CHAPTER 3
FIELD RESEARCH APPROACH

This chapter presents the basic research approach for performing an evaluation of the air quality impacts of a ramp metering system using field data collection methods. First the problem is defined, followed by presentation of the research hypothesis and research objectives. This is followed by a detailed discussion of the research scope of work. Data collection and analysis techniques considered for this research and the emissions modeling procedures are then outlined. This discussion provides the basis for the data collection plan and analysis procedures, which is addressed in the subsequent two chapters.

3.1 Problem Statement

As discussed in the previous chapter, despite advancements in pollutant emissions control brought about by the Clean Air Act and its amendments, urban air quality is still a serious problem throughout the U.S. Concurrent with this air quality problem, urban areas in the U.S. are experiencing a rapid increase in traffic congestion and travel delay. Indeed, growth in vehicle ownership and travel activity (more and longer trips), is resulting in an increase in the number of vehicle miles of travel (VMT), which is directly contributing to the increase in mobile source emissions and traffic congestion.

In light of diminishing capital funds and physical constraints on the construction of new transportation facilities, traffic congestion is being addressed by transportation professionals through optimization of the existing infrastructure. This optimization is accomplished through a variety of transportation management strategies, and federal agencies are encouraging the implementation of transportation control measures (TCMs) designed to simultaneously reduce congestion and motor vehicle emissions. One frequently implemented transportation program is freeway ramp metering, which is particularly popular due to its cost effectiveness for reducing congestion levels.

Traffic flow and travel time benefits of ramp metering are well documented in the literature (Piotrowicz and Robinson, 1995; Meyer, 1997), but the true emissions and air quality benefits are not. Therefore, the question of the air quality impacts of ramp metering remains unanswered. This is an important question in light of the current urban air quality and traffic congestion problems, given the fact that many cities are using ramp metering as a TCM in an effort to reduce vehicle emissions.

One reason that the emissions impact of ramp metering has been difficult to estimate is that the modeling regimes used to estimate vehicle emissions are not suited for the analysis of small scale traffic improvements such as ramp metering. The MOBILE series of average speed emissions rate models are aggregate models that are not sensitive to high emissions activity encountered on freeway onramps equipped with ramp meters. Emerging disaggregate modeling regimes, such as the MEASURE Aggregate Modal Model provide a basis for providing more accurate emissions estimate for ramp metering systems.
This analysis provides critical information to transportation planners and engineers regarding the comprehensive impact of a ramp metering system due to changes in modal activity brought on by ramp metering systems. This information can then be used to determine if a ramp metering system is an appropriate strategy depending on the particular air quality and congestion problem of a given area.

3.2 Research Hypotheses

Enrichment conditions for vehicles operating on onramps are likely to increase under metered conditions as vehicles accelerate rapidly to freeway speeds. The magnitude of the resulting emissions increase is uncertain, but most analysts anticipate that the negative ramp emissions impacts will be more than offset by positive emissions benefits from improved flow conditions on the mainline freeway segments. This would result from smoother operation on the mainline resulting in less enrichment and lower power demand and more efficient combustion. Because the number of vehicles operating on the mainline is much greater than that of the ramps, the net result is generally believed to be a decrease in vehicle emissions under congested traffic conditions. Therefore the research hypothesis is:

Ramp metering systems operating under peak period traffic demand will yield an increase in ramp HC, CO and NOx emissions, a decrease in mainline HC, CO and NOx emissions, and a net decrease in emissions for the combined system

To assess the emissions impacts of ramp metering systems, this research had four main objectives:

**Objective 1: Develop a method to sample representative modal activity on freeway onramps and mainline sections of the Atlanta ramp metering system**

To assess the emissions impacts of a ramp metering system using a disaggregate modeling approach, where emissions are predicted as a function of the way that vehicles are driven, it was necessary to gather speed/acceleration profile (modal activity) data. In addition to developing a representative sampling procedure, the data collection plan also needed to address issues of gathering data across all locations of the system simultaneously. The focus of this objective was on sampling modal activity data for passenger vehicles, although other vehicles such as trucks were not excluded from the sample. The sampling plan also included collecting modal activity data for both metered and non-metered conditions to provide data for a direct comparison of both conditions.

**Objective 2: Utilizing the modal activity data collected from the system as an input to the Aggregate Modal Model algorithms in MEASURE, estimate changes in vehicle emission rates and net vehicle emissions resulting from operations of ramp meters.**

The prime objective of this research is to determine the emissions and air quality impacts of a ramp metering system. Using the Atlanta system as a case study, researchers estimated vehicle emissions on ramps and mainline freeway segments, with and without the ramp meters in...
operation. Analyses included assessment of field-monitored vehicle activity operating conditions as well as simulated vehicle activity operating conditions.

**Objective 3:** Compare the emissions estimates for the Atlanta ramp metering system from the MEASURE Aggregate Modal Model to the emissions estimates produced by the USEPA MOBILE5b model.

The MOBILE series of emissions rate models produce inaccurate emissions estimates for some applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). In most cases, MOBILE emissions estimates are below observed onroad emissions rates due to the lack of sensitivity to off-cycle enrichment activity, such as hard accelerations. In addition, MOBILE is considered to be inappropriate for small-scale analysis, for example TCM evaluation. One objective of this research was to validate this limitation through a comparison of the current MOBILE model, MOBILE5b, estimates with the MEASURE Aggregate Modal Model estimates.

**Objective 4:** Assess prevailing mainline flow conditions and ramp configurations and designs (e.g. grade and acceleration distance) that influence ramp and mainline modal activity.

A final objective of this research was to determine the flow and design conditions that influence vehicle modal activity within the ramp metering system. The operational benefits of ramp metering are not realized under light traffic flow. That is, the delay realized by vehicles on the ramps is greater than the benefit gained to mainline traffic if ramp metering is implemented under low traffic volumes. Therefore ramp metering is typically only used under heavy traffic flow or during peak travel periods. The question this research answered was, under what traffic flow conditions (i.e. level of service) is the vehicle modal activity increased. In addition, the ramp geometry (e.g. grade and acceleration distance) and configuration (e.g. with or with out an auxiliary lane, loop ramp, etc.) was examined to assess the potential influence on modal activity.

### 3.3 Scope of Work

Several tasks were undertaken to guide and complete the field aspects of the overall research effort. The overall scope of the fieldwork was divided into eleven primary steps including the previously discussed hypothesis statement and research objectives. The eleven research approach steps were:

1. Statement of Hypothesis and Research Objectives  
2. Define Target Group/Population  
3. Identify Relevant Data to be Collected  
4. Determine the Degree of Data Precision  
5. Develop Survey/Data Collection Methods  
6. Determine Sampling Units  
7. Determine Sampling Procedure and Sample Size  
8. Pretest Survey Method and Field Procedures  
9. Develop Survey Management Structure  
10. Develop Analysis, Reduction and Summary Procedures  
11. Develop Data Storage System
The research hypotheses were outlined earlier. A detailed description of each of the remaining ten steps is addressed in detail in subsequent subsections.

Step two, the definition of the target group, may seem obvious for this research, but needs to be outlined. The target group for this study included vehicles operating on the freeway onramps and mainline section in the study area. All vehicles were included in the study, although the focus of the analysis is on passenger vehicles. Data were collected on all vehicles sampled in the study area in order to provide fleet mix information and a complete data set, but the emissions analysis was only performed on passenger vehicles (including SUVs). There are two reasons for this. One, emissions algorithms for heavy-duty vehicles have not been implemented in the MEASURE Aggregate Modal Model. Secondly, the majority peak period vehicle activity is associated with passenger vehicles.

The third step, identify relevant data to be collected, focuses on the information needed to perform the proposed research analysis. The data needed for this project is divided into two primary groups, one being vehicle activity data and the other being system information. The necessary vehicle activity data consists of instantaneous speed/acceleration profiles for a large sample of vehicles operating on the ramps and freeway mainline sections. Detailed data collection of operating conditions on the arterials was precluded by resource limitations and was not included in the original scope of analysis. The vehicle speed/acceleration profiles provides the core data for this research and is the critical information that was used to tie changes in vehicle operating modes with changes in emission rates. The system data include physical ramp and roadway characteristics, such as grade, curvature, acceleration distance, ramp design, and ramp metering rate. In addition, system traffic flow data were also included. This consisted of ramp and mainline 15-minute flow rates, lane distributions, average vehicle speeds, truck percentage and vehicle mix, and vehicle characteristics (e.g. engine type, fuel type, emissions control, transmission type, and accumulated mileage). For this research, only evening peak period conditions were of concern, since the ramp meters in the study area only operated during these peak hours of travel to assist with the outbound commute.

Step four, determine the degree of analysis precision, was performed in conjunction with the previous step. Once the relevant data are determined, the analysis precision needs to be established in order to refine the data collection methods. This study focused on vehicle activity at the microscopic level (i.e. second-by-second individual vehicle activity). Detailed speed/acceleration profiles were collected for a sample of vehicles operating in the study area. This empirical information was then used to draw conclusions regarding the operation of all vehicles in the fleet and as an input to the MEASURE Aggregate Modal Model and MOBILE5b. Therefore the activity data analysis was designed to be highly precise, although some findings were presented in the aggregate and as the average or variance of the discrete data points.

The fifth step, develop survey/data collection methods, is the process of gathering the data that has been identified as necessary for the research. For this project, survey and data collection procedures entailed the collection of several components of vehicle activity. First and foremost, this included the collecting of vehicle speed/acceleration profiles on the onramps and mainline sections of the study area. Secondary to this was the collecting of traffic volumes and vehicle license plate information. The speed/acceleration data and the license plate data were collected from only a sample of vehicles in the study area during the evening peak study period. Data
collection activities were performed during a four-hour evening peak period (3:00pm to 7:00pm) on eighteen weekdays. Four of the data collection days were conducted while the ramp meters were turned off. Chapter 4 is dedicated to a description of the data collection process, site selection, and field procedures.

*Determine sampling units*, was step six. Data are collected from individual vehicles, but individual vehicle data were binned into groups for analysis. Data bins were developed by location and time. In general, data from each ramp location and each mainline data collection site were grouped into fifteen-minute time bins. That is, for reasons that are discussed in later sections, the vehicle activity data with similar characteristics were analyzed in groups, and not as individual traces.

The related seventh step, *determine sampling procedure and sample size*, was developed in order to acquire a random sample that would provide the appropriate amount of data for the analysis. A sampling procedure was developed for each data collection site to yield a random and unbiased sample of vehicles. These procedures are discussed in the following Chapter 4. The necessary sample size was not known prior to the data collection phase and ultimately was determined by the resources available. That is, all available data were collected given the time and fiscal constraints stated above.

Step eight, *pretest survey method and field procedures*, was performed once the data collection process was refined. To gather the necessary data for this analysis, up to fifteen data collectors were required to be in the field at any given time during the process. Therefore, it was important to pre-test the methods and procedures before final collection deployment. The pretest for this research included four days of "dry" runs and data sampling tests.

Step nine, *develop survey management structure* was also performed before data collection was initiated. This entailed determining the appropriate data collection staff, field deployment and equipment setup procedures, safety procedures, and standard operating procedures for data collectors. This also included procedures for downloading, storing and archiving the field data.

Step 10, *develop analysis, reduction and summary procedures* was being performed before step 9 was complete. This ensured that the data collection process resulted in information that would fit the proposed analysis procedure. The primary thrust of this data collection was to gather vehicle speed profile information that could be used to develop joint acceleration-speed probability density functions (JASPROD), for use as inputs to modal emissions models and other vehicle modal activity procedures. This also included the transformation of the field data and measurements into information that was meaningful and could be easily analyzed.

The eleventh and final step, *develop data storage system*, consisted of constructing a database system for all of the data elements. Once the data were collected it was important to have a data storage routine so that it could be easily cleaned, processed, and analyzed. Again, the details of the database system and the other data collection and processing procedures are discussed in the following chapter. The following sections of this chapter discuss the specifics of the analytical procedures.
3.4 Analysis Procedures for Field Efforts

One of the most critical components of the research approach is the analysis procedure. These procedures define how the four research objectives were accomplished. The analysis procedure for the field research is divided into three primary components. These consist of: 1) the vehicle NOx emissions analysis of the Atlanta ramp metering system using the MEASURE Aggregate Modal Model emissions rate algorithms to estimate the vehicle emissions, 2) a comparison of the MEASURE Aggregate Modal Model and MOBILE5b estimates, and 3) an assessment of the traffic flow and ramp geometric design conditions influence on vehicle model activity levels and related estimated emissions rates.

3.4.1 Emissions Analysis

The Georgia Institute of Technology MEASURE Aggregate Modal Model, described in Chapter 2, is the basis for the emissions analysis. The Aggregate Modal Model is designed to be implemented on a regional level and incorporates numerous elements of mobile source emissions, including start emissions, evaporative and running exhaust emissions. This research is only concerned with changes in hot stabilized running exhaust emissions and therefore only incorporates certain sub-elements of the model. In short, the emissions rate algorithms, (which comprise just one component of the model), are the only element used for this analysis. Although only a single component of the overall MEASURE GIS-based modeling framework, these emissions rate algorithms are one of the distinct elements of the MEASURE framework.

The Aggregate Modal Model hot stabilized emissions rate algorithms were established from a data set of more than 13,000 dynamometer tests. The algorithms predict emissions rates of motor vehicles grouped by various technology criteria as a function of aggregate measures of vehicle speed and acceleration profile. The vehicle activity related variables modeled in the MEASURE framework include average speed, acceleration rates, deceleration rates, and surrogates for power demand imposed on the engine. The following section provides a description of the MEASURE Aggregate Modal Model algorithms.

3.4.1.1 Structure of the MEASURE Aggregate Modal Model Algorithms

Separate Aggregate Modal Model algorithms (Fomunung, 1999) are used in MEASURE for each of the pollutants of concern, CO, HC, and NOx. Each algorithm is statistically derived using a combination of parametric and non-parametric methods. Each of the three algorithms are presented in a functional form.

The CO model is based upon the regression equation:

\[ \text{LogR}_{\text{CO}} = 0.0809 + 0.002 \times \text{AVGSPD} + 0.0461 \times \text{ACC.3} + 0.0165 \times \text{IPS.60} - 0.0283 \times \text{ips45sar2} + 0.3778 \times \text{ips90tran1} - 0.0055 \times \text{tran3idle} + 0.1345 \times \text{tran5mil} + 0.3966 \times \text{finj3sar3} - 0.0887 \times \text{cat3tran1} - 0.2636 \times \text{sar3tran4} - 0.481 \times \text{flagco} \]

(Fomunung, 1999)  \hspace{1cm} (3-1)
Where:

\( R_{CO} \) is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);

\( AVGSPD \) is the average speed of the driving cycle in mph;

\( ACC.3 \) is the proportion of the driving cycle on acceleration greater than 4.8 kph/s (3mph/sec);

\( IPS.60 \) is the proportion of the driving cycle on inertial power surrogate (IPS) (speed x acceleration) greater than X mph2/sec (Washington et al., 1994). Thus, IPS.60 implies IPS greater than 60 mph2/sec;

\( ips45sar2 \) is an interaction between IPS.45 (IPS >= 45 mph2/sec) and a vehicle with no air injection;

\( ips90tran1 \) is an interaction variable for a vehicle with automatic transmission on IPS.90 IPS >= 90 mph2/sec;

\( cat3idle \) is an interaction variable for a 3-speed manual transmission at idle;

\( tran5ml1 \) is an interaction variable for a 5-speed manual transmission vehicle with mileage <= 25k miles;

\( finj3sar3 \) is an interaction variable for a vehicle that has throttle body fuel injection and pump air injection;

\( cat3tran1 \) is an interaction variable for a vehicle with automatic transmission and TWC;

\( sar3tran4 \) is an interaction variable for a vehicle with 4-speed manual transmission and pump air injection; and

\( flagco \) is a flag used to tag a high emitting vehicle under CO emissions.

The HC model is based upon the regression equation:

\[
\text{Log}R_{HC} = 0.0451 - 0.6707*my79 - 0.1356*my82 + 0.019*AVGSPD + 0.2021*finj2tran4 + 0.1795*cat2sar1 + 0.1651*cat3sar1 + 0.0318*cat3sar2 - 0.1189*sar3tran1 + 0.5646*sar1tran5 + 0.0004*cid - 0.2581*sar3kml - 0.0169*finj2km3 - 0.5144*flaghc - 0.0129*acc1finj2 - 0.1626*acc3cat2 - 0.3891*ips90sar3 + 0.0307*dps8finj2
\]

(3-2)

Where:

\( R_{HC} \) is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);

\( my79 = \text{model year} < 79; \)

\( my83 = 79 < \text{model year} < 83; \)

\( AVGSPD = \text{average vehicle speed (mph)}; \)

\( finj2tran4 = \text{interaction variable for a 4-speed manual transmission vehicle with a carburetor}; \)

\( cat2sar1 = \text{pre 1981 model year vehicle with "oxidation only" catalyst and unknown air injection type}; \)

\( cat3sar1 = \text{pre 1981 model year vehicle with a TWC and unknown air injection type}; \)

\( cat3sar2 = \text{vehicle with TWC and no air injection}; \)

\( sar3tran1 = \text{automatic transmission vehicle with pump air injection}; \)
sar1tran5 = pre-1981 model year, 5-speed manual transmission vehicle of unknown air injection type;
cid = cubic inches displacement;
sar3km1 = vehicle with pump air injection and mileage <= 25k miles;
finj2km3 = vehicle with pump air injection and 50k < mileage <= 100k miles;
flaghc = high emitting vehicle flag under HC emissions;
acc1finj2 = carburetor-equipped vehicle operating with acceleration greater than 1 mph/s;
acc3cat2 = oxidation only catalyst vehicle with acceleration greater than equal to 3.0 mph/s;
ips90sar3 = vehicle with air pump and inertial power surrogate greater than or equal to 90 mph2/s; and
dps8finj2 = proportion of drag power surrogate (DPS) speed x speed x acceleration greater than 8 mph3/s.

The NOx model is based upon the regression equation:

\[
\log_{10} R_{NOx} = -0.5864 + 0.0225 AVGSPD + 0.3424 \times IPS.120 + 0.6329 \times ACC.6 + \\
0.0247 \times DEC.2 + 0.0083 \times finj2km1 + 0.0028 \times finj2km2 - 0.0021 \times cat2km3 + \\
0.0026 \times cat3km2 + 0.0003 \times cat3km3 - 0.0085 \times finj1km3flagnox - \\
0.0068 \times finj3km3flagnox
\]  

(3-3)

Where:

\( R_{NOx} \) is the emission rate ratio for each vehicle technology group (the gram/second emission rate under the observed conditions divided by the gram/second emission rate under standard FTP laboratory test conditions);

IPS.120 = proportion of activity where IPS >= 120 mph2/sec;

ACC.6 = proportion of activity where acceleration >= 6.0 mph/s;

DEC.2 = proportion of deceleration <= -2.0 mph/s;

finj2km1 = carburetor equipped vehicle with mileage < 25k miles;

finj2km2 = carburetor equipped vehicle with 25K, mileage <= 50k miles;

cat2km3 = "oxidation only" catalyst vehicle with 50k < mileage <= 100k miles;

cat3km2 = TWC vehicle with 25K mileage <= 50k miles;

cat3km3 = TWC vehicle with 50K < mileage <= 100k miles;

finj1km3flagnox = second order interaction variable for a high emitting vehicle with port fuel injection and 50k < mileage <= 100k miles; and

finj3km3flagnox = second order interaction variable for a high emitting vehicle with throttle body fuel injection and 50k < mileage <= 100k miles.

To use these modal algorithms, accurate input data must be provided. Two main types of data drive these emissions models: 1) modal activity data in the form of speed/acceleration profiles, and 2) vehicle characteristic data. It is possible to use default activity and vehicle data that would be representative of the fleet in general in conjunction with these models. However, this
research proposes to employ detailed activity data collected in the field as opposed to a
generalized study. Rather than using average speed/acceleration profiles and regional fleet data,
the research team collected specific vehicle characteristics and representative speed/acceleration
data from vehicles operating on freeway and freeway onramps. Hence, model inputs are based
upon the fleet and modal activity data present on the system.

3.4.1.2 Vehicle Speed/Acceleration Profiles

To generate speed/acceleration profiles for ramp and mainline flows, vehicle trajectories are
required. Previous Georgia Tech research assessed a variety of procedures for collecting
speed/acceleration profiles (Grant, 1997a; Grant, et al., 1998). In 1996 and 1997, researchers
assessed the capability of video data processing as a means of collecting accurate vehicle trace
data. The researchers determined video resolution limitations, coupled with vibration and
camera angle problems, and constrained acceleration data below the desired accuracy level for
modal emissions modeling. Hence, supplemental means were developed to collect vehicle trace
data. Two alternative approaches are typically employed: 1) laser rangefinders (LRFs) record
traces for a large subset of vehicles over a relatively short distance (1000 to 2000 linear feet), and
2) floating cars equipped with onboard instruments are introduced into the fleet to record traces
of a few vehicles over the entire monitored facility.

LRFs are field-proven and are effective in collecting speed/acceleration profiles. Thus, LRFs
were relied upon extensively to perform data collection for this analysis. However, floating cars
equipped with distance measuring equipment were also used to collect speed acceleration
profiles for some areas. Specifically, floating cars were utilized to collect data on mainline
sections and curved sections of onramps where use of laser rangefinders was not effective or
practical.

LRFs were used to capture the speed-acceleration profile of vehicles operating on onramps and
mainline segments. Laser Atlanta's Advantage LRFs were employed in the field study. The
Advantage LRFs integrate faster components and new software that significantly improved the
performance of these hand-held laser devices compared to those used in previous studies.
Accuracy is 0.5 foot with a precision of 0.1 foot. The LRF operates by recording a vehicle
location at a rate of 238 times per second, with speeds and accelerations of vehicles computed
based upon these distance measurements. Variables used by the Advantage are programmed
through a keypad on the rear face of the unit, thus not requiring a laptop computer and cables to
make modifications. In addition, portability is excellent with the battery unit in the handle of the
gun and lightweight casing materials.

Data from the Advantage laser gun can be sent to a computer hard drive via serial port interface
or written directly to an internal PCMCIA card (which inserts into the rear of the laser gun unit).
The serial port interface allows a transmission rate up to 115.2 kBaum. The extremely transfer
high rate, when compatible with the portable computer, allows storage of ASCII data directly to
a file. Another method of storage is a SRAM PCMCIA card, which stores all data, streamed to
the output port in null data files created on the card. In real-time range mode, when a trigger is
pulled all data are stored to the first available null data file on the PCMCIA card. A subsequent
pull of the trigger stores every range reading to a separate file on the PCMCIA card.
The LRFs were operated from tripods along the onramps and overpasses to record the full trace of onramp activity, from onramp entry to merging with freeway traffic. The geometry of two of the sites required setting one LRF at the beginning of the onramp and one LRF in the shoulder of the ramp near the ramp stop bar to capture the full activity of each vehicle from entrance on the ramp to freeway merge. Modal activity of freeway traffic along the merge areas, weave areas, and basic freeway sections was captured by locating LRFs along the overpass at several different locations. Details of the data collection locations are provided in Chapter 4.

Dual locations of the LRFs were necessary to record the speed and accelerations of vehicles as they entered the ramp and approached the stop bar, then as the vehicle left the ramp meter and merged with traffic. The core of this research is to verify if the “hard” accelerations that send a small number of vehicles into enrichment at the onramp may significantly reduce the emissions benefit received by “smoothing” traffic along the mainline freeway section. Therefore, the focus of the LRF data collection effort was to record information as vehicles accelerated from the stop bar down the ramp to the merge area. For this reason, the data collection procedures and analyses separated vehicle onramp activity into two zones. The acceleration zone (described above) and the deceleration zone, which is the length from the start of the onramp to the ramp meter stop bar location.

LRF field-testing revealed range limitations for tracking vehicle activity. The distance that automobiles can be tracked is limited by line-of-sight, obstructions such as light standards, trees, and signage, as well as interference from other traffic. Automobiles can be reliably tracked for 1000 to 1500 feet. The maximum distance at which the laser will “lock on” to an automobile is approximately 1500 feet, with the most consistent data collected at shorter distances. Data returned from trucks and larger vehicles are more reliable because of the large front or rear area they provide for computing ranges. Distance reliability is potentially more of a problem in heavy traffic when vehicles appear close together. The data collection efforts for this project required the use of seven LRFs to collect the necessary speed/acceleration profiles. The seven LRFs provided for concurrent coverage of the four onramp and mainline, ramp metering system.

To supplement flow measurements along the mainline, two instrumented floating vehicles captured the flow of traffic using car following techniques. The instrumented vehicles allow for speed-acceleration measurement of vehicle flow in areas where the LRF cannot measure due to observation location constraints. Onboard instrumentation has been used extensively as a means to measure speeds and accelerations of onroad vehicles. The instrumentation has been used to quantify the modal activity of a large random sample of vehicles along the road using a car-mounted laser rangefinder to compare relative change in speed to that of the instrumented vehicle (Austin, et al, 1993). Other distance measuring instruments have been used to measure speeds and accelerations of a floating car for energy consumption analysis (Eisele, et al., 1996). This research seeks to expand the existing data collected to evaluate the impact of the ramp metering on operations of vehicles along the onramps and mainline freeway segments through a combination of remote sensing and floating car data.

The research team equipped two floating cars with distance measuring instruments (DMI). A DMI is installed on the vehicle by attaching magnets and a magnetic pulse counter to the transmission of the vehicle. The DMI records the number of transaxle pulses and translates the pulses into distance traveled. Traveled distance is measured with precision to the nearest foot at
1 Hz. The accuracy of the equipment is as good as the calibration procedure, with precision to the nearest foot. Sampling of the distance traveled is completed by a BASIC program, which saves the distance the vehicle has traveled once per second.

The speed/acceleration traces acquired from both the instrumented vehicles and the LRFs were used to develop speed/acceleration profiles. These profiles were then used to summarize vehicle modal activity, assess variations in modal activity, and feed the modal activity equations in MEASURE.

The speed/acceleration data were transformed into a JASPROD, which is a three-dimensional (tri-variable) function of speed, acceleration, and the joint probability for a given speed-acceleration bin (Watson, et al, 1982). These JASPRODs are often referred to as Watson plots. An empirical JASPROD is created by sampling the simultaneous speed and acceleration trace of a vehicle along a specified path (or cycle), such as a vehicle's trajectory from the point of queuing to some point downstream. Data were processed in one-second intervals so the resulting JASPROD are for one-second intervals. Parsing the second-by-second vehicle activity into a matrix of speed-acceleration bins creates each JASPROD. Each bin has a unique speed and acceleration range. A JASPROD is shown in both matrix form and graphic form in Table 3-1 and Figure 3-1. The probability of activity occurring in a bin is calculated by dividing the bin frequency by the sum of all bin frequencies. For each given geometric and operational condition investigated, the frequency of activity in a specific speed-acceleration bin is the number of seconds of operation in a given bin divided by the total number of seconds of activity. The sum of all frequencies for a vehicle trace equals one.

The MEASURE Aggregate Modal Model employs fractions of vehicle activity under specific modal conditions which have been shown to correlate with emission rates (i.e. the percent of activity where acceleration >= 6.0 mph/s). Vehicle activity data can be directly linked to applicable emission rate equations. However, a method that links each JASPROD with the emission rates is more desirable, since response variables may change in the future depending on results of ongoing emission rate modeling. This way, the activity data collected in this study can be used with any future emission rate model that identifies critical modal variables, as well as for other types of analysis. For example, if a 3-dimensional activity distribution is available and future research identifies acceleration greater than 5 mph/s as significant, the total fraction of activity that falls within this range can be selected from the JASPROD.
### Table 3-1
Matrix Form of a Joint Acceleration-Speed Probability Density Function (JASPROD)

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<th>Acceleration (mph/sec)</th>
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### Figure 3-1
Graphical Form of a Joint Acceleration-Speed Probability Density Function (JASPROD)
3.4.1.3 Vehicle Characteristic Information

In addition to modal activity data, the MEASURE Aggregate Modal Model also requires vehicle fleet information. Emission rates are applicable to vehicle technology groups that are defined by such factors as model year range, fuel delivery technology, accrued vehicle mileage, and transmission type. Researchers collected vehicle license plate data to develop vehicle technology information. The capture of license plate data allows for the determination of the onroad vehicle composition at each ramp and on the mainline through a two-step process. License plate data were tied to vehicle identification numbers (VINs) in the Georgia Department of Revenue registration database. The VINs were decoded using proprietary software to develop the actual onroad distribution of various vehicle technologies. These technology distributions were then used to match with the vehicle characteristic variables present in the MEASURE model emissions algorithms. To protect privacy a double blind process was employed. Plate information was gathered, but can not be linked to individuals vehicles nor their owners names or addressees.

3.4.1.4 MEASURE Aggregate Modal Model analysis

As discussed above, vehicle technology and activity measures are combined with technology and modal-specific NOx emission rates to produce the estimates. The actual MEASURE Aggregate Modal Model analysis was performed on sets of binned vehicle modal activity data and not individual vehicle speed/acceleration traces. The data were binned and analyzed in 15-minute time slices by location and metered condition (i.e. ramp meters on or off). Each bin was then treated as independent data points for analysis and aggregated for summary purposes.

The emissions analysis was conducted at two levels. The first emissions analysis assessed changes in gram/second emissions rates under various operating and ramp metering conditions. The second emissions analysis examined the predicted mass emissions levels based on the emissions rates and the observed traffic volumes. Mass emissions are a function of gram/second emission rates multiplied by seconds of vehicle operation. Changes in travel demand result in changes in freeway and ramp volumes, changing mass emissions. Changes in average speeds also result in different mass emission levels, even if the emissions rates remain the same. That is, even if gram/second emission rates remain constant, mass emissions can increase when speeds drop, since vehicles spend more seconds of operation on then facility.

The emissions analysis considered variations from ramp location to ramp location, but the focus of the research was on the impact of the system on the local transportation corridor. Specifically, the analysis considered the impact of NOx emissions levels. The emissions estimates from the MEASURE Aggregate Modal Model are presented in Chapter 5.

3.4.2 MOBILE5b Emissions Analysis

Emissions estimates from the USEPA MOBILE5b model were produced and compared with the estimates from the MEASURE Aggregate Modal Model analysis. To the degree possible, the MOBILE5b emissions analysis conformed to the MEASURE procedures, so that easily comparable estimates were produced. The MOBILE models are intended for application to
vehicles in the aggregate over the course of a complete trip (USEPA, 1992). This is one of the fundamental problems with using the MOBILE model for the evaluation of TCMs or other transportation improvements that only impact a portion of a trip. Indeed, one purpose of comparing the MOBILE analysis results with MEASURE Aggregate Modal Model estimate is to identify the specific drawbacks associated with using the trip based emissions rates in MOBILE for TCM analyses. This notwithstanding, every effort was made to use the highest level of aggregation and averaging to produce the most appropriate estimates from MOBILE5b.

All assumptions regarding fleet mix, fleet age, inspection maintenance programs, and reformulated fuels were the same as those used by the Georgia Department of Environmental Quality for the Atlanta conformity analysis for the year 1999. The regional fleet characteristics were used in comparisons so that the standard MOBILE5b control file used in Atlanta analysis could be employed (The MOBILE5b control files used for this analysis are presented in Appendix B). The MEASURE Aggregate Modal Model emissions rates were estimated using the modal activity data collected with laser guns in the field. The average speed data required to run MOBILE5b were derived from the same modal activity data.

The analysis was stratified by day, time, and location to match the analysis bins used for the assessment of the modal activity and MEASURE Aggregate Modal Model analysis. This allowed for a direct comparison of emissions estimates under varying conditions and ramp configurations. The comparison of the two modeling methods focused on the mass emission estimates as well as the emissions rates. Because the MOBILE5b emissions rates are in grams per mile and MEASURE Aggregate Modal Model emissions rates are in grams per second, the MOBILE5b rates were converted to grams per second units so that the two could be directly compared. The model comparison and result of the analysis are presented in Chapter 5.

3.4.3 Assessment of Ramp Design and Prevailing Traffic Conditions

In addition to the emissions analysis, this research also attempted to assess and identify the specific conditions that lead to vehicle modal activity on freeway onramps that potentially lead to elevated emissions levels. It is not enough to simply assess the emissions impact without investigating the specific cause for the changes. This portion of the research was designed to assess the traffic flow conditions and ramp design parameters that may contribute to higher emissions. This analysis focused on the assessment of vehicle modal activity changes under ramp metering conditions. Relevant operating mode variables from the emission rate models serve as the response variables for the analysis (Table 3-2 provides the modal variables tested).
Table 3-2
Modal Activity Description Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACC3</td>
<td>Proportion of Activity with Acceleration $\geq$ 3.0 mph/s</td>
</tr>
<tr>
<td>ACC6</td>
<td>Proportion of Activity with Acceleration $\geq$ 6.0 mph/s</td>
</tr>
<tr>
<td>DEC2</td>
<td>Proportion of Activity with Deceleration $\leq$ -2.0 mph/s</td>
</tr>
<tr>
<td>ISP90</td>
<td>Proportion of Activity with IPS $\geq$ 90 mph$^2$/sec</td>
</tr>
<tr>
<td>ISP120</td>
<td>Proportion of Activity with IPS $\geq$ 120 mph$^2$/sec</td>
</tr>
<tr>
<td>AVESPEED</td>
<td>Average Vehicle Speed (mph)</td>
</tr>
</tbody>
</table>

Because the detailed statistical analysis performed for the development of the MEASURE Aggregate Modal Model algorithms has shown that these variables are related to vehicle emissions, they have been chosen for use in this analysis (Fomunung, 1999). Using a variety of variables as measures of change in modal activity allows for a complete assessment of activity variations.

Numerous factors potentially influence vehicle modal activity. This research identified many factors and based on their relation to freeway and onramp operations and the availability of data, chose several to function as the independent variables for this analysis. It was not practical to assess all factors that potentially influence modal activity; therefore, this analysis focused on variables that are related to the operation and installation of ramp meters (HCM, 1998). Specifically, these include mainline flow rates, and ramp design elements. Several different flow variables where chosen along with geometric design variables such as grade and acceleration distance. The independent variables used in this analysis are listed in Table 3-3.

Ramp meters are intended to allow for a smooth transition of vehicles between the arterial system and the freeway system. This transition is typically not problematic during light or uncongested traffic levels. Thus, ramp meters are not needed under these conditions. The use of ramp meters during uncongested traffic conditions results in delays to vehicles on the onramp with little or no benefit to the mainline traffic flow. Thus, DOTs typically reserve ramp meter operations for congested peak period conditions. It is during these conditions that gaps between vehicles decline and merging becomes more difficult. The critical factor in this is the prevailing mainline traffic conditions; therefore this research was concerned with how modal activity changes as traffic volume changes at the merge area. As the ability to merge becomes more difficult for drivers, vehicle acceleration behavior also changes. The goal is to isolate these changes and identify any consistent patterns that indicate when operating ramp meters significantly increases emissions. To accomplish this, several different traffic flow measures were also selected for analysis, see Table 3-3.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOS</td>
<td>Mainline Level of Service at Onramp Merge Area, (A,B,C,D,E, or F)</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>Mainline Flow Rate at Onramp Merge Area, (Passenger Car Equivalent per Lane per 15-min)</td>
</tr>
<tr>
<td>Lane 1&amp;2 Flow Rate</td>
<td>Mainline Flow Rate for Lane 1 and 2 Only, at Onramp Merge Area, (Passenger Car Equivalent per Lane per 15-min)</td>
</tr>
<tr>
<td>Forced Flow</td>
<td>Forced Flow/Free Flow Conditions on Mainline, (Forced Flow Defined as Average Mainline Speed Less than 50 mph)</td>
</tr>
<tr>
<td>Percent Trucks ramps</td>
<td>Percentage of Trucks in the Ramp Traffic Mix</td>
</tr>
<tr>
<td>Percent Trucks Mainline</td>
<td>Percentage of Truck in the Mainline Traffic Mix</td>
</tr>
<tr>
<td>Grade</td>
<td>Onramp Grade (Percent)</td>
</tr>
<tr>
<td>Acceleration Distribution</td>
<td>Onramp Acceleration Distance (Distance from Stop Bar to End of Gore)</td>
</tr>
<tr>
<td>Ramp Design</td>
<td>Onramp Configuration (Parclo or Diamond)</td>
</tr>
</tbody>
</table>

Using Level of Service (LOS) as a measure of traffic level allows varying flow rates to be classified in groups to simplify analysis. Conversely, using the actual flow rate allowed for the analysis with the traffic condition as a continuous variable. In addition, conditions were assessed as either free flow or forced flow, using probe vehicle speed to identify the conditions. It was anticipated that the observed mainline conditions might not provide a wide spectrum of LOS for a comprehensive analysis. Thus, a simplified classification focusing on the critical traffic breakdown condition was included. Researchers also speculated that vehicles merging from the ramps would be influenced most by the vehicles in the immediately adjacent traffic lanes. To test this, the flow for the first two traffic lanes was analyzed separately. For this analysis, all traffic flow measures were converted to passenger car equivalents. To assess traffic mix impacts on the onramp and mainline, truck percentages were evaluated for their impact on modal activity.

All of the other variables assessed for this analysis were related to the ramp geometric design. In addition to impact of traffic flow on modal activity, it was also assumed that the design of the onramp would have an influence (Sullivan, 1993). The design features considered most important were grade, acceleration distance, and interchange design. Grade was measured as percent, acceleration distance measured in feet from the ramp meter stop bar to the end of the gore, and ramp designs elements included two designs: diamond and partial cloverleaf (parclo).
Other factors such as weather conditions, pavement conditions, driver characteristics, and vehicle type also have a potential influence on modal activity. These factors were either held constant or were not included in analyses due to data limitations (analyses were limited to modal activity of passenger vehicles and the data collection was limited to dry daylight conditions). These data were also collected during the evening peak period when most activity is associated with work commute trips. Thus, the influences of external factors, such as those listed above, were assumed to minimized by the data collection criteria and analysis conditions.

3.4.3.1 Statistical Analysis

The relevant operating mode variables from the emission rate models served as the response variables for the statistical analysis. Each variable was tested for influence on modal variables using the t-test, allowing for hypotheses testing to determine if two observed sample means are likely from the same populations (Neter et al., 1996). For this research, the null hypothesis was that two sample populations were not likely from the same population. If the average proportion of activity greater than 3 mph/sec under forced flow conditions appears to be from a different population than under free flow conditions, the t-test indicates that forced flow conditions is a likely influence on modal activity. If this test were conducted at the 95 percent confidence level, the conclusion would be that the difference in the sample means would only occur from the same population five percent of the time. Thus, one could conclude that it is likely that the means are from separate populations, but it is not absolute. Nonetheless, this allows for reasonable conclusions about which variable influence modal activity on freeway onramps. The findings of the analysis of the modal activity using the t-test are presented in Chapter 5.

3.5 Research Limitations

The goal of this research is to provide conclusions regarding the potential air quality impacts of ramp metering systems through the collection and analysis of modal vehicle activity of a ramp metering system under metered and non-metered conditions. The approach presented in this chapter provides an original and innovative method for drawing conclusions about the impacts of ramp metering systems that significantly add to the current base of knowledge. This notwithstanding, there are some limitations within this research that should be considered.

First, the emissions estimates are the product of a modeling exercise. As with all modeling work, conclusions based upon model results are only as accurate as the models that are applied in the analyses. Modeling assumptions can limit the applicability of the models to specific problems and can affect the accuracy of model results. The MEASURE Aggregate Modal Model takes into consideration numerous factors that influence vehicle emissions rates. This model is a new tool developed for modeling vehicle emissions from a disaggregate perspective. Validation work indicates that the MEASURE Aggregate Modal Model provides more accurate exhaust emissions estimates for those light-duty vehicles that were included in the validation study (Fomunung, et al., 1999). MEASURE Aggregate Modal Model modeling results are compared with those of MOBILE5b before drawing conclusions. However, model validation work is ongoing. Significant model improvements may be forthcoming that could change the predicted emission rate impacts of metering. As they are developed, alternative model
formulations should be tested with the data that were collected in this study. One of the
tremendous advantages provided by the research was the comprehensive modal activity database
that can be used to examine the predictions of future emissions model formulations.

All efforts were made to gather accurate, comprehensive, and unbiased data. Indeed this has
been accomplished to the highest degree possible, but with the project time and resource
constraints, some gaps in the data did occur. Procedures were developed to account for missing
data or small sample sizes. Consequently, the confidence associated with some data subsets is
higher than for others. Where data limitations occur they are identified, accounted for in the
analysis, and noted during the presentation of results. The data are therefore presented in
varying levels of detail to provide for a comprehensive assessment of an aggregate level and a
detailed assessment where warranted.

Finally, this is an empirical assessment of the modal activity associated with a specific ramp
metering system in Atlanta over a two-month period. The intent is to provide a data set that can
be used to draw general conclusions about ramp metering systems. The transfer of the data and
conclusions to other areas should be conducted with caution. This system is the only ramp
metered freeway section in Atlanta and is not necessarily representative of the most congested
freeway sections in the city. Hence, even though the researchers conclude that ramp meter
implementation on corridors such as the one investigated provide no air quality benefit, there
may be other corridors in the city that could benefit from ramp meter implementation. This issue
is discussed in more detail later in the report.

Atlanta drivers have been noted to behave differently than those on other metropolitan areas
(Ross, et al., 1995). Variations in travel demand and driver behavior occur from region to region
and over time, potentially limiting the transferability of the conclusions presented in this report.
In brief, the research conducted in Atlanta provides significant methodological improvements
and data that can help researchers draw more universal conclusions about the air quality impacts
of ramp metering systems. The findings of the study should be used in conjunction with
additional data, as they become available. Nevertheless, the research results from the Atlanta
study provide important findings related to the implementation of ramp metering systems and
also provides useful procedures for evaluating other TCMs.

3.6 Contributions of Research

This work provides a detailed modal activity assessment and emissions impact analysis for the
Atlanta ramp metering system. The research also provides analytical methods that can be
applied to the evaluation of other TCMs. One goal was to develop a detailed and comprehensive
data set unlike any that has been collected in the past, providing new and meaningful
information. A second goal was to develop an underlying research methodology that contributes
to and improves upon current analysis procedures in this area. The research was designed to
improve on past ramp metering studies by examining a ramp meter system (ramps and
concurrent mainline activity). By utilizing a modal modeling approach, researchers were able to
examine the impact of ramp design and traffic conditions (LOS) on the vehicle modal activity,
emissions rates, and net system emissions.