine start emissions. In sum, until tests are conducted under a hot stabilized Bag 1, there is no ideal baseline from which to develop cold start emissions. Regression tree analyses were performed for incremental engine start emissions to identify technology groups that behaved similarly.

The second stage improvement to the modeling approach will be similar to that proposed by the California Air Resources Board (Sabate and Agrawal, 1994) and will associate emissions puffs with length of vehicle soak time (i.e., time between engine shut down and start up). Two improvements will be made: 1) the gram/start emissions rate will be derived as a function of both soak time and modal activity undertaken after the engine is started; and 2) although the majority of the engine start emissions are allocated to the engine start zone, a portion of these emissions will be allocated to network links using activity probability distributions (based upon infrastructure characteristics). However, new testing data will be required to develop these relationships.

The final phase of model development is a probabilistic approach which models gram/start emission rates as a function of vehicle characteristics, environmental parameters, vehicle activity prior to soak, soak time, influence of driver behavior, and modal activity undertaken after the engine is started (including idle, cruise, acceleration and road grade effects). The final model will allocate the majority of the engine start emissions to the engine start zone, and a portion to network links proximal to the engine start zone as a function of vehicle activity distributions.

On-Network Running Exhaust Emissions

On-network running exhaust emissions refer to those emissions produced by vehicles in non-start conditions along road segments for which prognostic vehicle activity data exists. Initially, these road segments are those modeled in the regions travel demand forecasting model. However, the MEASURE model design allows for the incorporation of vehicle activity from any number of monitoring or simulation tools. Three different emission rate modeling approaches for are implemented in the Georgia Tech's GIS-based modal emissions model: 1) the standard MOBILE5a modeling approach employing baseline zero-mile exhaust emission rates and speed correction factors, 2) an aggregate modal emissions model that predicts emission rates as a function of vehicle technology and operating mode interactions, and 3) a load-based modal emissions model that predicts the fraction of vehicle technologies operating under stoichiometric and enrichment conditions and predicts emission rates for each component (not yet operational).

MOBILE5a Emission Rates and Speed Correction Factors

The current model includes standard MOBILE5a modeling approaches, using the baseline zero-mile (no deterioration) exhaust factors by model year and standard EPA speed correction factors (5 mph increments). The research included the BEF/SCF modeling approach so that comparisons between current practice and modal modeling approaches can be made.

Aggregate Modal Emissions Model

An aggregate modal modeling approach has been developed and implemented in the existing Georgia Tech modal emissions model (Washington, et al., 1997). Hierarchical tree-based regression analysis is the statistical technique employed. The complete emissions testing database (more than 700 vehicles and 4000 vehicle-cycle tests) was analyzed. Vehicle technology characteristics as well as operating cycle characteristics were employed as variables to explain emissions variation. This modeling approach allows power demand surrogate variables (for example, percentage of cycle operated with (speed) x (acceleration) above a set level) to be employed as potential explanatory variables.

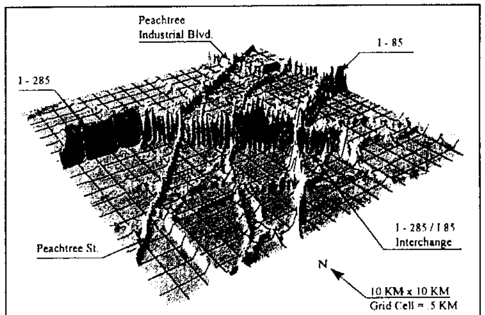

Figure 3 - CO Running Exhaust Emissions in Northeast Atlanta between 7 and 8 AM

The tree-based model searches for variables that explain the most variance in emissions response. Hence, the model can determine for a set of vehicles tested on a variety of test cycles, whether the differences in modal characteristics across the cycles is more significant in explaining emissions variation than the technology differences across these vehicles. Preliminary results indicate that such a modeling approach provides significant benefits over baseline exhaust relationships and speed correction factors currently employed in emissions models and that the predictive results make sense with respect to causal theory.

Some preliminary CO analytical results for normal emitters are reported in Figure 3. Only the first nine regression tree splits are provided in the figure. The leaves of the regression tree provide grams/second emission rates for the specific mutually-exclusive vehicle technology groups and operating characteristic combinations that naturally result from regression tree analysis. Individual vehicle technology characteristics (such as model year, engine displacement, and catalyst control technology) appear in the groupings. Plus the operating mode characteristics represented by acceleration conditions or power demand surrogates (PKE, POW) also appear in the model. Note that the final leaves that result represent interactions between vehicle technology and operating conditions.

A detailed explanation of the chart can be found in Washington, et al., (1997). In a nutshell, if the vehicle operating cycle contains more than 15.5% operation above the PKE power surrogate value of 90, the appropriate emission rates for all vehicles are found on the right hand side of the tree. At the next split, vehicles older than 1979 under these operating conditions are assigned an emissions rate of 0.1415 grams/second. More modern vehicles are tested for another load surrogate (POW) and directly assigned an emission rate of 0.0934 grams/second for higher power operations, or assigned an emissions rate as a function of onboard catalyst technology for lower power operations. The regression tree modeling technique allows for interactions between vehicle technology and operating characteristics. In fact, when OLS regression is run using dummy variables representing the interactions found in regression tree analysis, these variables prove to be statistically significant. The modeling approach is limited by the representativeness of vehicles and cycles tested. Hence, the greater the diversity in vehicles and emissions testing cycles, the more reliable the regression tree model.

The complete EPA emissions testing database, with more than 10,000 individual tests conducted under a variety of testing cycles are available for analysis will be employed in the final regression tree analyses for the aggregate modal model. Final analyses will proceed in Spring 1998, after the variables missing from the public domain files are appended from the original EPA testing database. Once completed, final hot stabilized emissions rates, engine start emissions rates, vehicle technology group selection (by emissions type), and outputs will be integrated into the modal model. The final selection of variables will be justified only after detailed analyses of

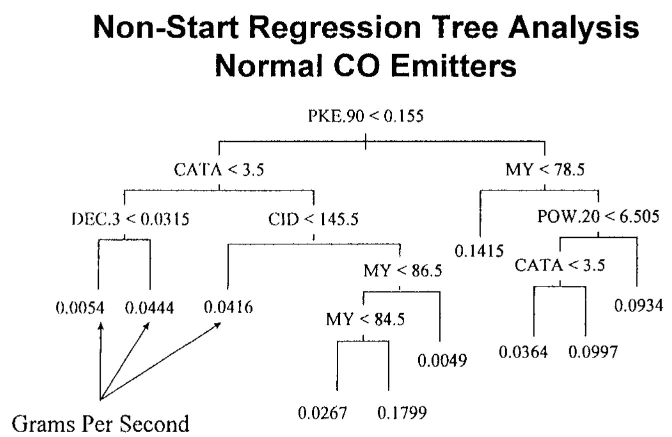

Figure 4 - Preliminary Regression Tree Results for CO Normal Emitters

statistical validity are conducted and after the noted interactions are reconciled with

engine and emissions theory. The modeling approach will even be capable of examining potential deterioration effects, once the age of vehicle at the time of the test and accumulated VMT for each vehicle is integrated into the analytical database.

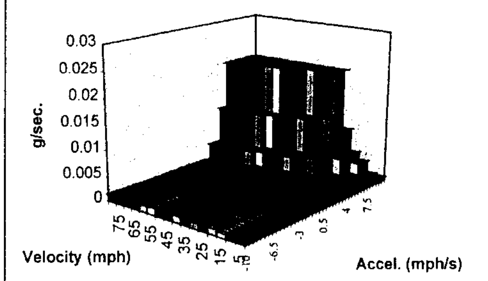

Figure 5 - MEASURE NOx Emission Rates by Speed an Acceleration

Load-Based Enrichment Model

The basic premise of the load-based enrichment model is to treat the probability of enrichment as a function of the ratio of horsepower demand over to available engine brake horsepower. As the demanded horsepower rises, the probability that the engine will enter into enrichment also rises. At Georgia Tech, six instrumented vehicles have been field tested with enrichment data provided by second-by-second emissions monitoring. For all six vehicles, enrichment occurrence was highly correlated to specific engine load trigger levels. Further, remote sensing data from over 50 sites and 200,000 vehicle passes provide a large dataset for load analysis. Currently, this data is being analyzed for the development of load module. Once completed, it will provide better assessment of conditions that cause enrichment, thus aiding the analysis of appropriate, location-specific mitigation strategies.

Off-Network Running Exhaust Emissions

Off-network activity (vehicle seconds) is allocated to zones bounded by major roads as a function of trip ends (trip generation) and network access time distributions. Whereas on-network roads consist of interstates, ramps, arterials, and major collectors, off-network roads consist of minor collectors and local roads. The off-network vehicle activity is based on network access distance distributions, speed/acceleration profiles, road grade.

The three basic emission rate modeling approaches for running exhaust can be applied to the local road activity. Appropriate technology groups, based upon registration data, are applied to increase the accuracy of the estimates. Aggregated hourly start zone trip origins from the travel demand forecasting model are combined with speed/acceleration profiles. Emissions from hot-stabilized and enrichment operations are predicted in accordance with the speed correction factor, aggregate modal model, or load-based model approach.

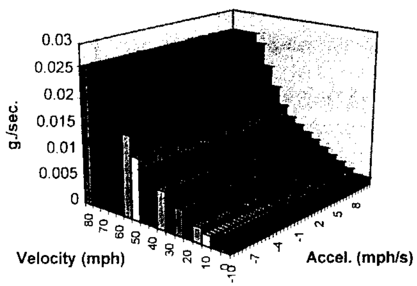

Figure 6 - MOBILE5a NOx Emission Rates by Speed and Acceleration

Gridded Emissions Inventories

The specific emissions modules in the modal modeling regime develop spatially and temporally allocated emissions estimates, with emissions allocated to line sources (roads) or polygons (census blocks, traffic analysis zones, etc.). The desired grid cell structure for photochemical modeling is overlaid on top of the various emissions layers. Of course, line and polygon emissions will overlap across grid cells. The GIS has built-in capabilities to spatially allocate emissions from underlying layers into overlying cells so that emissions from specific lines and polygons are allocated correctly to the overlying grid. The process is completed for each emissions source (engine starts, on-network activity, off-network activity, evaporation, etc.) so that the total emissions in each grid cell (by hour) can be used in photochemical modeling.

Supporting RESearch activities

For the past four years, the research team has been assembling existing emission rate and activity data, and collecting new emissions and activity data for use in developing the modeling framework and algorithms. In addition, models such as MOBILE5a, TRANPLAN (a 4-step travel demand model), TRAF-NETSIM (a simulation model) have been procured and modified/enhanced to provide compatible output formats for emissions modeling. This section describes the data collection and analysis tasks relevant to model development that have been or currently being undertaken by the Georgia Tech research team.

Analysis of USEPA and Other Emissions Testing Databases

The research team has assembled the largest collection of public domain laboratory emissions test results (bag tests) currently available. More than 10,000 individual tests, conducted under a variety of testing cycles are available for analysis. In conducting preliminary analyses of the data, a large number of vehicle variables (such as transmission type, gross vehicle weight, date of vehicle test, etc.) were found to be

incomplete. The research team has procured the original files from the public agencies and is in the process of completing (by hand) the data missing from the public files. Once complete, final analyses of the database will yield final hot stabilized emissions rates, engine start emissions rates, vehicle technology group selection (by emissions type), and outputs for the aggregate modal model.

Continuous Atlanta Fleet Evaluation:

The continuous Atlanta Fleet Study is a long-term measurement and monitoring program for the vehicle fleet emissions in the Atlanta, GA metropolitan area using road-side optical remote-sensing. A pilot program was conducted at two sites in November and December of 1991 and continuous measurements began in April of 1993. Measurements are now conducted at 63 sites on a rotating basis on an average of 30,000 vehicles/month. The focus of the program, funded by the Georgia Department of Natural Resources as cost-sharing on the EPA/Georgia-Tech Research Partnership, is on evaluation of the evolution of the Atlanta fleet and I/M program effectiveness. The data from this effort assist in the model development in a number of ways:

Remote Sensing Siting Evaluations: The impacts of site characteristics (grade, vehicle loading, average velocity, etc.) on measurement uncertainty is being conducted.

Evaluation of High Emitter Profiles: Data from the continuous Atlanta fleet study data are used to evaluate the distribution of high, moderate and normal emitting vehicles among different vehicle ages, socio-economic groupings, and vehicle technology classes. These data allow the emissions model to predict the impact of a variety of vehicle parameters on emissions distributions.

In-Use Vehicle Deterioration: Data from the continuous Atlanta fleet study data are being used to evaluate in-use vehicle deterioration on both a fleet average and a vehicle-specific basis. The program has collected approximately 30,000 multiple measurements for vehicles collected more than 6 months apart. Approximately one third of these observations were collected for the same vehicle at the same measurement site. Analyses on these data are on-going but indicate a statistically significant deterioration for all but the newest vehicles between measurement periods.

I/M Program Effectiveness: Measurements are compared between vehicles registered in I/M and non-I/M counties to evaluate the effectiveness of the Atlanta I/M program. These results indicate that I/M is more effective than predicted by MOBILE for automobiles but is ineffective on light-duty trucks. These data are also used in the multi-city I/M evaluation study.

Relationship between Emissions and Socio-Economic Status: Continuous Atlanta fleet study data are currently being used to evaluate the influence, if any, of socio-economic status of the owner (inferred from registration records) on age-normalized vehicle emissions.

Onroad High Emitter Activity: Once emission rate relationships are developed for normal and high emitting vehicles, the onroad fractions of high and normal-emitting vehicles must also be identified so that the correct emissions rates can be applied to the onroad activity. Onroad high emitter fractions will be modeled using relationships currently being derived between RSD %CO cutoff values and the FTP cutoff values. Field studies have indicated that remote sensing and FTP test databases are roughly gamma distributed, with very stable RSD median emissions rates across time and space. The main differences across time and space appear to lie in the slope of the tail (i.e. the resulting fraction of high-emitting vehicles). Differences in the slope of the gamma distribution tail (and resulting fraction of high-emitting vehicles) are hypothesized to arise from differences in emission control programs (such as inspection and maintenance or oxygenated fuels programs). The fraction of onroad high emitting vehicles (i.e., gamma distribution parameters) will be modeled as a function of socioeconomic and I/M program characteristics. These estimates will be falsifiable through additional and ongoing remote sensing studies.

Policy Impacts on Emitter Groups: The MEASURE model diverges from existing modeling methods in the estimation of emissions from high emitting vehicles. A number of emissions controls strategies are designed to reduce the emissions contributions of high-emitting vehicles. Inspection and maintenance, on-board diagnostics, vehicle scrappage, and other strategies attempt to either return high-emitting vehicles to normal emitter status through repair or to remove the high emitter from the fleet altogether. Rather than model these strategies as affecting the emission rates from specific model year vehicle subfleets, the Georgia Tech approach is to model the effects of these policies as directly impacting the fraction of high emitting vehicles in the fleet. Not only is the approach more direct, but the estimates can be field validated through the use of remote sensing.

Multi-City Remote Sensing Study (Road Show):

The research partnership maintains an on-going program of remote sensing studies to evaluate the representativeness of the Atlanta, GA data used to develop the emissions model. Studies have been conducted in Baltimore, MD; Nashville, TN (2 studies); Burlington, VT; Raleigh, NC (ongoing); New York City (focus on Taxicab emissions) and Boston, MA. Future studies are planned for Houston, TX; San Diego, CA; Salt Lake City, UT; Kansas City, MO and Spokane, WA. Specific analyses include:

I/M Effectiveness: Data from Burlington, VT (no-I/M program); Baltimore, MD (centralized test only); Nashville, TN (centralized idle only test); and Atlanta, GA (decentralized test/repair) have been analyzed to determine the relative effectiveness of different I/M programs. Results indicate that centralized programs are more effective than decentralized programs but less than the 50% discount attributed by MOBILE.

Emissions from High Mileage Fleets: Special studies have been conducted in New York City and Atlanta on taxicab emissions. New York has a rigorous taxi I/M program while Atlanta taxis are regulated as regular vehicles. Atlanta taxis have much higher emissions than the fleet-at-large where those of New York taxis are comparable or lower than those of the fleet-at-large. A new study is planned on delivery vehicles.

Instrumented Vehicles

The research partnership conducts an aggressive instrumented vehicle program. To date, seven Georgia Tech vehicles (Table 1) plus two General Motors vehicles have been instrumented for emissions measurements to support a variety of research purposes. The ongoing studies that are integral to the research model development include:

Power Enrichment Frequency: Each of the vehicles has been evaluated under different weights, accelerations, and velocities on a series of measured grades (-3, 0, 3, 6, 13%) to evaluate the influence of engine load on emissions, especially on the onset of commanded power enrichment. These results have indicated the for all of the manufacturers evaluated, demanded power is the primary determinant for the onset of commanded power enrichment. These results are being incorporated into the power demand (load) model described elsewhere to predict frequency of power enrichment in the fleet.

Typical Urban Routes: Four vehicles have been driven by a series of drivers demonstrating different driving styles to evaluate the impact of driver behavior on typical urban driving.

Remote Sensing Calibration: Six of the vehicles have been used for calibration of the remote sensing equipment used in the multi-city and CAFE experiments. This systematic calibration is essential to validate the stability of the remote sensing instruments. Results have been used to develop RSD field sampling QA/QC plans. Detailed RSD site selection criteria have been developed through this program.

Model Validation

Meticulous uncertainty analysis and extensive model validation are the keys to improving existing models. A primary requirement in the development of the modal model has been that each module or element make a specific prediction that can be confirmed or falsified by comparison with ambient atmospheric and/or traffic observations. While many more validation studies need to be implemented, a number of ambient validation studies have already been conducted. These include:

Olympic Measurement Program: The 1996 Olympics provide a unique situation for investigating the air quality effectiveness of transportation measures that will be put in place for the Olympic games and of testing forecasting tools that relate to these types of measures. An extensive ambient measurement program was conducted to measure the influence of the Atlanta Olympic Games on ozone precursor emissions. These measurements included continuous chemical measurements at five field sites (including more than 2000 speciated hydrocarbon measurements), FTIR and DOAS long path measurements and supporting meteorological observations before, during, and after the Olympics. These data are currently completing QA/QC checks.

Ambient Parking Lot Studies: In these studies, fluxes of the compounds of interest (typically CO or hydrocarbons) are evaluated using micro-meteorological techniques. These are normally gradient studies with measurements made on both a horizontal grid and with vertical profiling. Currently two studies have been completed on evaluation of cold start emissions following high school football games.

Advantages of MEASURE

- *GIS Platform* - The GIS platform is an off-the-shelf technology that is readily available and currently used by most, if not all, metropolitan and state DOT professionals. The travel demand model outputs, HPMS traffic counts, or other real-time data sources can be readily linked to the emissions modules through the GIS framework. Thus, spatial and temporal activity resolution can be provided. Model results can be visualized through the GIS package and potential errors can be identified visually
- *Discrete Treatment of Emissions Categories* - The model treats emissions sources and relationships in a manner that combines emissions interactions and separates independent emissions effects. The separate treatment of normal and high emitting vehicles, start and non-start activity, and hot start and enrichment activity will improve model performance.
- *Subfleet Characterization* - For the first time, spatially and temporally resolved vehicle subfleets will be employed directly in emissions modeling
- *State of the Art Statistical Applications* - The model treats emissions sources and relationships in a manner that combines emissions interactions and separates independent emissions effects. The aggregate modal model significantly expands the efficient use of existing test cycle data.

- *Deployment Stages are Incremental* - The model is modular in nature and the range of model implementation spans from the use of simple regional defaults to the input of real-time monitored onroad vehicle activity data. The framework provides ready linkages with simulations models as well, providing expandability as activity modeling continues to improve.
- *Compatibility with Gridded Airshed Models* - The gridded model outputs available through the GIS subroutines are directly compatible with regional photochemical models.
- *Implicit Treatment of Uncertainty* - The statistical nature of the modeling regime allows for discrete treatment of uncertainty. Because all internal model relationships are derived from statistical analyses, the confidence bounds around any internal modeling parameter are known. By building a Monte Carlo simulation package within the framework, confidence intervals will be directly available as a component of model output results.
- *Develop Tradeoffs Between Model Specification and Data Input Error* - As discussed in the introduction, one of the main goals in developing the modal model was to analyze the sensitivity of the model outputs to aggregation of input parameters. Model results will be capable of identifying how much disaggregation is too much disaggregation.
- *Model Components can all be Falsified* - Perhaps the most important advantage of the modeling approach being developed at Georgia Tech is the fact that every single component of the modeling regime is designed to be validated through data collection in the field. When the model fails to provide good emissions predictions, the wide variety of predicted components such as fleet mix, traffic volumes, operating mode profile, etc. can be directly measured for the site in question and potential explanations of why the model failed under a specific scenario can be examined. Both top-down and bottom-up validation efforts are being undertaken in 1997-98.

Conclusions

Over the past two years, research demonstrated that a stochastic model could be based upon a limited number of significant operating modes and a large volume of data has been collected to make this possibility a reality. The importance of mobile source emissions to air quality management, coupled with emerging concepts and technologies that have improved estimation capabilities, suggests that now is the time to undertake a continuous and systematic research program to develop improved mobile source emission inventory methodologies. With this in mind, the Georgia Tech Research Partnership has undertaken a comprehensive research program to develop a next generation mobile source emissions model. This model is modal in nature, is developed entirely within a GIS framework, is based upon new emission relationships that are identified through innovative statistical techniques, and will be capable of evaluating the impacts of a wide variety of policy initiatives.