

Spatial and Temporal Modeling of Start and Soak Emissions

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ABSTRACT

Engine start and hot soak emissions contribute a significant fraction of hydrocarbon and carbon monoxide emissions in urban areas. In most of today's modeling efforts, light-duty vehicle engine start activity estimates are derived through a four-step travel demand forecasting modeling process¹, based upon origin-destination studies². Estimates for trip generation and attraction at the traffic analysis zone level provide highly aggregate activity estimates that are averaged across these large analytical zones. Through a geographic information system (GIS) framework, there are significant opportunities for improving the way starts are handled in the emission inventory modeling process.

The improved modeling approach is being employed in a research grade mobile emissions model that is derived from the four-step process for the region, but provides improved estimation and spatial allocation by targeting key land uses that naturally generate or attract large numbers of vehicle trips (e.g., residential areas, regional malls, business parks, etc.). Major destination types (classified generally as shopping, employment, and special trip attractors) are located spatially in the GIS through the use of county employment data, county retail sales data, state labor statistics, and land use data from the local Metropolitan Planning Organization (the Atlanta Regional Commission). Residential locations are located in the GIS using US Census Bureau data. Census journey-to-work data are used in conjunction with data collected during the Federal Test Procedure (FTP) improvement project³ for the Atlanta metropolitan region to estimate

¹ A four-step travel demand forecasting process predicts travel behavior on a network (volume, speed) given certain socioeconomic characteristics of the origin and destination analysis zones. The process is used extensively in transportation planning to estimate the changes in travel behavior which result from changes in socioeconomic variables (population, income, etc.).

² Origin-destination studies involve surveys of people's travel patterns. The survey results are used to develop 'trip rates' for a variety of trip types (home to work, home to school, etc.) which are used in the four step travel forecasting process.

³ The Clean Air Act Amendments required the USEPA to undertake research designed to ensure that vehicles are tested under circumstances which reflect the actual onroad operating conditions (USEPA, 1992; USEPA, 1993a; USEPA, 1993b). Data were collected from instrumented vehicles in Baltimore, Spokane, and Atlanta pursuant to the FTP Improvement Program.

start time distributions for work-based trips. Specific sites and mini-zones (aggregated sites) provide improved spatial allocation of engine start and soak activity. The Atlanta three-parameter database, developed as a part of the FTP improvement project, is used to reconcile survey-estimated activity and observed activity, providing estimates of false starts and short duration and distance trips that are typically overlooked in travel diaries. Furthermore, vehicle registration data are used to assign vehicle types to household block locations through address matching, providing improved estimates of local subfleet composition.

Parking turnover studies in regional malls, industrial sites, airport, strip malls, professional office complexes, etc., define relationships between parking duration and land use, further improving spatial and temporal activity estimates of hot soak emissions. These soak time distributions will be linked with new engine start and hot soak emission rate algorithms during Phase II of model development.

INTRODUCTION

Emissions from engine starts and hot soaks (evaporation of unburned fuel while the engine cools down after making a trip) account for significant percentages of the overall mobile emissions for an urban area. For example, in 1987, in the Los Angeles region, approximately 35% of CO, 25% of HC, and 20% of NOx basin-wide emissions are estimated to be contributed by engine start operations (CARB, 1990). In addition, about 15% of HC emissions are associated with hot soak activity (CARB, 1990). The research grade motor vehicle emissions model, which is GIS-based and modal in nature, is expected to refine the spatial and temporal allocation of the emissions from these significant activities. This paper describes the engine start emissions modeling regime, GIS-based emissions modeling, activity and emission rate algorithms, integration of travel demand forecasting, and parking turnover rate and subfleet characteristic field studies currently underway.

ENGINE START AND HOT SOAK EVAPORATIVE EMISSIONS

Motor vehicle emission rates are elevated during the first few minutes of vehicle operation. The magnitude of the elevation is a function of: commanded air/fuel ratios, catalyst temperature, and engine temperature (Jacobs, et al., 1990; Heywood, 1988; Joy, 1992; Stone, et al., 1990; Pozniak, 1980). Most onboard computer control systems initially mandate an enriched fuel mixture so that the engine will not stall or hesitate during the warm-up period. Thus, the high pollutant concentrations in the exhaust plume are often initially a direct function of the computer control system which varies from vehicle to vehicle. Commanded enrichment may cease when a specific time has passed or when a specific coolant temperature is reached. As engine temperatures rise, combustion efficiency improves and emissions concentrations are gradually reduced. Finally, to be effective, catalytic converters must reach "light-off" temperatures of roughly 300 °C. Until the catalyst reaches this temperature, emission concentrations in the exhaust plume

remain high. Catalyst temperature rise is a function of initial catalyst temperature, exhaust gas temperatures, exhaust gas volumes passed through the converter, and pollutant concentrations (conversion of hydrocarbons by the catalyst is exothermic). Thus, the magnitude of elevated emissions associated with engine starts are also a function of the amount of time the vehicle has remained inactive (which affects the catalyst and exhaust gas temperatures) and is likely to also be a function of the manner in which the vehicle is operated after the engine is started (which affects exhaust gas volumes and hydrocarbon loading).

Two approaches have typically been employed to address engine start emission rates. 1) models would treat starts as discrete emission-producing activity, or a "puff." 2) models would adjust the emission rate for the parent activity (e.g. the running exhaust emissions elevated by the cold start) when the conditions that cause elevated emission rates are noted (Guenstler, 1994). The California Air Resources Board's (CARB's) emission rate model (EMFACT7F), for example, treats the elevated engine start emissions as a single "puff" (i.e. separate from running exhaust) and multiplies the number of engine starts by a cold start emission rate (Guenstler, 1993). The US Environmental Protection Agency's (USEPA's) emission rate model (MOBILE5a), on the other hand, increases the calculated running exhaust emission rate for vehicles, based upon an assumed fraction of vehicles operating in cold start, hot start, and hot stabilized modes (Guenstler, 1993).

The first phase of the research grade motor vehicle emissions model will employ a "puff" modeling approach similar to that employed in the California Air Resources Board's EMFACT7F model. Although the engine start emissions occur over a period of one to three minutes or so, the emissions associated with engine start activity will be modeled as occurring within the mini-zone where the start occurred, at the time the engine was started. In the early stages of the model development, engine start emissions for the various technology groups of the vehicle fleet are based upon constant grams/start emissions rates derived from the USEPA's FTP emission testing database, and a review of other background literature. The simplified modeling approach outlined above will be enhanced during later phases of model development to account for the variables that impact commanded start enrichment and catalyst light-off time. Hence, the improvements will model the effects of: 1) temperature, 2) vehicle operating characteristics prior to soak, 3) soak duration (i.e., time between engine shut down and subsequent engine start), and 4) vehicle operating characteristics after the engine start.⁴ The research team will link their research efforts with similar efforts being undertaken by the California Air Resources Board (Sabate and Agrawal, 1994) and Systems Applications International (Fieber, Shepard, and Cohen, 1993) which would associate emission puffs with lengths of vehicle soak time. Ultimately, two major improvements will be provided through the GIS

⁴ Vehicle characteristics to be examined include: vehicle class (weight, engine size, HP, etc.), model year, accrued vehicle mileage, fuel delivery system (e.g. carbureted or fuel injected), emission control system, onboard computer control system, control system tampering, and inspection and maintenance history. Operating modes (or vehicle operating conditions) will include analysis of the effects of speed/acceleration distribution, engine load, and influence of driver behavior (as evidenced by throttle position behavior patterns).

modeling approach to engine starts: 1) the grams/start emissions rate will be derived as a function of vehicle characteristics, environmental conditions, soak time, and the modal activity undertaken before and after the engine is started, and 2) a portion of the start emissions will be allocated to network links using activity probability distributions (based upon infrastructure characteristics), allowing the GIS model to begin serving as an input to microscale air quality impact modeling.

When an engine is shut down, a significant amount of unburned fuel evaporates from engine components (especially from carbureted vehicles). The rate of evaporation from the engine components declines over time, but evaporative emissions are typically modeled as a puff, occurring at the point and time where the vehicle's trip ends. The research grade emissions model will employ the default hot soak evaporative emission rates currently employed in the MOBILE5a model.

GIS BASED VEHICLE ACTIVITY APPROACH

Existing start and soak models use estimates of vehicle activity predicted by travel demand forecasting models. These models provide estimates of trip productions and attractions by trip type. Generally, the algorithms, or trip rates, used for trip generation are based on origin-destination surveys. Emission rate models are then applied to the number and location of starts.

The long-term approach of the engine starts module in the GIS modeling regime is to spatially and temporally estimate vehicle trip ends using a variety of socioeconomic variables and land use data which can be correlated to trip generation and attraction. A geographic information system (GIS) is a spatial analysis tool that can be used to model the inter-relationships of geographic entities. A GIS consists of a data base containing spatially referenced land-related data as well as procedures for systematically collecting, updating, processing, and distributing that data. The fundamental base of a GIS is a uniform referencing scheme which enables data within a system to be readily linked with other related data. A true GIS can be distinguished from other systems through its capacity to conduct special searches and overlays that actually generate new information (Bachman, et al., 1995). Several large databases can be combined to accurately estimate the number of productions and attractions to an area by a variety of trip types. The GIS has network analysis capabilities which can be used to allocate a portion of start emissions to zones and/or links. The GIS also provides the graphical user interface and map-making capabilities needed to communicate intermediary analyses and results to decision makers. Three specific research undertakings are envisioned for quantifying vehicle activity for the engine starts module: 1) spatial database development for activity modeling, 2) integration of travel demand theory, and 3) sources of field data (such as parking turnover rate and duration characteristics).

An off-the-shelf software package was used as the GIS engine for this analysis. The system uses geographically referenced 'layers' of databases. The database is called a 'coverage'. Coverages consist of either polygon, line, or point data. Each coverage can have many attributes. For example, a coverage of roadways (line) could have attributes consisting of, length, name, highway number, average daily volume, etc. Table 1 contains

a list of some of the zone (polygon), link (line) and point attributes used in the research grade emission model.

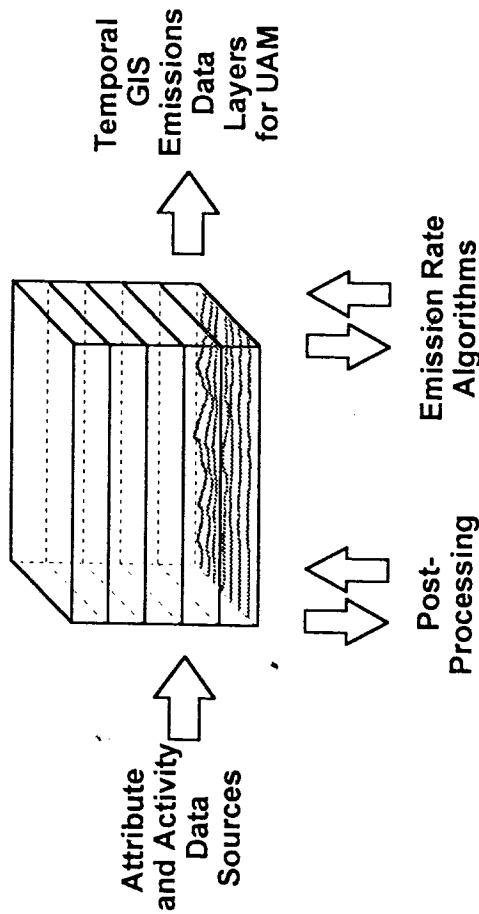
Table 1 - Zone, Link, and Point Attributes in the GIS Model

<u>Zone</u>	<u>Link</u>	<u>Point</u>
Zone area	Link length	Major attractors
Population	Number of lanes	Shopping centers
Housing units	Roadway classification	Parking lots
Income	Traffic volume	Other
Vehicle fleet composition	Road grade	
Fleet ownership	Fleet composition	
(private/public/corporate)		
Employment	Speed limit	
Land use	Infrastructure parameters	
CTTP data		

The emissions data layers for engine starts and hot soaks are integrated with other emissions data layers (from hot stabilized, enrichment, refueling, and other emissions modules) and aggregated to the grid cell level for use in Urban Airshed Modeling for air quality impact analysis. The GIS can employ callout routines in C, BASIC, FORTRAN, or through direct linkages to other software, resulting in a flexible modeling approach. A statistics package is being used through the GIS for developing fleet distribution profiles for each census block. Other routines are accessed by the model through a client/server process. The GIS can make requests to other programs which access the spatial databases, provide some additional manipulation, and return the data for further spatial analysis. This capability provides great modeling flexibility and allows for the development of a single user interface which handles all the needs of the user. Figure 1 provides the basic GIS framework, which includes the ability to post-process input data and jump out to external model subroutines. Note that multiple data sources and/or estimation methods can be used in the GIS model. GIS-based menus can allow a modeler to select which data sources and subroutines should be used in the emissions estimation.

Figure 1: The GIS Framework of the Research grade Modal Emissions Model

GIS Framework



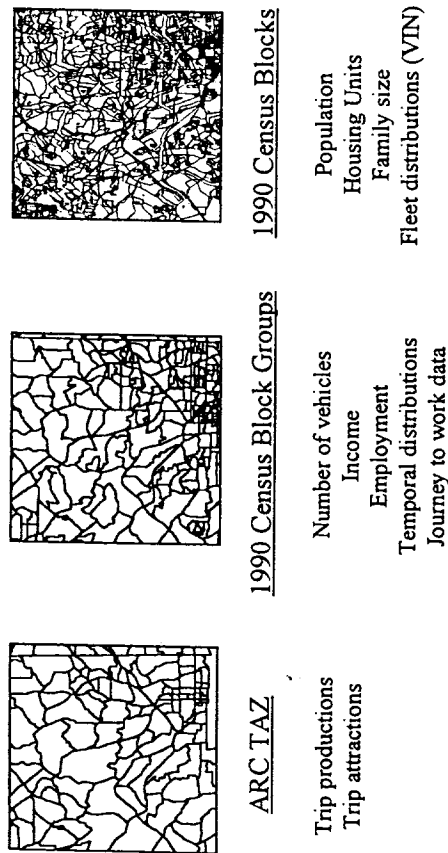
ACTIVITY MODELING

For the purposes of modeling engine start emissions, the appropriate vehicle activity data are the number, location, and time of engine starts. Working within a GIS framework, it is possible to directly associate engine starts with the land use from which the trip is made. Inherent in this module is the assumption that number of trips (and hence engine starts) will be functions of land use, trip type, and the various socioeconomic variables currently employed in transportation demand analysis (such as household income, number of persons/household, vehicle ownership, etc.). In addition, these vehicle activity data must be estimated as a function of time of day so that engine start emissions can be temporally allocated. Thus, for example, engine start activity would be spatially allocated in the GIS framework to actual household locations by time of day (i.e. large numbers of engine starts in the morning period associated with the journey to work) and to actual retail locations (e.g. shopping malls) by time of day (i.e. large numbers of engine starts in the afternoon periods associated with shopping trips).

Currently, the Atlanta Regional Commission (ARC), which is Atlanta's Metropolitan Planning Organization estimates trip productions (trips originating from home) from a matrix of family size and income for five trip purposes: home-based work (HBW), home-based shopping (HBSH), home-based other (HBO), non-home based (NHB), and home-based school (HBSC). The ARC matrix was developed from origin-destination data collected in each of the regional traffic analysis zones (TAZs). There are 1005 TAZs employed in a ten county area of Atlanta. Trip attractions (originating from work) are estimated by linear regression for seven trip types and are predicted by socioeconomic variables including population, employment, school enrollment, and households. The original data used to calculate attractions came from a 50 zone system for the ten counties surrounding Atlanta. The linear fit equations were then applied to each of the 1005 TAZs.

The GIS based model will further divide the TAZs to improve the spatial and temporal distributions of modeled starts. Gaining insight into the population distributions within each TAZ can improve the spatial resolution of the trips they produce. Improved resolution of productions (starts) will come from 1990 Census block data (~33,000 census blocks) which provides population and household size for the Atlanta metro area. Vehicle registration data are also available at the census block level. The 1990 Census block group data (~2000 census block groups) provides socioeconomic variables. The temporal distributions of the tripmaking activity are derived from the census long form journey to work data also available by census block group. Block group data are assumed, when lacking better data sources, to be uniform across the census blocks which the block group boundary encloses. Figure 2 illustrates the differences in the spatial resolution of TAZ, census block group, and census block data.

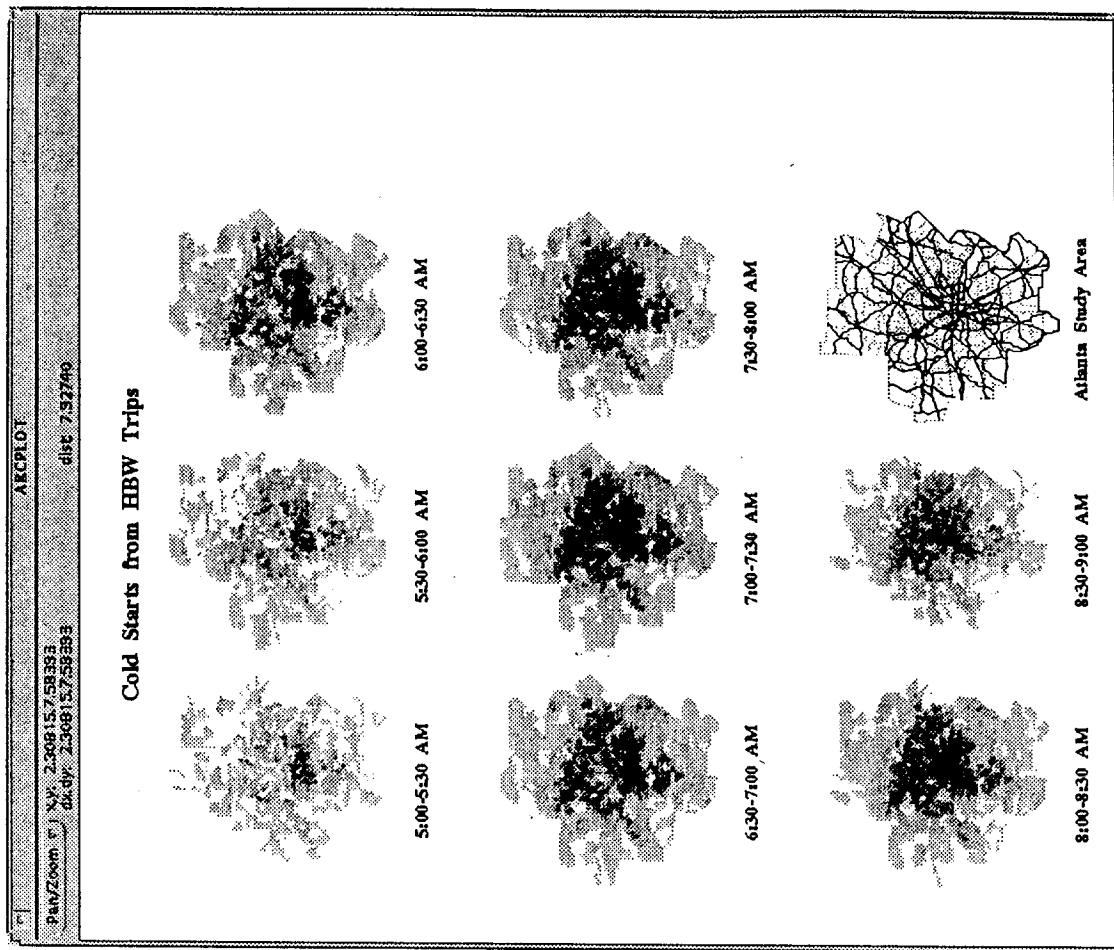
Figure 2: A Comparison of Transportation Analysis Zones, Census Block Groups, and Census Blocks and Associated Data



Land use data will further divide trip productions by identifying clusters of multi-family housing as well as improving attraction resolution by identifying clusters of industrial use, commercial use, etc. A database of major attractors, such as shopping malls, hospitals, etc., will also help to identify major trip end locations.

Trip end emission calculations are undertaken at the census block or mini-zone level, using census block data and associated census block group data. The estimated emissions for each block are aggregated to the 1km grid cell level so that they can be combined with other emissions module results and used in urban airshed modeling. Figure 3 shows an example of the spatial and temporal distributions of starts produced by HBW trips between 5:00 AM and 9:00 AM.

Figure 3 - Carbon Monoxide Emission Contributions from Home-Based-Work Cold Start Trips



INTEGRATION OF TRAVEL DEMAND FORECASTING

The GIS program is capable of jumping to the travel demand algorithms for any given period of the day (in 15 minute or one hour intervals depending upon trip type and time of day) to estimate the number of trips generated for each land use and where they are while operating under an engine start mode.

As discussed earlier, the location of an engine 'start' is not static. Elevated emissions exist until the engine warms up, which could occur after the vehicle has left its origin and is traveling on the network. For this reason, engine start modeling must ultimately include network or route information as well as the location of origins and destinations. As discussed previously, the number of trips generated by a land use is currently modeled in travel demand models as a function of a variety of socioeconomic variables. Trip generation algorithms are developed (and will be improved by the research team through re-analysis of travel diaries) for the variety of land use classifications integrated into the GIS system as a function of time of day and a variety socioeconomic parameters.

Current travel demand model algorithms are capable of providing estimates of traffic volumes (after calibration), using the trip generation, trip distribution, mode split, and route assignment algorithms. Ultimately, trip distribution and assignment algorithms will also be used in the distribution of vehicles and their engine start mode conditions to the network so that the vehicle activity data on the network links can be employed in microscale dispersion impact modeling. The algorithms will be based upon a detailed review of the trip generation algorithms currently integrated into the four-step travel forecasting model for the Atlanta region. If feasible, the model algorithms will be improved based upon a statistical review of the data employed by the Atlanta Regional Council to develop these algorithms. Trip generation algorithms will be coded in FORTRAN and results will be integrated into the GIS system as an additional data layer associated with each land use. The 1990 ARC model is currently being integrated into the GIS model, and the 1995 improved ARC model will be integrated once the final subroutines and data are available from the ARC. Vehicle activity estimates will be validated through field studies, using both parking lot turnover data and neighborhood trip production observation.

PARKING TURNOVER RATE AND DURATION CHARACTERISTIC STUDY

Georgia Tech research staff have undertaken a comprehensive literature review of the planning and engineering literature to prepare a background paper on parking turnover rates. Unfortunately, there are very few studies reported in the literature that have examined parking turnover rates as a function of various land uses. Hence, much of the 1995 summer activities in Atlanta were associated with identifying various land uses to be examined, testing data collection technologies and techniques, and specific site characteristics affecting sampling methods.

For those land uses that have been identified as having a significant impact on parking duration, field research will be undertaken this year to quantify the relationships between land use, employment/socioeconomic characteristics, and parking duration. Data

collection includes specific ingress and egress times for vehicles over extended periods so that parking duration distributions can be quantified.

The types of land uses that are proposed for field investigation include such uses as: regional malls, retail, restaurants, movie theaters, industrial sites, airports, strip malls, medical centers, professional office buildings (service), professional office buildings (non-service), government agencies, schools, universities, fast food chains, video rental stores, grocery stores, hospitals, hotels, recreational facilities, convention centers, etc. While there are many potential land uses to investigate, resources for field work in this task are limited. The determination of land use to be studied and number of sites to be visited per land use (to gather a representative sample) have yet to be determined, but will be based upon initial research findings.

Some data collection for the field work will be carried out by video monitoring of license plates, and some manual data collection will be undertaken by graduate and undergraduate student teams using paper, palmtop computers, or hand-held tape recorders. For those parking lots with limited egress, one or two cameras can be used to cover the entrances, provided a secure camera location can be obtained. For sites where video data collection is precluded, due to weather or security reasons, manual data collection must be undertaken.

One of the parking lot scoping studies conducted this summer involved a multi-level parking deck on Butler Street located in the downtown Atlanta CBD. The parking deck is a seven level garage with a capacity of 797 parking spaces. The parking deck services primarily governmental employees. Public parking is controlled by either a parking attendant or card access. In addition to public parking, there is a vehicle service depot for government vehicles located on the first level of the parking deck. The parking deck has only one access point located off Butler Street which has four entry lanes and two exit lanes spanning over a distance of approximately 80 feet.

The parking deck is open from 6:00 am to 7:00 pm. The peak traffic hours of operation are from 6:45 am to 8:00 am and 3:30 pm to 5:00 pm. The parking duration and turnover rate study was conducted from 6:30 am to 5:30 pm using a hand held tape recorder to record the tag numbers of vehicles entering and exiting the facility. A tape recorder was chosen to record the tag number because of the high volume and vehicle turnover at the parking deck. The study was segmented into two observation shifts with one observer in the AM and another in the PM. The purpose for this was to prevent the observers from becoming fatigued during the study.

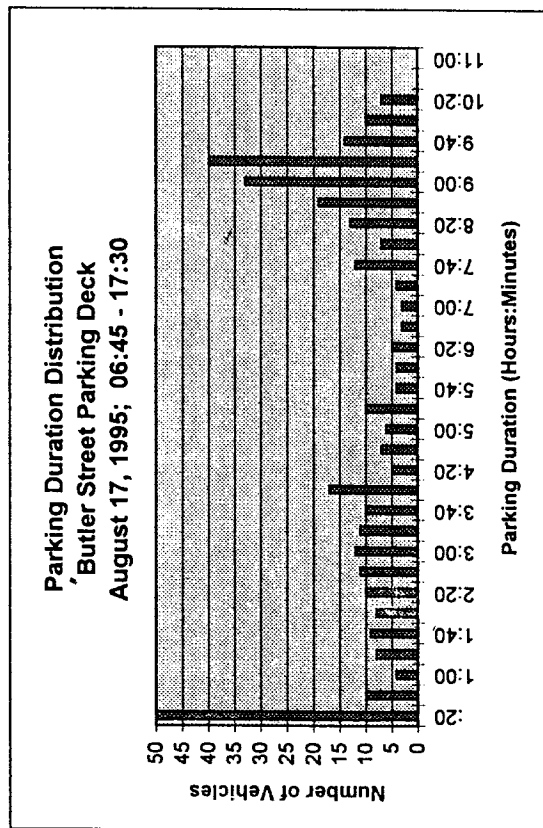
Once the tag numbers and their associated entry and exit times were entered into a database, the entering tag numbers were matched with the exiting tags and parking durations were calculated. The 46% tag matching rate was due in part to: 1) the fact that during peak periods, traffic was often too overwhelming for one observer to record all the tag numbers, especially when there was a mix of vehicles entering and exiting at the same time, 2) the fact that the driveway was composed of four entry lanes and two exit lanes, approximately 80 feet across, where it was often hard to see the tag numbers clearly when standing at any one point along the driveway, and 3) the fact that government fleet vehicles were being picked up from an overnight stay or dropped off from multi-day use.

Table 2 Butler Street Parking Deck, Parking Duration Study Findings

Minimum duration	1 minute
Maximum duration	10 hours and 16 minutes
Average duration	5 hours and 21 minutes
Standard deviation	0.144
% of tags matched	46%

The following graph provides the distribution of parking durations obtained during the Butler parking lot study. The high number of vehicles with durations of 20 minutes or less is due to the constant entering and exiting of government vehicles. It should be noted that it took approximately 20 hours to post-process the data collected during this single study.

Figure 4 - Parking Duration Distribution



The results from this and other parking pilot studies are being used to develop a parking lot study manual.

Based upon the results of preliminary summer research, a decision tree has been developed to aid in the selection of the data collection method for any given site. Factors such as number of entrance points, distance between points, and peak entrance volumes determine the type of data collection technology to be employed and the number of students required throughout the day (Kasbo, et al., 1996).

Site characteristic data will be collected for each study, including: type of facility, number of employees, square footage, office hours, freeway access, etc. Data reduction and statistical analysis all of the parking field studies will be undertaken to identify potentially important causal relationships between parking duration, land use, site characteristics, etc. The regional characteristics of each site location (urban, suburban, rural, and potentially additional subcategories) will be controlled in comparative analyses.

Hypothesis testing will attempt to correlate parking time (engine soak time employed in engine start and engine soak analyses) with: land use, commercial/retail activity type, vehicle and/or driver characteristics (where available), time of day, zone characteristics, etc.).

Probability distributions will be prepared for parking duration by land use category as a function of the important variables identified. These relationships will be coded as algorithms external to the GIS system using C programming language. If an operator requests, the GIS program is capable of jumping to these algorithms for any given period of the day to estimate vehicle soak time (engine off time or parking duration) for any trip generated. The predicted soak time can then be integrated into the GIS system in the same data layer used to track trip generation. Hence, the modeler can employ soak time duration estimates that are based upon sampled data for the Atlanta region, rather than regional or travel-demand-model-based assumptions. Results of the studies should also provide a robust database for comparison of modeled and measured results.

FLEET DISTRIBUTION

Because the magnitude of emission rates is affected by a wide variety of vehicle characteristics, the fleet composition associated with engine starts is a critical parameter if spatial and temporal modeling resolution is to be improved. Fleet registration data exhibits significant spatial variation (Rajan, 1993). Hence, onroad fleet characteristics can also exhibit significant spatial variation. The research grade GIS-based modal emissions model currently includes the fleet and engine parameter distributions for each of the 33,000 1990 Census Block in the study area (~300 vehicles per block). These factors will be employed in the emission rates used for home-based start and soak emissions. Therefore each block will employ a different emission rate based on its individual characteristics. Similarly, analysis of onroad data collected through remote sensing studies has provided a great deal of insight into local fleet composition. Hence, non-home-based trips will employ more specific vehicle fleet composition data that the currently employed regional fleet. Because parking duration studies involve the collection of license plate data, fleet distribution characteristics can be developed. Confidentiality issues require that the study team submit a list of license plate numbers for conversion into a cross-tabulated list of manufacturers' vehicle identification numbers (VINs), without receiving associated ownership or address information. These VINs are readily converted into distributions of fleet characteristics.

SUMMARY

Given the importance of start and soak emissions, the ability to accurately estimate or predict emissions is important to the first generation of the research grade GIS-based modal emissions model. Research of emission rates and vehicle activity, combined with a GIS modeling environment, could result in improvements in emission modeling. The improvements come from the incorporation of several spatial databases which allow the spatial and temporal resolution of estimates to be increased.

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