MODAL VEHICLE ACTIVITY ON FREEWAYS AND FREEWAY ONRAMPS:
AN ASSESSMENT OF THE OXIDES OF NITROGEN EMISSIONS IMPACTS
RESULTING FROM CHANGES IN VEHICLE OPERATING MODE DUE TO
RAMP METERING SYSTEMS

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ACRONYMS

ATMS: Advanced Traffic Management System
CAAA: Clean Air Act Amendments
CARB: California Air Resource Board
CFR: Code of Federal Regulations
CMAQ: Congestion Mitigation and Air Quality Program
CO: Carbon Monoxide
CO₂: Carbon Dioxide
DMI: Distance Measuring Instrument
EGR: Exhaust Gas Recirculation
FHWA: Federal Highway Administration
FTP: Federal Test Procedure
GDOT: Georgia Department of Transportation
GIS: Geographic Information System
HC: Hydrocarbons
HONO: Nitric Acid
HUD: Heads-Up Display
IPS: Inertial Power Surrogate
ISTEA: The Intermodal Surface Transportation Efficiency Act of 1991
ITE: Institute of Transportation Engineers

ITS: Intelligent Transportation Systems

JASPROD: Joint Acceleration-Speed Probability Density Function

LDV: Light Duty Vehicle

LOS: Level of Service

LRF: Laser Rangefinders

MEASURE: Mobile Emission Assessment System for Urban and Regional Evaluation

MPO: Metropolitan Planning Organization

NAAQS: National Ambient Air Quality Standards

NCHRP: National Cooperative Highway Research Program

NMHC: Non-Methane Hydrocarbon

NO: Nitrogen Oxide

NOx: Oxides of Nitrogen

NO₂: Nitrogen Dioxide

O₃: Ozone

OH: Hydroxyl Radical

PARCLO: Partial Cloverleaf

PM: Particulate Matter

PPM: Parts Per Million

Pb: Lead

ROG: Reactive Organic Gas

SCAQMD: South Coast Air Quality Management District
SI: Spark Ignition
SIP: State Implementation Plan
SOx: Oxides of Sulfur
SUV: Sports Utility Vehicle
TCM: Transportation Control Measure
TEA-21: Transportation Equity Act for the 21st Century
TMC: Traffic Management Center
TTI: Texas Transportation Institute
USDOT: United States Department of Transportation
USEPA: United States Environmental Protection Agency
VOC: Volatile Organic Compounds
VIN: Vehicle Identification Number
VMT: Vehicle Miles Traveled
V/C: Volume to Capacity Ratio
SUMMARY

The Clean Air Act Amendments of 1990 and the most recent US Department of Transportation funding bill, the Transportation Equity Act for the 21st Century, signed in 1999, both contain provisions that encourage the use of transportation control measures (TCMs) to help reduce motor vehicle emissions. The primary goal of these provisions is to assist the attainment efforts of communities that do not comply with the National Ambient Air Quality Standards. One widely implemented class of TCMs throughout the US is traffic management strategies that improve traffic flow. In 1992, 36 percent of the Congestion Mitigation and Air Quality program funds were obligated to traffic flow improvement projects. Ramp metering systems are one type of traffic flow improvement strategy that is gaining popularity in many urban areas throughout the US.

This research analyzed the vehicle modal activity on freeway on-ramps and mainline sections under ramp metered and non-metered conditions. Under the premise that vehicle emissions are a function of modal activity (as well as vehicle parameters and operating environment), such as idle, cruise, and acceleration rates, this research used modal activity data, collected in the field to assess the air quality implications of ramp metering systems.
The Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) model was used to evaluate the air quality impacts of the Atlanta ramp metering system. The results produced from the MEASURE model were also compared with emissions estimates produced from the USEPAs MOBILE5b emissions rate model. The MOBILE5b model is an average speed model that is not sensitive to vehicle modal activity.

In addition to producing vehicle NOx emissions estimates, this research assessed the parameters that influence vehicle model activity on freeway on-ramps and in turn vehicle emissions. Roadway design, traffic volume, and metering plans were tested for their impact on modal activity. This information allowed for the development of ramp meter operation guidelines that will lead to metering systems that optimize operations and minimize air quality impacts.
CHAPTER I

1 INTRODUCTION

The Clean Air Act Amendments of 1990 (CAA Amendments) and the Transportation Equity Act for the 21st Century (TEA21), the US Department of Transportation (USDOT) funding bill signed in 1999, both contain provisions that encourage the use of transportation control measures (TCMs) to help reduce motor vehicle emissions. The primary goal of these provisions is to assist the attainment efforts of communities that do not comply with the National Ambient Air Quality Standards (NAAQS). One of the most widely implemented classes of TCMs throughout the US, in attainment areas and non-attainment alike, is traffic management strategies that improve traffic flow. In 1992, 36 percent of the Congestion Mitigation and Air Quality (CMAQ) program funds were obligated to traffic flow improvement projects, second only to transit related projects (FHWA, 1994). Freeway ramp metering is one type of traffic flow improvement strategy that is gaining popularity in many urban areas throughout the US.

A rapid increase in vehicle-miles of travel and congestion levels, coupled with limitations on construction of additional lanes to handle increased traffic demand, has increased the importance of ramp metering as a freeway traffic control. Ramp metering
is one of the most cost effective ways to alleviate freeway traffic congestion (Meyer, 1997). It can slow the flow of traffic onto a freeway to: 1) ensure that demand does not exceed freeway capacity, and 2) break up vehicle platoons (natural fluctuations in entering traffic streams) that impair optimal freeway flows. The balanced entry of vehicles reduces the potential for freeway traffic flow breakdown and thereby significantly reduces overall system delay. Thus, mainline travel time is significantly reduced by inducing small delays on the onramps. Freeway flow control is optimized through a system strategy: controlling entry at numerous ramps to stabilize the flow approaching critical network locations.

The CAA Amendments and TEA21 encourage the use of traffic flow improvements, such as ramp metering, as a means to improve air quality based on the fact that they mitigate traffic congestion. However, emissions from motor vehicles are not in direct proportion to traffic congestion and vehicle delay. Research has demonstrated that emissions are not a function of delay measures (e.g. average speed), as inferred by the current US Environmental Protection Agency (USEPA) MOBILE or the California Air Resources Board (CARB) EMFAC emission rate models, but rather a function of the modal operation of the vehicle (associated with speed/acceleration profile). As a result the current version of the USEPA model (MOBILE5b) does not produce accurate emissions estimates under certain applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). The MOBILE5b mode utilizes speed correction factors to adjust emissions, measured using the federal test procedure (FTP) to account for average speeds that are different form the average speed of the FTP drive cycle.
Although, the FTP drive cycle does not adequately represent the range of driving conditions encountered under most typical driving scenarios. To date, modeling techniques have not been capable of capturing off-cycle conditions and in turn unable to analyze the true air quality impacts of many traffic management strategies, including ramp metering systems. A modeling approach that takes into account the physical operating mode of the vehicle would provide a method for assessing the impacts of a ramp metering system.

When the USEPA MOBILE5b model is used to determine the air quality impacts of ramp metering systems, the results indicate a lowering of emissions levels (Sierra Research, 1997). As stated, the MOBILE models have been found to be inaccurate and under-predict emissions levels under many scenarios. Additional research has indicated that when vehicle operating mode is considered, emissions rates for vehicles operating on freeway onramps would possibly increase when ramp meters were in place (Sullivan, 1993). Recent findings indicate that this is the expected result, as a disproportionate amount of emissions occur under limited levels of modal activity, such as load induced enrichment, i.e. low air/fuel ratios (LeBlanc, et al., 1994). That is, a large amount of vehicle emissions, particularly carbon monoxide and hydrocarbons, are a result of a small amount of vehicle activity. Studies have shown that roadway gradient (i.e. an acceleration against gravity) can increase emissions more than ten fold and one sharp acceleration may cause as much pollution as the remaining portion of a trip (Cicero-Fernandez and Long, 1995; Kelly et al., 1993). Indeed, vehicle acceleration to freeway speed after stopping at a ramp meter would be a likely scenario for high power demand
and enrichment conditions. What is not known is precisely to what level on ramp emissions are elevated and what the modal activity and related emissions impact would be for vehicles operating on the freeway mainline. Also, it is not known what ramp design factors (i.e. geometric design, grade, acceleration distance) and what mainline flow conditions influence the most significant changes in emissions rates. This research utilized a physical emissions modeling approach to answer these questions.

Over the past several years the Georgia Institute of Technology has been developing a modal emissions model that associates vehicle emissions with certain types of engine and vehicle modal operation (i.e. cruise, acceleration, deceleration, idle, and power demand) rather than average speed. The Mobile Emissions Assessment System of Urban and Regional Evaluation (MEASURE) is a statistically based model that replaces the drive cycle with disaggregate vehicle operating mode distributions. Since this model is sensitive to changes in vehicle modal activity, similar to those that would be expected with the implementation of a ramp metering system, it was the basis for evaluating the emissions impacts of the Atlanta ramp metering systems. This research provides a comprehensive evaluation of the air quality impacts of ramp metering through the assessment of the modal activity associated with the introduction of a ramp metering system. Given the findings regarding the importance of vehicle operating mode on emissions, it is important to assess how the introduction of ramp meters will change the operations of vehicles, both along the ramps and along the freeway segment. The case study for this research was the Atlanta ramp metering system.
In conjunction with installation of the Atlanta Advance Traffic Management System (ATMS), five ramp meters were installed along the northbound corridor of Interstate 75 in metropolitan Atlanta. The existing ramps were retrofitted with variable interval meters to control flow of traffic onto the freeway mainline. The ramp meters are only located on the northbound direction for five consecutive interchanges, Northside Drive, Howell Mill Road, Moores Mill Road, West Paces Ferry Road, and Mount Paran Road. Each interchange offers a unique geometry that has the potential to affect the vehicle activity of the merging traffic, and impact the response of the vehicles operating along the corridor.

This research focuses on the collection of vehicle activity data from the existing onramps and mainline facility, analyze the modal operation (speed/acceleration profiles) of vehicles along the corridor, and estimate the emissions for the metered system. Video equipment, traffic counters, laser rangefinders, and floating cars equipped with distance measuring instruments were employed to collect activity and speed/acceleration profiles on the freeway and metered ramps. Approximately four hours of data was collected during each field study, and 18 studies were conducted over a period of three months.

The goal of the research was to quantify the impact of the Atlanta ramp meter operations on facility emissions using the MEASURE and MOBILE5b emission rate modeling functions. Also, identify the advantages and disadvantages of each emission rate modeling approach and the level of data collection refinement necessary to develop future system predictions. A significant portion of this research included the assessment of how varying mainline congestion levels and flow rates influence on ramp emissions.
rates. The results of the congestion and air quality analyses were used to identify the
design parameters that significantly impact the emissions from the metered system. The
final recommendations include optimum strategies for the installation of ramp metering
that balance average mainline speed increases and vehicle emissions reductions.

The following Chapter provides a discussion of the background of this research
including a review of air pollution issues, motor vehicle emissions, and air quality and
emissions rate modeling. The research approach is presented in chapter Three. This will
includes a discussion of the research hypothesis and objectives, in addition to the
proposed experimental design. Chapter Four provides information regarding the research
procedures—focusing on the data collection process and field deployment, site
descriptions, and data analysis methods. The research findings and results are presented
in Chapter Five. The final Chapter, Six includes the research conclusions and final
recommendations.
CHAPTER II

2 BACKGROUND

Over the past thirty years since the signing of the Clean Air Act (CAA) in 1970, great strides have been made in reducing the level of air pollution from automobiles and factories. Despite improvement made by industry, air quality problems still persists today in almost every metropolitan area in the country—174 urban areas in total. One of the primary contributors to this condition is emissions from mobile sources, such as trucks and automobiles. Despite considerable improvements in vehicle emissions control, mobile sources still account for a significant portion of urban air pollution (USEPA, 1996). Even though individual vehicles emit fewer pollutants from the tailpipe with each model year, the total emissions are still increasing due to increases in vehicle activity and ownership. With each passing year there are more vehicles, driving more miles, contributing to our current air pollution problem in US cities.

The CAA Amendments of 1990 have strengthened the air pollution legislation through more stringent tailpipe standards and rules for metropolitan areas developing transportation and air quality plans. One portion of the legislation encourages the use of transportation control measures (TCMs) as a means to help mitigate air pollution resulting from mobile sources. TCMs are transportation improvements or programs that
result in a decrease in pollution levels through vehicle trip reductions, transportation system efficiency improvement, vehicle inspection programs, higher vehicle occupancy, mode shift to transit, or the use of less polluting alternative fuels. This includes transit improvements, travel demand management strategies, public fleet conversion to clean fuels, and traffic flow improvements. Included within the latter category is freeway ramp metering.

To help encourage the implementation of ramp metering and other TCMs, the US Department of Transportation (USDOT) has included specific funding provisions for TCMs in the last two federal transportation bills. The Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 and the Transportation Equity Act for the 21st Century (TEA-21) both contained Congestion Mitigation and Air Quality (CMAQ) programs. The CMAQ program specifically sets aside federal transportation funds for air quality friendly transportation improvements, such as ramp metering systems. The current legislation, TEA-21 has earmarked 8.1 billion dollars for the CMAQ program over the next six years (FHWA, 1999). The question is, whether or not appropriate strategies are being selected under this policy considering the uncertainty associated with the air quality impacts of many TCMs.

2.1 Air Quality Standards and Criteria Pollutants

Under the CAA Amendments of 1990, the US Environmental Protection Agency (USEPA) promulgates air pollution standards for six criteria pollutants. The intent of the National Ambient Air Quality Standards (NAAQS) is to establish protection of public health and welfare. The six criteria pollutants are oxides of nitrogen (NOx), oxides of
sulfur (SOx), carbon monoxide (CO), particulate matter smaller than 2.5 microns (PM), lead (Pb), and tropospheric ozone. The NAAQS establish a primary and secondary standard for most of the six criteria pollutants. In 1995 approximately 80 million people in the US lived in areas that did not meet at least one of the NAAQS (USEPA, 1996).

Under the CAA Amendments the USEPA is required to review and update the NAAQS every five years. The current NAAQS are shown in the following Table 2-1.

Table 2-1, NAAQS Primary and Secondary Standards (40 CFR 50)

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Primary</th>
<th>Secondary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type of Average</td>
<td>Standard</td>
</tr>
<tr>
<td>CO</td>
<td>8-hour</td>
<td>9 ppm</td>
</tr>
<tr>
<td></td>
<td>1-hour</td>
<td>35 ppm</td>
</tr>
<tr>
<td>Pb</td>
<td>Maximum quarterly average</td>
<td>1.5 µg/m^3</td>
</tr>
<tr>
<td>NO₂</td>
<td>Annual arithmetic mean</td>
<td>0.053 µg/m^3</td>
</tr>
<tr>
<td>O₃</td>
<td>1-hour average</td>
<td>0.12 ppm</td>
</tr>
<tr>
<td></td>
<td>8-hour average</td>
<td>0.08 ppm</td>
</tr>
<tr>
<td>PM-10</td>
<td>Annual arithmetic mean</td>
<td>50 µg/m^3</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>150 µg/m^3</td>
</tr>
<tr>
<td>PM-2.5</td>
<td>Annual arithmetic mean</td>
<td>15 µg/m^3</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>65 µg/m^3</td>
</tr>
<tr>
<td>SO₂</td>
<td>Annual arithmetic mean</td>
<td>0.03 ppm</td>
</tr>
<tr>
<td></td>
<td>24-hour</td>
<td>0.14 ppm</td>
</tr>
</tbody>
</table>

¹ Only for areas designated nonattainment before adoption of 8-hour standard in July 1997
2.1.1 Oxides of Nitrogen

NOx compounds, such NO, NO\textsubscript{2}, and NO\textsubscript{3} are the result of the combustion process. Nitrogen is often bound to combustion fuels and the ambient air is composed of 79 percent nitrogen, therefore NOx compounds are an unavoidable result of the combustion process. Details of why this occurs are provided in the discussion of combustion in the following section.

Ten percent of the NOx compounds resulting from combustion are NO\textsubscript{2}, and the NO\textsubscript{2} concentration is what the NAAQS for NOx is based. Brownish in color with a pungent smell, NO\textsubscript{2} is one of the primary contributors to visible urban haze and brown smog. Relative to other criteria pollutants NO\textsubscript{2} is not considered a health risk, although in high concentrations it can result in damage to cells in the respiratory tract (SCAQMD, 1997). Currently there is not a single area in the US that is in violation of the NO\textsubscript{2} standard (USEPA, 1999). Ninety percent of the NOx compounds resulting from combustion are in the form of nitric oxide (NO). In the presence of sunlight and other combustion byproducts such as volatile organic compounds (VOCs), NO will contribute to the formation of tropospheric ozone. That is, NO and other NOx compounds are not serious pollution problems in and of themselves, but are precursors to more hazardous ozone formation. It is estimated that approximately 50-70 percent of NOx emissions result from motor vehicles, with the residual resulting from electric utilities and industrial boilers.
2.1.2  Oxides of Sulfur

Formed by the oxidation of elemental sulfur in fuel, SOx is a colorless gas with a distinct odor, and is also the result of combustion. SOx is not a serious automobile pollutant since sulfur levels in gasoline and diesel fuels are highly regulated. The primary sources of SOx pollution are from industry and power plants that use coal with a high content of sulfur.

2.1.3  Carbon Monoxide

A colorless and odorless gas, CO is the result of incomplete combustion of hydrocarbons. It is primarily a localized pollution concern or what is referred to as a ‘hot spot’ problem. This is due to the fact that it disperses well and will not typically have time to accumulate at ground level. An exception to this is at high elevation or during cool weather conditions that occur during winter months. Almost all CO air pollution (i.e. 90 percent), is the result of automobile tailpipe emissions (USEPA, 1997).

When CO does accumulate in high concentrations it is a deadly pollutant. When inhaled it interferes with the oxygen carrying capacity of the blood, which results in drowsiness, headaches, and impairment. At high concentrations CO poisoning can be fatal, although such conditions do not typically occur in ambient air (SCAQMD, 1997).

2.1.4  Particulate Matter

Solid or liquid particles composed of smoke, ash, pollen, or chemical droplets, particulate matter becomes an air pollutant when it is small enough to stay suspended for
prolonged periods. Particulate matter can be a hazard by itself or act as a carrier for other air toxins. It also contributes significantly to visibility degradation.

Combustion is the primary source of direct particulate matter, producing particles that range from .01 to 10 microns in diameter. Automobile and other on-road combustion accounts for approximately one quarter of all direct particulate matter with the remainder coming from stationary sources (USEPA, 1997). Particulate matter can also result from fugitive sources such as agricultural activity, construction sites, road dust, and naturally occurring wind erosion.

As can be seen in Table 2-1, there are two standards for particulate matter, one for particles less than 10 microns in diameter (PM$_{10}$) and one for particles less than 2.5 microns in diameter (PM$_{2.5}$). Large particles can cause scaring of lung tissue and aggravate respiratory and heart problems, while fine particles less than 2.5 microns can enter the blood stream and lead to more serious health problems and premature death. As with most air pollution, health problems are accentuated for the young, elderly, and those with respiratory problems such as asthma (Wilson and Suh, 1997).

2.1.5 Lead

Added to automobile fuel as an anti-knocking compound and performance-enhancing agent, lead enters the air carried on combustion particulates. Lead is a toxic heavy metal that, when air-born, can enter the lungs and bloodstream and result in brain and nervous system damage. This is particularly a problem for developing individuals. Starting in 1978 lead additives to fuel were phased out and are not allowed in gasoline. As a result, lead air pollution from automobile sources, has been virtually eliminated.
2.1.6 Ozone

Ozone (O$_3$) is a serious air pollution problem when it accumulates at the ground level. Unlike stratospheric O$_3$, which provides protection from ultra-violet rays from the sun, ground level or tropospheric O$_3$, can damage lung tissue and reduce lung capacity. Tropospheric O$_3$ is the primary component of urban smog. When exposed to O$_3$ for six to seven hours, even at relatively low concentrations, it has been found that lung function is significantly reduced in normal, healthy individuals during moderate exercise. The current air quality standard for O$_3$ is 0.12 ppm one-hour maximum concentration over a twenty-four hour period. Many health studies have indicated that negative effect of O$_3$ can occur at lower concentration if exposure is for an extended period of time (USEPA, 1996). In light of this the USEPA has recommended an additional O$_3$ standard of 0.08 ppm maximum 8-hour concentration over a twenty-four hour period (62 CFR 138). This new standard promulgated in 1997 is currently being challenged in court and was not in effect at the time of this research.

Unlike the other five criteria pollutants O$_3$ is not emitted directly into the air by specific sources. It is formed when NOx compounds and VOCs react with sunlight in the lower layers of the atmosphere. These precursors to O$_3$ can be the product of numerous sources. As discussed NOx compounds are the result of combustion. VOCs in the form of hydrocarbons can also be the result of combustion as well as other industrial processes and natural sources. Often these precursors will be emitted in one area and transported in the atmosphere for miles before reacting to form O$_3$. As a result, high O$_3$ concentrations
can occur over areas that are distant from the precursor source and in areas low in air pollution emissions.

2.1.6.1 Volatile Organic Compound Emissions

VOCs in the form of reactive hydrocarbons are one of the primary contributors to the formation of ground level O$_3$. VOCs are emitted as many different forms of hydrocarbons, but do not include methane and other non-reactive compounds. Some of the more reactive and problematic VOCs include ethylene, acetylene, ethane, propylene, and even toxic compounds such as benzene. There are numerous sources of VOCs including solvents and other industrial processes, waste disposal, evaporation and incomplete combustion of motor vehicle fuels, and natural sources. In some areas, forest canopies can contribute up to 50 percent of the VOC emissions in the form of isoprenes.

2.1.6.2 Meteorology and Atmospheric Photochemical Reactions

When VOCs mix in the lower layers of the atmosphere with NOx compounds in the presence of sunlight, O$_3$ is formed. The resulting concentration of O$_3$ is a complex function of weather conditions and precursor emissions. As a result O3 pollution levels are very difficult to predict and control.

Under many different conditions trace species of O$_3$ are created and destroyed in the atmosphere. When NOx compounds are present in the atmosphere, O$_3$ is created as a result of the photolysis of the NO$_2$ molecule (Seinfeld, 1998). Photolysis is the process of atoms being disassociated under the sun’s energy ($hv$). This is illustrated in the following reactions:
NO\textsubscript{2} + hv $\rightarrow$ NO + O \hspace{1cm} (2.1)

O + O\textsubscript{2} $\rightarrow$ O\textsubscript{3} \hspace{1cm} (2.2)

The result of this process does not lead to the accumulation of O\textsubscript{3} as it is converted back to NO\textsubscript{2} as quickly as it is formed, by reacting with NO in the atmosphere. That is, O\textsubscript{3} is stabilized when O\textsubscript{2} or N\textsubscript{2} absorb the excess vibrational energy. When VOCs are present, O\textsubscript{3} concentrations are allowed to accumulate. The hydroxyl radical (OH) is the key reactive species in the chemistry of O\textsubscript{3} formation. The OH radical is formed through a photolysis process of nitrous acid (HONO) similar to that illustrated above for NO\textsubscript{x}. Since the OH radical does not react with most constituents common to earth’s atmosphere, such as N\textsubscript{2}, O\textsubscript{2}, H\textsubscript{2}O, or CO\textsubscript{2}, it typically present as a trace species. The OH radical is highly reactive with VOCs and as a result initiates a chemical reaction that results in the accumulation of O\textsubscript{3}. The reaction mechanism of the VOC does not lead directly to the formation of O\textsubscript{3}, but allows it to occur. During the reaction mechanism of assorted hydrocarbons, NO resulting from the photolysis of NO\textsubscript{2} is converted directly back to NO\textsubscript{2}. For some hydrocarbons, such as alkanes, this process can happen several times during a reaction mechanism. When NO reacts to form NO\textsubscript{2} through an alternate process than the photolysis of O\textsubscript{3}, the net result is an increased accumulation of O\textsubscript{3}. That is, since NO is not available to react with oxygen atoms they combine with the available O\textsubscript{2} atoms to react back to O\textsubscript{3}. The specific detailing of all of these hydrocarbon reaction mechanisms is beyond the scope of this research. However, an appreciation of the
The general process is critical to the understanding of the complexity of the urban air pollution problem.

The OH radical will also react directly with NOx and therefore the formation of O₃ is a result of a competition between VOCs and NOx compounds. The OH radical will tend to react with the NOx compound before trace hydrocarbon species. The VOC to NOx ratio needs to be on the order of 5:1 before the OH radical will react with the available VOCs. As a result, if the VOC concentrations are not high enough relative to the NOx levels, the NOx will react with the available radicals, scavenging them from the VOC compounds, and under certain conditions, result in a decrease in O₃ concentrations. The highest O₃ concentrations occur when the VOCs and NOx levels are increased, while the 5:1 VOC to NOx ratio is maintained. The following O₃ isopleth Figure 2-1 illustrates this by showing the expected O₃ concentration relative to the VOC and NOx concentrations. It also reveals how a decrease in NOx concentrations can lead to an increase in O₃ concentrations. This occurs when VOC are in small abundance leading to a higher VOC to NOx ratio.
As a result of the complexity of O$_3$ formation, O$_3$ pollution is a problem that is widely reaching and difficult to control. Although VOCs are not a criteria pollutant, they are an important player in the formation of O$_3$. It is therefore just as important to monitor and control VOC emissions as it is other criteria pollutants. This is particularly important in urban areas where motor vehicles can contribute up to 27 percent of the total VOC emissions.
2.2 Motor Vehicle Emissions

Motor vehicle emissions contribute to four of the six criteria pollutants, CO, NO₂, PM, and O₃, as well as O₃ precursors (i.e. VOCs). Of these four pollutants motor vehicle emissions compose significant portion of the pollution, 70-90 percent of CO emissions, 30-50 percent of NO₂ emissions, and 15 percent of PM emissions result from motor vehicles. Apart from hydrocarbon emissions due to refueling and evaporation, all of the motor vehicle related pollution is the result of combustion. In an effort to control vehicle emissions, the CAA Amendments require that new vehicle meet tailpipe emissions standards established by the USEPA. Automobile manufacturers are required to control the emissions of VOCs (i.e. non-methane hydrocarbons (NMHC) or reactive organic gases (ROG)), CO, NOₓ, and PM. Manufacturers are also responsible for developing emissions control systems that are durable for the full life of a vehicle. That is, the USEPA has established standards for new vehicles and in-use vehicles, at 50,000 and 100,000 accumulated miles (USEPA, 1998). The exhaust emissions standards that vehicles are certified against are based on the Federal Test Procedure (FTP) drive cycle and measured in grams per mile for HC and each of the criteria pollutants. The FTP procedure and its development will be discussed in detail in section 2.3.

Although the tailpipe emissions standards have been in place since the passage of the original CAA in 1970, the 1990 amendments included stricter standards. These new emissions certification standards are referred to as Tier 1 and Tier 2 standards. The original standards are referred to as Tier 0 standards. Tier 1 standards were put into effect through USEPA rule making in 1994 with 100 percent of the new vehicles
reaching the standard to date, and the tier 2 standards taking effect in the year 2000 with all new vehicles reaching the standard by 2002 (40 CFR). The following Table 2-2 shows the in use tailpipe standards for Tier 0 and Tier 1 vehicles (40 CFR, 86).

### Table 2-2, Federal Exhaust Emission Certification Standards (grams/mile)

<table>
<thead>
<tr>
<th>Type</th>
<th>Cat.</th>
<th>THC</th>
<th>NMHC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
<th>THC</th>
<th>NMHC</th>
<th>CO</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDV</td>
<td>Tier 0</td>
<td>0.41</td>
<td>0.34</td>
<td>3.4</td>
<td>1</td>
<td>0.2</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>0.41</td>
<td>0.25</td>
<td>3.4</td>
<td>0.4</td>
<td>0.08</td>
<td>-</td>
<td>0.31</td>
<td>4.2</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>LDT1</td>
<td>Tier 0</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.8</td>
<td>0.67</td>
<td>10</td>
<td>1.2</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>-</td>
<td>0.25</td>
<td>3.4</td>
<td>0.4</td>
<td>0.08</td>
<td>0.8</td>
<td>0.31</td>
<td>4.2</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>LDT2</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.8</td>
<td>0.67</td>
<td>10</td>
<td>1.7</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>-</td>
<td>0.32</td>
<td>4.4</td>
<td>0.7</td>
<td>0.08</td>
<td>0.8</td>
<td>0.4</td>
<td>5.5</td>
<td>0.97</td>
<td>0.1</td>
</tr>
<tr>
<td>LDT3</td>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.8</td>
<td>0.67</td>
<td>10</td>
<td>1.7</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>-</td>
<td>0.32</td>
<td>4.4</td>
<td>0.7</td>
<td>-</td>
<td>0.8</td>
<td>0.46</td>
<td>6.4</td>
<td>0.97</td>
<td>0.1</td>
</tr>
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<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>0.8</td>
<td>0.67</td>
<td>10</td>
<td>1.7</td>
<td>0.13</td>
</tr>
<tr>
<td></td>
<td>Tier 1</td>
<td>-</td>
<td>0.39</td>
<td>5</td>
<td>1.1</td>
<td>-</td>
<td>0.8</td>
<td>0.56</td>
<td>7.3</td>
<td>1.53</td>
<td>0.1</td>
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</tbody>
</table>

Tailpipe standards have contributed significantly to the reduction of motor vehicle pollution. Since the introduction of tailpipe standards in 1970, per mile vehicle emissions have declined 69 percent for CO, 53 percent for NOx, 78 percent for VOCs, and 69 percent for PM10 (Davis, 1997). In addition, the CAA Amendments also contain provisions to reduce motor vehicle related emissions through vehicle inspection and maintenance (IM) programs for in-use vehicles to ensure that they maintain acceptable emissions levels. Fuel transfer technology, fuel additives (e.g. oxygenates), and fuel quality standards are also mandated to help reduce mobile source emissions.
Despite this on-road emissions are still are serious problem due to the increase in vehicle travel. From 1970 to 1995 the vehicle miles of travel (VMT) in the US increased by 118 percent. Since vehicles being currently produced are 70–90 percent cleaner than they were 30 years ago. Although there is still significant room for more technological improvements, future reductions in mobile source emissions will need to come from changes in travel behavior and activity as well as other changes in vehicle technology that accommodate alternative energy sources. Due to their relation to combustion and the associate health concerns this research focuses on VOCs (primarily NMHC) and two criteria pollutants, CO and NOx. More over PM is also of great concern due to its health impacts and emissions uncertainty.

2.2.1 Combustion

Until alternate technology is in place, the internal combustion engine will be the primary means for powering motor transportation for the near term, as it has been for the last 100 years. Apart from evaporative HC emissions, pollution from motor vehicles is the result of fuel combustion. Combustion is the process of converting chemical energy into mechanical energy or force that is used to power transportation vehicles. The basic combustion process consists of the oxidation of a fuel to create heat and other byproducts. The majority of highway vehicles utilize gasoline as the combustion fuel, although diesel fuel is also used for a significant portion of the total fleet, particularly heavy trucks. This notwithstanding, gasoline is still the primary fuel for light-duty vehicles (LDV). Therefore, the following discussion will focus on the emissions impacts of gasoline spark ignition (SI) engines.
Since the combustion process is not always carried to completion and since it does not take place in pure oxygen, byproducts secondary to CO$_2$ and H$_2$O result. These include aldehydes, ammonia, lead, sulfur oxides, NOx, CO, and HCs. The later three being the most important due to their quantities and the fact that they are criteria pollutants or criteria pollutant precursors.

NOx is formed as a result of the nitrogen present in the air used in the combustion process. The oxygen used in the process comes from the ambient air, which is composed of 20 percent oxygen and 79 percent nitrogen. This nitrogen and the nitrogen often bound in the fuel can result in the presence of NOx in the combustion exhaust under certain high temperature and pressure conditions. It is the high the temperature and pressure conditions that drive the NOx exhaust formation rate and magnitude. In addition if the combustion process is not carried to completion CO and HC emissions can result. That is, if the CO is not be fully oxidized to CO$_2$ and not all of the fuel is not burnt, undesirable byproducts will be produced. Complete combustion is favored by excess air and high temperatures, which will reduce CO and HC emissions but run counter to the control of NOx emissions. The critical component in the combustion process for determining the level of motor vehicle emissions control is the air/fuel ratio in the combustion chamber (Heywood, 1988).

2.2.1.1 Air Fuel Ratio

When an exact balance between the fuel and the air needed to oxidize the fuel exists during combustion it is referred to as stoichiometric. The stoichiometric ratio for most spark ignition engines is near 14.7:1. The optimum air/fuel ratio is a trade off between
efficiency, optimum power, and pollution formation. If the engine has a need for increased power for acceleration or to climb a hill, more fuel will be introduced into the cylinder and the air/fuel mix will be rich. When the air/fuel mix is highly rich there is not enough oxygen present to chemically convert the HC in the gasoline to CO₂ and H₂O. Hence, CO and unburned HC increase dramatically when the air/fuel mixture is rich. For smooth operation and to ensure reliable performance most spark ignition engines operate slightly fuel rich (i.e. 12.5:1). The result of this operation optimizes the engine power, but slightly compromises fuel efficiency. The following Figure 2-2 shows this relationship, where power measured as torque is highest when the air/fuel ratio is slightly rich, while the specific fuel consumption is lowest when the air/fuel ratio is slightly lean (Bosh, 1996). As can be seen in this same figure the NOx emissions concentrations are highest just lean of stoichiometric levels and CO and HC emissions are lowest at this level and increases as the air/fuel ratio becomes richer or excessively lean. NOx levels are low under rich mixtures due to the low combustion temperatures and lack of oxygen available to bond with nitrogen to form NO and NO₂. If the air/fuel ratio becomes too lean engine misfire will occur and high concentrations of CO and HC emissions will result. An engine operating slightly lean will yield low CO and HC concentrations until misfire occurs. In addition, under cold operation when a vehicle is first started and the fuel vaporization level is low, the fuel flow is increased to provide an easily combustible rich air/fuel mix. The inefficient combustion that occurs during such cold mode operation also results in elevated CO and HC concentrations. The critical factor is that air/fuel
rations that result in lower levels of CO and HC concentrations run counter to the level of
NOx concentrations (Heywood, 1988).

**Figure 2-2, Power Output, Emissions, Fuel Consumption, and Air/Fuel Relationship**

When increased concentrations of NOx, CO, and HC are present in the combustion chamber after the ignition stroke, these compounds become part of the combustion exhaust and can exit the system as tailpipe pollutants. The air/fuel ratio conditions that result in these pollutants, particularly CO and HC, only occur during a small portion of activity that comprises a typical vehicle trip. As stated, air/fuel ratios are rich during cold operations resulting in higher CO and HC levels. In addition, fuel rich combustion mixtures will also occur during high power demand such as during rapid acceleration or
grade climbing, and negative power demand, such as during deceleration activity (Kelly and Grolicki, 1993; Cicero-Fernandez et al. 1997). During the majority of a typical trip a vehicle engine is warm and operation at gradual acceleration and deceleration rates or cruising at a constant speed. The length of a trip, the type of road traveled (e.g. arterial or freeway), and the congestion level will contribute to the percent of a given trip spent in enriched operation. Since the introduction of vehicle emissions certification standards in 1970 automobile manufacturers have been continually improving engine technology in an effort to balance vehicle performance with exhaust emissions. The basic principals of the internal combustion engine used by most passenger vehicles has not changed over the last 100 years, yet numerous advancements have continued to occur. The past 10 years have brought more advancement in engine technology than the previous 90 years. With the innovation of lightweight materials, synthetic lubricants, and onboard computer controls today’s automotive manufactures can produce engines with better performance, emissions control, and fuel economy than in years past (Guensler, 2000).

2.2.1.2 Vehicle Emissions Control

The high performance motor vehicles produced by today’s manufacturers have allowed for a rapid increase in vehicle ownership and travel over the last 20 years, without comparable increases in vehicle emissions. There are five primary technological areas of emissions control in most spark ignition engines that have allowed the above condition to occur. These consist of evaporative controls, crankcase controls, exhaust gas recirculation, exhaust gas after treatment, and onboard computer engine controls and diagnostics (Jacobs, 1990).
Although not directly related to the combustion process, evaporative controls are highly important for reducing HC emissions. Unlike exhaust emissions, evaporative emissions can occur during vehicle operation, as well as after operation, during refueling, and during storage. Evaporative emissions controls are primarily comprised of sealed gasoline filler caps, sealed fuel lines, and modified fuel tanks.

Crankcase emissions are caused by HCs, which bypass the cylinder piston and rings and enter the crankcase and potentially the ambient air. Crankcase emissions are controlled by a ventilation system that captures the ‘blowby’ HCs and recirculates them back into the cylinder to be reburned (Jacobs, 1990).

Evaporative and crankcase emissions controls are both aimed at limiting HC emissions. Exhaust gas recirculation (EGR) systems are intended to reduce NOx emissions levels. The EGR system operates by recirculating exhaust gas back into the cylinder intake manifold with the net effect of reducing the peak combustion temperature. Since NOx formation is increased under high temperatures, the result is a decrease in NOx formation. Although a secondary effect of diluting the intake mixture is to compromise the combustion quality and the engine efficiency (Heywood, 1988).

Exhaust gas after treatment consists of the use of catalytic converters to reduce CO, HC, and NOx tailpipe emissions. There are two types of catalytic converters found in vehicles in the current fleet. They consist of the oxidation catalyst and oxidation/reduction catalyst, also known as the three-way catalyst. In an oxidation catalytic converter the exhaust gas passes through a substrate in the exhaust system that is coated with small amounts of an active catalyst (i.e. noble metals of platinum (Pt) and
palladium (Pd)). In a high temperature environment these metals oxidize the HC and CO compounds in the exhaust. The high temperature requirements result in ineffective operation during cold start conditions. The three-way catalytic converters work the same way, but also reduces the NOx exhaust gases to \( \text{N}_2 \) and \( \text{O}_2 \). It should be noted that the catalytic converter performance is optimized during stoichiometric combustion with an air fuel ratio of 14.7:1. If the mix is rich, the conversion of CO and HC is reduced, while a lean mix limits the reduction of NOx (Guensler, 2000). Thus, stoichiometric combustion is desired despite the fact that NOx emissions from combustion are typically higher as shown in Figure 2-2.

Onboard computer engine control and diagnostics are the final emissions control technology found in today’s motor vehicles. Modern vehicles are equipped with numerous sensors and actuators that are under computer or electronic control. These systems monitor and adjust numerous engine operating parameters that are important to the level of exhaust emissions. For example ignition timing, fuel injection, engine temperature, exhaust oxygen concentration, air/fuel ratio, and manifold pressure are all controlled by precise computer systems in a modern vehicle. As a result the engine is able to operate more efficiently and will operate in enriched modes less frequently even under high levels of power demands (Jacobs, 1990). As stated, despite these controls motor vehicles still account for a large portion of air pollution in urban areas. In turn, it is important to understand physical properties of motor activity that override emissions control and lead to rich air/fuel mixtures and potentially elevated emissions levels.
2.2.2 Vehicle Acceleration and Power Demand

The power or torque available at the drive wheels produces the motive force needed to overcome resistance and allow a vehicle to accelerate. Since the power at the drive wheels is derived from the engine any time the vehicle accelerates a load is placed on the engine. The engine load for typical vehicle is a function of the speed of the vehicle, change in speed, accessory scavenge (e.g. air conditioning or fan), and load on the vehicle (e.g. towing or grade). When power demands are in a normal range the engine will operate at a near stoichiometric air/fuel ratio. When excessive power demands are placed on the engine, the air/fuel ratio will go rich and increased CO and HC emissions will result along with lower fuel economy. An engine in a typical passenger vehicle has enough power available to accelerate at 3-5 mph/s² at low speeds without leading to enriched air/fuel conditions (Newton, et al, 1996). At higher speeds the power available is much less due to drag resistance. Therefore, power demands for acceleration rates higher than those listed above will result in enrichment. Rich air/fuel mixtures are often produced as a direct result of how the emissions control system is programmed. Automobile manufactures allow for rich operations under certain conditions to provide for better performance and protection of engine parts (Guensler, 2000).

It is the drivetrain, shown in Figure 2-3 that carries power from the engine to the vehicle axle and wheels. It is this power or torque delivered by the drivetrain that allows a vehicle to accelerate. Indeed, it is components of the drivetrain such as the transmission that allow for the high level of torque, needed for acceleration, to be
available at the drive wheels. This is accomplished through the gearing of the engine torque in the transmission.

Figure 2-3, Typical, Passenger Vehicle Drivetrain

Where:
1. Engine
2. Transmission
3. Transfer Case
4. Rear Drive Shaft
5. Differential
6. Drive Shaft to front Differential

Gear ratios change the relative revolutions between the crankshaft and the wheels, but they also change the engine torque. Torque is turning or twisting effort, such as that used to loosen a lid on a jar. The pistons inside of an engine exert torque on the crankshaft and cause the shaft to rotate, in turn the crankshaft turns the gears inside the transmission (Crouse, 1976).

Although certain amount of force is delivered to the drive axle not all of this force is converted to vehicle motion (i.e. velocity) as some of the acceleration force is used to overcome resistance to the vehicle acceleration. That is, some of the force is used to overcome forces acting on a body (e.g. a vehicle) at rest. In terms of an accelerating motor vehicle these forces are referred to as running resistance. Total running resistance for a motor vehicle is comprised of three forces, rolling resistance ($F_{RO}$), aerodynamic or
frontal drag ($F_L$), and climbing resistance or drag ($F_{ST}$). The following Figure 2-4 provides a graphic illustration of these forces acting on a vehicle (Bosh, 1996).

**Figure 2-4, Forces Acting on a Vehicle in Motion**

It is these resistance forces that determine the specific power demand of a particular vehicle in motion. When a vehicle accelerates or climbs a grade (i.e. acceleration against gravity) additional power is needed to generate torque at the drive wheels and, in order for the engine to generate this power the rate of combustion must be increased. As discussed earlier if this power demand is extreme it will lead to enrichment in the combustion chamber and potentially increased levels of HC and CO emissions. As a result the vehicle emissions associated with a given trip can vary greatly depending on the level and frequency of the power demand and other vehicle technology, fuel and
environmental parameters. Figure 2-5 shows how HC emissions will vary over the course of a typical trip (Bachman et al., 1995).

**Figure 2-5, HC Emissions from a Hypothetical Vehicle Trip**

Despite the numerous advancements in automobile engine technology the continued growth in travel motor vehicle related pollution remains as a serious urban air quality concern. As a result the CAA Amendments require continued efforts to the reduction of air pollution from the transportation sector or mobile sources. Therefore areas that do not meet the NAAQS are under mandate to develop air quality management plans that include the monitoring and control of motor vehicle emissions.
2.3  **Air Quality Planning**

Vehicle emissions certification standards have resulted in great strides in the reduction of motor vehicle exhaust emissions. As discussed, vehicles manufactured today are in the order of 70-90 percent cleaner than they were 30 years ago, but motor vehicles are still are significant contributor to air pollution problems. Therefore the CAA Amendments require additional counter measures and plans to reduce motor vehicle emissions, particularly in areas with existing air quality problems. These requirements are implemented in air quality problem areas as part of the State Implementation Plan.

2.3.1  **State Implementation Plans**

Areas that do not meet the NAAQS, which were discussed in the first section of this chapter, fall under a nonattainment designation under the most recent CAA Amendments. The specific nonattainment designation is a function of the type severity of the pollution problem. For example, if the NAAQS for $\text{O}_3$ is violated in an area four times over a three-year period it would be classified as a nonattainment area for $\text{O}_3$. There are different nonattainment classification ranging from marginal to extreme depending on the number of annual violations averaged over a three-year period. Areas that fall under any designation for any of the criteria pollutants are required to prepare an air pollution management plan, which is referred to as a State Implementation Plan (SIP).

The SIP is a blueprint developed by a given state environmental quality division for outlining their process for reaching and maintaining attainment of the NAAQS. The SIP, which must be approved by the USEPA, identifies specific actions and programs to be undertaken to control emissions within the nonattainment boundary. The plan consists of
a monitoring and inventory process for emissions from all sources, including stationary, area, indirect, and mobile. Emissions control programs for stationary sources, such as power plants and manufacturing factories are outlined in the CAA Amendments as specific rules and regulations. Apart from the tailpipe emissions certification standards, the control of motor vehicle emissions is less defined. Under the SIP requirements the state must demonstrate reasonable progress toward achieving the NAAQS and be within their allowable emissions budget under the predetermined timeline. Mobile source emissions play an unavoidable role in this process. Part of the demonstration includes how the emissions from motor vehicles will be reduced over time. In addition, there are several requirements in the regulations that call for the monitoring of mobile source emissions. The primary condition within the CAA Amendments for mobile source emissions is that transportation plans developed by metropolitan planning organizations (MPOs) in nonattainment areas must conform with the SIP (USEPA, 1995).

2.3.2 Air Quality Plans and Conformity

As part of the SIP development process, the state will determine a mobile source portion of the total nonattainment area emissions budget. Typically this budget shrinks as the plan emissions reduction requirements take effect in future years. Most of the mobile source emissions reductions are achieved through the influx of newer and cleaner vehicles in the fleet. The conformity process insures that the efforts of the state and the expectations of the SIP are not compromised through increased vehicle travel induced by transportation plans at the metropolitan level. If the emissions estimates from the implementation of certain transportation plans do not conform with the emissions budget
milestones set in the SIP, then the plans cannot be adopted for implementation and projects in the plan can not be built. In such a case the transportation plan must be revisited and developed in such a way that it will conform to the SIP. The CAA Amendments contain provisions for areas to offset motor vehicle related emissions through the use of Transportation Control Measures.

2.3.3 Transportation Control Measures

Transportation control measures (TCMs) are intended as a means to help mitigate air pollution resulting from mobile sources. TCMs are transportation improvements or programs with the intended result of a decrease in pollution levels through vehicle trip reductions, transportation system efficiency improvement, vehicle inspection programs, higher vehicle occupancy, mode shift to transit, or the use of less polluting alternative fuels. The specific TCMs that are included in the CAA Amendments and outlined in Section 108(f)(1)(A) of the 1990 Amendments are as follows:

(i) programs for improved public transit;
(ii) restriction of certain roads or lanes to, or construction of such roads or lanes for use by, passenger buses or high-occupancy vehicles (HOVs);
(iii) employee-based transportation management plans, including incentives;
(iv) trip reduction ordinances;
(v) traffic flow improvement programs that achieve emissions reductions;
(vi) fringe and transportation corridor parking facilities serving multiple-occupancy programs or transit service;
(vii) programs to limit or restrict vehicle use in downtown areas or other areas of emissions concentration particularly during periods of peak use;
(viii) programs for the provision of all forms of high-occupancy, shared-ride services;

(ix) programs to limit portions of road surface or certain sections of the metropolitan area to the use of non-motorized vehicles or pedestrian use, both as to time and place;

(x) programs for secure bicycle storage facilities and other facilities, including bicycle lanes, for the convenience and protection of bicyclists, in both public and private areas;

(xi) programs to control extended idling of vehicles;

(xii) reducing emissions from extreme cold-start conditions;

(xiii) employer-sponsored programs to permit flexible work schedules;

(xiv) programs and ordinances to facilitate non-automobile travel, provisions and utilization of mass transit, and to generally reduce the need for single-occupant vehicle travel, as part of transportation planning and development efforts of locality, including programs and ordinances applicable to new shopping centers, special events, and other centers of vehicle activity;

(xv) programs for new construction and major reconstruction of paths, tracks or areas solely for the use by pedestrians or other non-motorized means of transportation when economically feasible and in the public interest. For purposes of this clause, the Administrator shall also consult with the Secretary of the Interior;

(xvi) programs to encourage the removal of pre-1980 vehicles.

This list includes wide range of transportation improvements and programs intended to provide flexibility to transportation and air quality planners. An additional result can be the programming of a transportation project as TCMs that have an unknown emissions impact. Indeed, the legislation requires that all TCM projects demonstrate an emissions reduction, but as will be discussed this process is often crude and imprecise (Crawford, et al, 1995). One area that has generated controversy is the fifth TCM on the
CAA Amendment list above—traffic flow improvement programs that achieve emissions reductions.

2.3.4 Traffic Flow and Transportation Management

With the combination of an increase in both physical and fiscal limits for more transportation infrastructure, the focus of many transportation agencies has been on the management of the existing system, with new construction occurring only when absolutely necessary. This is particularly true in urban areas where congestion problems are the worst and land values are high. One of the most common forms of transportation management is in the shape of traffic flow improvements (ITE, 1992). The concept behind these improvement and transportation management strategies in general is to improve the efficiency of the existing transportation system through a better utilization of the present infrastructure. Traffic flow improvements focus on freeway and arterial traffic congestion and strategies that optimize capacity and throughput. Most every urban area in the US is experiencing increases in congestion levels (FHWA, 1996). According to the Texas Transportation Institute (TTI) during the period from 1982 to 1996, congestion levels, based on vehicle density, in San Francisco, Denver, and Atlanta, have increased by 32, 27, and 36 percent respectively (TTI, 1998). Similar increases have been experienced by most other cities across the country. This has led to the increased popularity of the practice of implementing traffic flow improvement projects. In light of this it is becoming increasingly important to understand the air quality impacts of these projects.
Under the basic assumption that traffic flow improvements that are likely to increase average travel speeds will also lead to lower vehicle emissions, many such project are undertaken across the US. As discussed in the previous section, motor vehicle emissions are the result of a complex process related to power demand and not simply the function of average vehicle speed. Due to the fact that the operations impacts of traffic flow improvements are highly variable and difficult to predict accurately, and that the analysis tools used to evaluate the emissions changes are also limited, the true emissions impact of a given project is difficult to estimate (Hartner and Lawlor, 1995). Despite this, traffic flow improvements and related transportation management strategies are the most popular TCM in US cities. In 1992, 85 of the total 183 TCM projects in nonattainment areas funded through the congestion mitigation and air quality (CMAQ) improvement program were composed of traffic flow improvement projects (FHWA 1994). One traffic flow improvement that is becoming increasingly popular due to its low cost and high effectiveness is freeway ramp control in the form of onramp metering (Hellinga, 1995). Currently 27 cities in the US have ramp meting systems or are planning systems and the largest system, composed of 800 ramp meters, is located in Los Angeles County, which is one of the most severe O₃ problem areas in the country (Piotrowicz and Robinson, 1995).

2.3.4.1 Ramp Metering

Freeway onramps are the transition link between the arterial street system and the freeway or access controlled systems. Due to this, they are unique features of the transportation system and as a result display exemptions from traditional facility design
and operation. For this reason they deserve special attention and study as a roadway facility. Since freeway onramps are designed differently than most other facilities they will be characterized by different vehicle operation and related emissions levels. Such differences can be compounded by the introduction of ramp controls such as ramp meters.

Since vehicles operating on the arterial system often platoon together as the result of traffic signals or other design constraints, these same vehicles will enter the freeway system in platoons. Benefits exist for vehicles operating as a unit on the arterial system (e.g. signal progression), but vehicles entering the freeway system as a unit can compromise the freeway flow and operation. Ramp metering devices are designed to break up vehicle platoons entering the freeway so that only one vehicle is merging onto the freeway at a time. A ramp meter is signal placed at the mid point of a freeway onramp, which is used to pace the entry of vehicles onto the freeway. When the meter is operational (usually only during congested periods) all vehicle using the ramp are required to stop at the meter location. When the meter flashes a green light the vehicle at the front of the queue is allowed to enter the freeway. The result is a smooth and safe vehicle transition from the arterial system to the freeway system (Piotroicz and Robinson, 1995).

Ramp metering can slow the flow of traffic onto a freeway to; 1) ensures that demand does not exceed freeway capacity, and 2) break up vehicle platoons that impair optimal freeway flows. The balanced entry of vehicles reduces the potential for freeway traffic flow breakdown and thereby significantly reduces overall system delay. Thus,
mainline travel time is significantly reduced by inducing small delays on the onramps (May, 1990). Freeway flow control is optimized through a system strategy, controlling entry at numerous ramps to stabilize the flow approaching critical network locations. That is, ramp metering is most effective when implemented as a system of metered ramps in network or corridor (McShane and Roess, 1990). In addition, the benefits of ramp metering are appreciated under heavy mainline freeway demand, typically experience during peak travel periods. Ramp metering under light traffic conditions result in little benefit to mainline travel while incurring unnecessary delay to onramp traffic.

Case studies preformed in Portland and Minneapolis have shown that peak period travel times decreased by 60 and 35 percent respectively, after ramp metering systems were installed. In addition, ramp metering systems have also been found to reduce traffic accidents commonly associated with merging activity, such as rear-end and side swipe accidents. The result is an important safety benefit as well as an added flow improvement. The same cities experience a 43 and 32 percent reduction in traffic accidents after the ramp metering systems were installed (Piotrowicz and Robinson, 1995).

To help encourage the implementation of ramp metering and other TCMs, the USDOT has included specific funding provisions for TCMs in the last two federal transportation bills. ISTEA and TEA-21 both contained CMAQ programs. The CMAQ program specifically sets aside federal transportation funds for air quality friendly transportation improvements, such as ramp metering systems. The current legislation,
TEA-21 has earmarked 8.1 billion dollars for the CMAQ program over the next six years (FHWA, 1999).

Based on the fact that ramp metering increases mainline travel speeds and overall system performance they are considered valid TCM projects. This overlooks the impact that ramp meters will likely have on the operating mode of vehicles on the ramp and the varying emissions impacts this could induce. Requiring vehicles to come to a complete stop midway down an onramp before accelerating to freeway speed will undoubtedly result in a measurable change in vehicle activity, such as acceleration rates. This change in modal activity will also likely lead to changes in vehicle emissions rates. By design, ramp metering will also result in changes in modal activity on the mainline. Although these changes will likely be less significant than changes on the onramps, they will impact a much larger number of vehicles. Since emissions estimates for ramp metering systems are simply based on changes in average speeds on the mainline and not sensitive to speed and acceleration interactions, emission reductions will be estimated through the use of MOBILE models, although the true emissions impacts are unknown. This is confirmed by the ramp metering emissions impact estimates calculated by agencies across the US, which are planning ramp metering systems as TCMs. These calculations will be discussed in more detail in the following section. One basic premise of this research is to assess the emissions impacts of an entire ramp metering system through the use of a physical approach that utilizes power demand inputs to produce emissions estimates. This warrants a discussion of the current and emerging vehicle emissions rate modeling regimes.
2.3.5 Vehicle Emissions Modeling

A great deal of regulatory, policy, and research attention is focused on improving motor vehicle emissions estimates. For example, the USEPA Federal Test Procedure (FTP) improvement project is redesigning the certification process to better represent on-road driving and emissions (USEPA, 1993). The average speed motor vehicle emissions modeling regimes suffer significantly from aggregation techniques employed in model development, such that the confidence bounds of model outputs make predictions less than useful from a policy perspective (Chatterjee, et al., 1997). Recent studies indicate that motor vehicle emissions are even higher than reported by the USEPA and CARB and much research over the past several years has focused on identifying limitations in existing emissions modeling methodologies (NRC, 1991). One reason for these limitations is that the current mobile source emission rate models do not account for high power and load conditions, which produce significant emissions (Barth et al., 1996). Studies have shown that one hard acceleration event may cause as much pollution as the remaining trip and that a small percentage of a vehicle’s activity may account for a large fraction of that vehicle’s emissions (LeBlanc, et al., 1994). Other modal events, such as deceleration, also appear to produce significant emissions, and geometric conditions, which can be modeled as an acceleration against gravity, can increase emissions more than tenfold. New, statistically-based modal emissions models are being developed to provide emissions estimates as a function of disaggregate vehicle activity, or modes of operation such as acceleration, deceleration, idle, and cruise (Bachman et al., 1995).
2.3.5.1 USEPA MOBILE Model

The current MOBILE model, MOBILE5b, which is also known as the USEPA mobile source emissions rate model, is a computer program that estimates the emissions rates of CO, HCs, and NOx for eight different types of gasoline and diesel motor vehicles classes. The model algorithms are used to develop emissions rates for each of the three pollutants on a grams per mile basis. Emissions estimates can then be produced by applying the emissions rate for a given average speed to the number of miles that compose a trip. The MOBILE model is used in this fashion to develop aggregate emissions estimates for a given nonattainment area for use in the mobile source emissions inventory portion of the area SIP.

The emissions rates are based on actual tailpipe emissions collected from vehicle run on the FTP drive cycle. The FTP is technically the aggregate of all Federal emissions test, but the FTP traditionally refers to exhaust tests, which is a chassis dynamometer test designed to replicate a typical urban commute trip. One of the primary drawbacks to the MOBILE model is that the FTP drive cycle is not representative of actual vehicle activity. The average speed of the FTP is 19.5 mph, the maximum acceleration rate is 3.5 mph/sec², and the maximum acceleration rate is 56.3 mph, as shown in the following Figure 2-6. The argument is that many typical urban trips include activity outside of the above ranges or are ‘off cycle.’ To account for this and average trip speeds different from the FTP improvements have been made to the MOBILE model through the use of data from other high speed and high acceleration drive cycles. These data are used to develop speed correction factors to adjust emissions from the FTP to produce estimates
for varying average speeds. Although this allows for estimating emissions for any given trip, these correction factors are highly inaccurate and have been shown to underestimate emissions predictions. The FTP speed correction factors suggest that emissions rate vary between 0.5 and 3.0 times the FTP, while emissions test have shown that the variation can be up to 9.5 times the FTP cycle for some pollutants (Sierra Research, 1997).

**Figure 2-6, FTP Drive Cycle**

These findings have shown that the MOBILE model is inadequate for the analysis of emission impacts for certain types of roadways and roadway improvements. One such type of roadway would be freeway onramps, which exhibit vehicle activity significantly different from FTP cycle. The USEPA currently incorporating new facility specific driving cycles and other improvements into the new generation MOBILE model,
MOBILE6, in an effort to address current limitation in MOBILE. While these efforts have the potential to represent a substantial improvement in the accuracy of the emissions rates for use in analysis, they will not be sufficient to provide an improved basis for the analysis of TCMs or many other types of roadway improvements. Therefore, even the newest version of the MOBILE model, MOBILE6, (which had not been released at the time of this research) would not be appropriate for the assessment of TCM such as a ramp metering system. This notwithstanding, the MOBILE model is currently used by most air quality and planning agencies for the assessment of TCMs. Areas in California use the CARB EMFAC model, which is also an average speed emissions rate model similar to the MOBILE model. Although recently, a new generation of disaggregate emissions models are being developed that have potential for providing a basis for a greatly improved analysis method for many different transportation improvements, including TCMs.

2.3.5.2 MEASURE Model

Georgia Tech has made significant progress in the development of a fully functional modal model known as MEASURE (Mobile Emissions Assessment System for Urban and Regional Evaluation)(Bachman, et al., 1996; Guensler et al., 1997). The basic point of departure of the MEASURE model from conventional models is that mobile source emissions are a function of vehicle operating profiles such as cruise, acceleration, deceleration, idle, and other power demand conditions that lead to enrichment (high fuel:air ratios) rather than a function of average speed. In developing the model, the team
employed a variety of advanced statistical techniques. Ongoing field and emission laboratory measurements are being used to validate and further refine research findings.

The MEASURE model is developed on a geographic information systems (GIS) platform. The GIS serves as a tool for storing all of the spatial and temporal attributes of the modeling regime, and integrating a wide variety of data sources, spatial attributes, and temporal distributions for use by external programs to estimate emissions. The coded GIS contains the transportation network physical characteristics (link length, number of lanes, grade, etc.), terrain, roadway operational characteristics (capacity, vehicle mix, etc.), analysis zones, intersections, onramp locations, and other locations of potential enrichment activity.

The MEASURE emission rates were developed using a regression tree analysis of available dynamometer tests. The comprehensive database contains 30,834 test results from 19,092 vehicles on the FTP and 17,417 test results from 8171 vehicles on alternative hot-stabilized testing cycles (Wolf, et al., 1998). Advanced statistical methods were applied to the data to develop an improved emission rate model (Washington, et al., 1998). Inherent in such a modeling approach is the replacement of nominal driving cycle assumptions with actual vehicle operating mode (speed/acceleration) distributions. To evaluate transportation projects and strategies to reduce congestion and delay, it is therefore necessary to evaluate the effects of proposals on activity operating mode patterns.

Facility-specific speed/acceleration profiles were developed from analysis of field data and are predicted as a function of roadway classification, geometry, and measures of
congestion. In this research effort, these average modal distributions were replaced by actual measured operating mode profiles from the ramp metering study measurements.

As will be outlined in the next chapter, the MEASURE model emission rate algorithms will be used to estimate the air quality impacts of the ramp metering system in Atlanta. This research will identify how ramp metering impacts the overall changes in vehicle operating patterns along the mainline freeway and onramp, and will estimate the resulting emissions impacts using applicable MEASURE emission rates and MOBILE 5b emissions rates. Vehicle technology and activity measures are combined with technology and modal specific emission rates to produce the estimates. Vehicle technology distributions were developed from the registered fleet of automobiles in the study area (i.e. I-75 corridor).

2.3.6 Ramp Metering and Vehicle Emissions

When ramp metering is implemented, stop-and-go congestion on the freeway segment is replaced by delay and acceleration (from stop to freeway speeds) for vehicles at the onramps. Ramp delays before and after metering systems are installed, can change significantly (ITE, 1992). The vehicle modes of operation along the mainline and the onramps both have the potential to change dramatically due to introduction of ramp meters. Large acceleration changes can result for the small number of vehicles entering the freeway, and smaller changes in operating modes (i.e. cruise, idle, acceleration, and deceleration) occur for large numbers of vehicles operating on the freeway. That is, emissions under most ramp metering scenarios are expected to be less than non-metered scenarios. However, it is unclear to what extent the increase in hard acceleration activity
on the onramps may increase emissions. Some extreme ramp metering scenarios may increase system emissions.

One estimate of ramp metering systems using MOBILE emissions rates, showed that ramp metering will increase emissions levels. An evaluation of a proposed ramp metering system in Birmingham concluded that the system would result in an increase in both HC and NOx emissions. The study speculated that the emissions increase was due to the fact that the system was proposed in a relatively un-congested corridor and that the operational benefits were small as a result. The study estimated that the ramp metering operations would only result in a one mph increase in mainline travel speeds. As a result the small emissions benefit estimated by MOBILE due to the improved travel speed was offset by the increased ramp emissions brought about by lower average speeds on the ramps (PBSJ, 1995). A similar TCM analysis study performed for the Pennsylvania Department of Transportation estimated that ramp metering systems would result in a four percent increase in average peak period freeway speeds. The study concluded that this resulting flow improvement would result in a net decrease in vehicle emissions rates (COMSIS, 1994).

Apart from the assessment of ramp metering systems as TCM projects there are only two significant ramp metering air quality studies found in the literature. These include one preformed in 1993 for the California Department of Transportation by Edward Sullivan and one performed by Sierra Research in 1997 as part of NCHRP 8-33.

The Sierra Research report documents the process and findings that were undertaken to investigate vehicle emissions associated with driving on freeway onramps.
as part of a project to improve the air quality analysis methodology for TCM projects. This project included the collection of onramp speed and acceleration activity used for the development of two ramp drive cycles. One drive cycle was developed for vehicle activity on freeway onramps under ramp metering conditions and the other was for non-metered conditions. The activity data used for the development of the drive cycles were from a limited amount of data from the Sacramento California area, collected through the use of an instrumented chase car. Once the two drive cycles were established, emissions tests for four mid to late model vehicles were preformed on a chasse dynamometer. The following Table 2-3 shows the operating parameters for the two cycles (Sierra Research, 1997).

<table>
<thead>
<tr>
<th>Condition</th>
<th>Average Speed (mph)</th>
<th>Maximum Speed (mph)</th>
<th>Maximum Acceleration Rate (mph/sec)</th>
<th>Length (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metered</td>
<td>15.1</td>
<td>55.3</td>
<td>8.1</td>
<td>1.42</td>
</tr>
<tr>
<td>Non-Metered</td>
<td>40.8</td>
<td>61.4</td>
<td>4.6</td>
<td>2.93</td>
</tr>
</tbody>
</table>

Part of this report included a comparison of the emissions from the two drive cycles with that of the emissions from the average FTP cycle. The following
Figure 2-1 shows the average HC, NOx, and CO emissions for the metered, non-metered drive cycles, and the FTP cycle for four mid to late model passenger cars. As can be seen, the emissions on a grams per mile basis are highest for the metered conditions and lowest for the FTP cycle.

This provides further evidence that average speed emissions rate models are inadequate for use in TCM analysis. In addition, this also provides indication that the ramp metering will result in an increase in vehicle emissions. Despite this, this study suffers from several drawbacks that need to be considered before final conclusions are drawn. First, this study is based on limited modal activity data and therefore the drive cycles may not be representative of actual average driving behavior. Second, there was no effort made during this study to control for effect of ramp geometry or length. Third, the emissions estimates were based on a limited number (four) of vehicles. Fourth, this
study only considered changes in vehicle activity on freeway onramps and did not account for changes in mainline activity. Therefore, although this study provides some important information about the emissions impacts of ramp metering the findings are limited and inconclusive.

The Sullivan report *Vehicle Speeds and Accelerations Along Onramps: Inputs to Determining the Emissions Effects of Ramp Metering* provides more data than the Sierra Research study, but suffers from its own limitations. In the Sullivan study, speed and acceleration data were obtained and analyzed for nineteen freeway onramp locations in urbanized areas of four different California Department of Transportation districts throughout California. The Sullivan study sample was split between ramps with and without ramp meters and included ramp speed and acceleration data with and without mainline congestion. The primary product of the Sullivan study was to develop a comprehensive set of data describing the speed and acceleration of light–duty vehicles along onramps under various conditions with an emphasis on the presence or lack of presence of ramp meters. The intent was to develop a data set that could feed modal specific emissions models, but since this modeling was not part of the Sullivan study, actual emissions estimates were not determined. In addition, the Sullivan study only evaluated ramp activity and did not include observations of vehicles operating on the mainline. Although the Sullivan study provides important modal activity information for vehicles operating on freeway onramps, it is limited as it does not provide any conclusive findings regarding the emissions impacts resulting from the changes in modal activity.
This research will improve on these past studies in several important areas. First, a comprehensive system wide data set, including ramp and mainline activity, was gathered. In addition to including vehicle modal activity profiles for metered and non-metered conditions, this research will include data for varying ramp designs and mainline flow conditions. Third, the modal activity data collected as part of this research will be used to drive a modal specific emissions rate model to produce emissions estimates. The following chapter discusses these improvements and the overall research approach in detail.
CHAPTER III

3 RESEARCH APPROACH

This chapter presents the basic research approach developed to perform an evaluation of the air quality impacts of a ramp metering system. 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 in section 3.3. Data collection and analysis techniques considered for this research and the emissions modeling procedures are discussed in section 3.4. This discussion provides the basis for the data collection plan and analysis procedures, which will be 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 (CAA) and its amendments, urban air quality is still a serious problem throughout the US. Although motor vehicles being currently manufactured are far more efficient and clean than vehicles of the past, motor source emissions are a significant contributor to the current urban air pollution problem.
Concurrent with this air quality problem, urban areas in the US are experiencing a rapid increase in traffic congestion and travel delay. Indeed, the growth in vehicle ownership and travel activity, in the form of 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. At the same time the US Department of Transportation (USDOT) and the US Environmental Protection Agency (USEPA) have developed transportation control measures (TCMs), which are transportation programs with intent to provide marginal reductions in emissions from motor vehicles. One class of TCMs is aimed at the reduction of vehicle emissions through the improvement of traffic flow. The traffic flow improvements are also a transportation management strategy used to mitigate traffic congestion. That is, there are some transportation programs developed with the goal of both improving air quality and alleviating traffic congestion. One such transportation program is freeway ramp metering. This program is particularly popular due to its cost effectiveness.

The 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 and the fact in many cities ramp metering is used as a TCM to offset overall 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 encounter on freeway onramps equipped with ramp meters. Emerging disaggregate modeling regimes, such as the MEASURE model provide a basis for providing an accurate emissions estimate for ramp metering systems.

This analysis will provide 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

Despite the fact that vehicle enrichment conditions for vehicles on the onramp will likely be induced under metered conditions and the resulting level of emissions increase is unknown, it is anticipated that these negative emissions impacts will be offset by positive emissions impact for vehicles operating on the mainline. This will be the result of smooth operation on the mainline resulting in less enrichment and lower power demand. Since the number of vehicles operating on the mainline is much greater than
that of the ramps the net result will be a decrease in vehicle emissions under congested traffic conditions. Therefore the three hypotheses of this research are:

1. **Ramp metering systems operating under peak period traffic demand, will result in a decrease in vehicle NOx emissions for vehicles operating on the onramp.**

2. **Ramp metering systems operating under peak period traffic demand, will result in a net increase in mass vehicle NOx emissions system wide.**

To assess the emissions impacts of ramp metering systems, this research had four main objectives, which are detailed below.

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

In order to assess the emissions impacts of a ramp metering system using a disaggreate modeling approach it was necessary to gather modal activity data for vehicles operating on the system. In addition to developing a representative sampling procedure, the data collection plan would also need to address issues of gathering data across all location 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 concessions
for collecting modal activity data for both metered and non-metered conditions to provide data for a direct comparison of both conditions.

**Objective 2: Utilize the modal activity data collected from the system as an input to MEASURE, to estimate the vehicle emissions change resulting from the ramp metering system.**

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, this research estimated the vehicle emissions, with and without the ramp meters in operation, through the use of a modeling approach that will utilize physical modal activity to estimate emissions rates. Subroutines from the MEASURE model were used to determine the vehicle emissions rates.

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

It has been well documented the MOBILE series of emissions rate models produces inaccurate emissions estimates for some applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). In most cases MOBILE emissions estimates are below actual emissions rates due to the fact that it is not sensitive 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 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. It is well understood that 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 that 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 without an auxiliary lane, loop ramp, etc.) was analyzed in order to assess the influence on modal activity.

### 3.3 Scope of Work

An analysis procedure was developed to answer the research questions posed in section 3.2. Before this procedure will be presented in section 3.4, an overview of the general work scope will be discussed. Several tasks were undertaken to guide and
complete this research. The overall scope of work was divided into eleven primary steps including the previously discussed hypothesis statement and research objectives.

The eleven research approach steps are as follows:

1. Statement of Hypothesis and Research Objectives
2. Define Target Group/Population
3. Identify Relevant Data to be Collected
4. Determine the Degree of Analysis 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

As stated, the first step has been discussed in the second section of this chapter. An overview of following ten steps will be discussed in this section. A detailed description of the important elements related to the data analysis will be addressed in detail in subsequent sections. 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 will be on passenger vehicles. Data was 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, MEASURE emissions algorithms for heavy-duty vehicles have not been developed. 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 in order 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 sample of vehicles operating both on the onramps and freeway mainline sections. The vehicle speed/acceleration profile data 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 importance of this data warrants further discussion, which will be included in the following section 3.4. The system data includes physical ramp and roadway characteristics, such as grade, curvature, acceleration distance, ramp design, and ramp metering rate. In addition, system traffic flow data was 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 ramp meters only operate during peak hours of travel. Therefore, the relevant data was gathered only during the evening peak period and peak direction of traffic.

Step four, *determine the degree of analysis precision*, was performed in conjunction with the previous step. Once the relevant data is 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 modeling regimes, such as MEASURE and MOBILE5b. Therefore the analysis was designed to be highly precise, although some findings were presented in the aggregate and as the variance or average 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 the 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. The traffic count data and vehicle mix information was collected for all vehicles. 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 Four is dedicated to a description of the data collection process, site selection, and field procedures.
The fifth step was followed by *determine sampling units*, which is step six. The individual sampling units are indeed vehicles, but for this research the individual vehicle data were binned into groups for analysis. The bin grouping was determined 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 will be discussed in later sections, the vehicle activity data was analyzed in groups with similar characteristics 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 Four. The necessary sample size was not known prior to the data collection phase and ultimately was determined by the resources available. That is as much data was collected as allowed under the given time and fiscal constraints.

Step eight, *pretest survey method and field procedures*, was performed once the data collection process was refined. In order 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 highly important to test the methods and procedures before full data collection deployment occurred. 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.

Before the data collection process was finalized step ten, *develop analysis, reduction and summary procedures* was being performed. This was to ensure 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), that could be used as an input 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 was 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 will be discussed in the following chapter. The following sections of this chapter will now turn to a discussion of the specifics of the proposed analysis procedures.
3.4 Analysis Procedures

One of the most critical components of the research approach is the analysis procedure. These procedures outline how the four research objectives were accomplished. The analysis procedure for this 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 emissions rate algorithms to estimate the vehicle emissions, 2) a comparison of the MEASURE analysis with 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 proposed emissions analysis will be based on estimates from a disaggregate modal model. The Georgia Institute of Technology MEASURE model described in Chapter Two will be the basis for this analysis. The MEASURE 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 will only incorporate certain sub-elements of the model. In short, the emissions rate algorithms, (which comprise just one component of the model), will be the only element used for this analysis. Although only a single component, these emissions rate algorithms are one of the fundamental and distinct elements of the MEASURE model. The hot stabilized emissions rate algorithms within MEASURE 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 MEASURE 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 algorithms.

3.4.1.1 Structure of the MEASURE Algorithms

A separate algorithm exists within the MEASURE model 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. Although the NOx algorithm was the only one used for this research the structure of each of the three algorithms are presented in a functional form.

The CO model: is presented in an estimation form. The estimation form is the regression equation 3-1:

\[
\text{LogR}_{CO} = 0.0809 + 0.002*\text{AVGSPD} + 0.0461*\text{ACC}.3 + 0.0165*\text{IPS}.60 - 0.0283*\text{ips45sar2} + 0.3778*\text{ips90tran1} - 0.0055*\text{tran3idle} + 0.1345*\text{tran5mi1} + 0.3966*\text{finj3sar3} - 0.0887*\text{cat3tran1} - 0.2636*\text{sar3tran4} - 0.481*\text{flagco}
\]

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

Where:
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 mph^2/sec (Washington et al., 1994). Thus IPS.60 implies IPS greater than 60 mph^2/sec;

ips45sar2 is an interaction between IPS.45 (IPS >= 45 mph^2/sec) and a vehicle with no air injection;

ips90tran1 is an interaction variable for a vehicle with automatic transmission on IPS.90 IPS >= 90 mph^2/sec;

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

tran5mi1 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: was derived similar to the CO model. The final emission rate model for HC is (Fomunung, 1999):
\[ \text{LogR}_{\text{HC}} = 0.0451 - 0.6707*\text{my79} - 0.1356*\text{my82} + 0.019*\text{AVGSPD} + 0.2021*\text{finj2tran4} + 0.1795*\text{cat2sar1} + 0.1651*\text{cat3sar1} + 0.0318*\text{cat3sar2} - 0.1189*\text{sar3tran1} + 0.5646*\text{sar1tran5} + 0.0004*\text{cid} - 0.2581*\text{sar3kml} - 0.0169*\text{finj2km3} - 0.5144*\text{flaghc} - 0.0129*\text{acc1finj2} - 0.1626*\text{acc3cat2} - 0.3891*\text{ips90sar3} + 0.0307*\text{dps8finj2} \]  

(3-2)

Where:

- \( \text{my79} \) = model year < 79;
- \( \text{my83} \) = 79 < model year < 83;
- \( \text{AVGSPD} \) = average vehicle speed (mph);
- \( \text{finj2tran4} \) = interaction variable for a 4-speed manual transmission vehicle with a carburetor;
- \( \text{cat2sar1} \) = pre 1981 model year vehicle with "oxidation only" catalyst and unknown air injection type;
- \( \text{cat3sar1} \) = pre 1981 model year vehicle with a TWC and unknown air injection type;
- \( \text{cat3sar2} \) = vehicle with TWC and no air injection;
- \( \text{sar3tran1} \) = automatic transmission vehicle with pump air injection;
- \( \text{sar1tran5} \) = pre-1981 model year, 5-speed manual transmission vehicle of unknown air injection type;
- \( \text{cid} \) = cubic inches displacement;
\textit{sar3km1} = vehicle with pump air injection and mileage \(\leq\) 25k miles;

\textit{finj2km3} = vehicle with pump air injection and 50k < mileage \(\leq\) 100k miles;

\textit{flaghc} = high emitting vehicle flag under HC emissions;

\textit{acc1finj2} = carburetor-equipped vehicle operating with acceleration greater than 1 mph/s;

\textit{acc3cat2} = oxidation only catalyst vehicle with acceleration greater than equal to 3.0 mph/s;

\textit{ips90sar3} = vehicle with air pump and inertial power surrogate greater than or equal to 90 mph\(^2\)/s; and

\textit{dps8finj2} = proportion of drag power surrogate (DPS) speed x speed x acceleration) greater than 8 mph\(^3\)/s.

**The NOx model:** was derived similar to the CO and HC model. The final emission rate model for NO\(_x\) is (Fomunung, 1999):

\[
\log R_{nox} = -0.5864 + 0.0225 \text{AVGSPD} + 0.3424 \times \text{IPS.120} + 0.6329 \times \text{ACC.6} + 0.0247 \times \text{DEC.2} + 0.0083 \times \text{finj2km1} + 0.0028 \times \text{finj2km2} - 0.0021 \times \text{cat2km3} + 0.0026 \times \text{cat3km2} + 0.0003 \times \text{cat3km3} - 0.0085 \times \text{finj1km3flagnox} - 0.0068 \times \text{finj3km3flagnox}
\]  \tag{3-3}

Where:

\textit{IPS.120} = proportion of activity where IPS \(\geq\) 120 mph\(^2\)/sec;
\( ACC.6 = \) proportion of activity where acceleration \( \geq 6.0 \text{ mph/s} \);

\( DEC.2 = \) proportion of deceleration \( \leq -2.0 \text{ mph/s} \);

\( finj2km1 = \) carburetor equipped vehicle with mileage \( < 25k \text{ miles} \);

\( finj2km2 = \) carburetor equipped vehicle with \( 25K, \text{ mileage} \leq 50k \text{ miles} \);

\( cat2km3 = \) "oxidation only" catalyst vehicle with \( 50k < \text{ mileage} \leq 100k \text{ miles} \);

\( cat3km2 = \) TWC vehicle with \( 25K \text{ mileage} \leq 50k \text{ miles} \);

\( cat3km3 = \) TWC vehicle with \( 50K < \text{ mileage} \leq 100k \text{ miles} \);

\( finj1km3\text{flagnox} = \) second order interaction variable for a high emitting vehicle with port fuel injection and \( 50k < \text{ mileage} \leq 100k \text{ miles} \); and

\( finj3km3\text{flagnox} = \) second order interaction variable for a high emitting vehicle with throttle body fuel injection and \( 50K < \text{ mileage} \leq 100k \text{ miles} \).

In order for these algorithms to be used for an emissions analysis of any kind, accurate input data needs to 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. This research proposes to employ a detailed alternative to a generalized study. Rather than using national or regional data averages to drive these models for this analysis, a data collection procedure designed to gather detailed modal activity data and specific vehicle characteristics information is proposed. That is, rather than using average
speed/acceleration profiles and regional fleet data, this research will gather representative speed/acceleration data from vehicles operating on freeway and freeway onramps to provide the modal activity data and collect vehicle characteristic data from a sample of the same vehicles. Only the NOx algorithm will be used as part of this research.

3.4.1.2 Vehicle Speed/Acceleration Profiles

Vehicle trajectories must be collected in order to generate speed/acceleration profiles for ramp and mainline flows. Previous research has been conducted to assess the most effective procedure for collecting speed/acceleration profiles (Grant, 1997a; Grant et al., 1998). In 1996 and 1997, researchers physically 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) are used to record traces for a large subset of vehicles over a relatively short distance (1000 to 2000 linear feet), or 2) floating cars are equipped with onboard instruments and introduced into the fleet to record traces of 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 were laser rangefinders are not effective or practical.

LRFs were used to capture the speed-acceleration profile of vehicles operating on onramps and mainline segments. The LRFs used were the Advantage, manufactured Laser Atlanta with faster components to improve the technology of hand-held laser devices used in the past. 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 storage on the Advantage can be sent to a computer hard drive via serial port interface or directly to a PCMCIA card (which inserts into the rear of the laser gun unit). The serial port interface allows a transmission rate up to 115.2 kBaud. 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 are set on tripods along the onramps and overpasses to record the activity of the vehicles from the point of entry onto the onramp until 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 the following Chapter Four.

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 accelerate from the stop bar down the ramp to the merge area. For this reason the data collection procedures and analysis was designed to separate 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.

Field-testing has shown some limitations on the range at which the laser rangefinder can track 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. The maximum distance at which the laser will “lock on” to an automobile is approximately 1500 feet, with the most consistent data being returned the closer the automobile is to the LRF. Data returned from trucks and larger vehicles are more reliable because of the large front or rear area they provide for computing ranges. Automobiles can be reliably tracked for 1000 to 1500 feet. Distance reliability is potentially more of a problem in heavy traffic.

This data collection effort 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 were used to capture the flow of traffic using car following techniques. The instrumented vehicle will also allow for speed-acceleration measurement of vehicle flow in areas where the LRF cannot measure due to site constraints.

On-board instrumentation has been used extensively as a means to measure speeds and accelerations of on-road 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 beyond the existing data collected to evaluate the impact of the ramp metering on operations of vehicles along the onramps and mainline segments through a combination of remote and floating car data.
Vehicles equipped with distance measuring instruments (DMI) will be used for this research.

A DMI is installed on the vehicle by attaching a sensor to the axle of the vehicle, to measure distance traveled by the vehicle, with precision to the nearest foot at 1 Hz. A distance measuring instrument records the number of pulses from the axle, and uses a calibration number to translate the pulses into distance traveled. 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 display vehicle modal activity, assess variations in modal activity, and feed the modal activity requirements of the MEASURE emission model.

The speed/acceleration trace information was 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). 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. JASPRODs are created by dividing vehicle traces into a matrix of speed and associated acceleration bins. Each bin has a unique speed and acceleration range. A JASPROD is shown in both graphical and matrix
form in Figure 3-1 and Figure 3-2. Once data are binned, the probability of any bin can be calculated by dividing its frequency by the sum of the frequencies of all bins. For each given geometric and operational condition that is 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 the vehicle trace will equal one.

The MEASURE model only requires the fraction of activity for the specific modal variable which have been shown to correlate with emission rates (i.e. the percent of activity where acceleration \( \geq 6.0 \) mph/s). Data could have been analyzed in this manner, however a method that allowed a distribution of data as output was desirable, since response variables may change in the future depending on results of on-going emission rate modeling. With output in the form of a distribution of data, the model output can be used with any 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.
Figure 3-1, Matrix Form of a Joint Acceleration-Speed Probability Density Function (JASPROD)

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Acceleration (mph/sec)</th>
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<td>0</td>
</tr>
</tbody>
</table>

Figure 3-2, 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 model also requires vehicle fleet information, for example transmission or fuel delivery system type. This information was obtained by sampling vehicle license plates at the data collection sites. The capture of license plate data allows for the determination of the on-road 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 on-road 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.

3.4.1.4 MEASURE 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 analysis was performed on sets of binned vehicle modal activity data and not individual vehicle speed/acceleration traces. The data was 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. One assessed emissions rates under various operating and ramp metering conditions, and a second evaluated the
estimated mass emissions levels based on the emissions rates and the observed traffic volumes and average speeds. This is important since in addition to the expected influences on modal activity ramp metering can also impact travel demand, traffic patterns and travel speeds. Changes in travel demand will result in changes in freeway and ramp volumes and in turn different mass emissions levels. Changes in average speeds will also result in different mass emission levels even if the emissions rates were the same. This is due to the fact that the emissions rates are based on a per second level of operation, resulting in higher mass emissions under longer operating periods experienced at slower travel speeds.

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 transportation corridor as unit. Specifically, the analysis considered the impact of NOx emissions levels. The actual MEASURE NOx emissions estimates will be presented in Chapter Five.

3.4.2 MOBILE5b Emissions Analysis

Emissions estimates from the USEPA MOBILE5b model were produced and compared with the estimates from the MEASURE analysis. To the degree possible the MOBILE5b emissions analysis conformed to the MEASURE procedures, so that easily comparable estimates were produced. The MOBILE models area 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, the purpose of comparing the MOBILE analysis results with MEASURE estimate is to identify the specific drawbacks associated with using the trip based emissions rates in MOBILE for a TCM analysis. This notwithstanding, every effort was made to use the highest level of aggregation and averaging to produce the most appropriate estimates from MOBILE5b.

The emissions estimates were calculated using the emissions rates NOx for the Atlanta regional fleet associated with the actual average vehicle speeds observed during the study and used for the development of the modal activity variable for the MEASURE analysis. The necessary speed and traffic volume data to run MOBILE5b was gathered as part of the overall research plan and no additional data were needed. All assumption 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 MOBILE5b control files used for this analysis are presented in Appendix A.

The analysis was stratified by day, time, and location to match the analysis bins used for the assessment of the modal activity and MAESURE 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. Since the MOBILE5b emissions rates are in grams per mile and MEASURE emissions rates are in grams per second of operation the MOBILE5b rates were converted to grams per second of operation so that
the two could be directly compared. The model comparison and result of the analysis are presented in Chapter Five.

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. This analysis focused on the assessment of vehicle modal activity changes under ramp metering conditions. The relevant operating mode variables from the emission rate models will serve as the response variables for the analysis. The modal activity variables that will be tested are shown in the following Table 3-1.

Table 3-1, 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>
Since the detailed statistical analysis performed for the development of the MEASURE 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 measure of change in modal activity will allow for a complete assessment of activity variations.

It was hypothesized that there are numerous factors that potentially influence vehicle modal activity. This research identified many factors and based on the 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. Sever different flow variable where chosen along with geometric design variable such as grade and acceleration distance. All of the independent variables used in this analysis are listed in the following Table 3-2.
Table 3-2, Modal Activity Analysis Independent Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LOS</strong></td>
<td>Mainline Level of Service at Onramp Merge Area, (A,B,C,D,E, or F)</td>
</tr>
<tr>
<td><strong>Flow Rate</strong></td>
<td>Mainline Flow Rate at Onramp Merge Area, (Passenger Car Equivalent per Lane per 15-min)</td>
</tr>
<tr>
<td><strong>Lane 1&amp;2 Flow Rate</strong></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><strong>Force Flow</strong></td>
<td>Force Flow/Free Flow Conditions on Mainline, (Force Flow Defined as Average Mainline Speed Less than 50 mph)</td>
</tr>
<tr>
<td><strong>Percent Trucks Ramps</strong></td>
<td>Percentage of Trucks in the Ramp Traffic Mix</td>
</tr>
<tr>
<td><strong>Percent Trucks Mainline</strong></td>
<td>Percentage of Truck in the Mainline Traffic Mix</td>
</tr>
<tr>
<td><strong>Grade</strong></td>
<td>Onramp Grade (Percent)</td>
</tr>
<tr>
<td><strong>AccelDist</strong></td>
<td>Onramp Acceleration Distance (Distance from Stop Bar to End of Gore)</td>
</tr>
<tr>
<td><strong>Ramp Design</strong></td>
<td>Onramp Configuration (Parclo or Diamond)</td>
</tr>
</tbody>
</table>

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 and thus ramp meters are needed. The use of ramp meters during uncongested traffic conditions will result in delays to vehicles on the onramp with little or no benefit to the mainline traffic flow. Due to this ramp meter operation is reserved for typically congested peak period conditions. It is during these conditions that gaps between vehicles are smaller 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 will also likely change. The goal here is to isolate these changes and identify any consistent patterns that will indicate when not to operate ramp meters if vehicle emissions levels are of concern. To accomplish this several different traffic flow measures will be analyzed, see Table 3-2.

Using Level of Service (LOS) as a measure of traffic level allows for varying flow rates to be classified into a set number of groups in order to simplify the analysis. Conversely, using the actual flow rate allowed for the analysis with the traffic condition as a continuous variable. In addition, conditions will be assessed as either free flow or force flow, using travel speed from the probe vehicle to identify the conditions. This level of analysis was performed as 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 brake down condition was included. It was also speculated that merging vehicles would be influence most by the vehicles in the immediate traffic lanes. To test this the flow for the first two traffic lanes was separated and analyzed. For this analysis all traffic flow measures were converted to passenger car equivalencies. To provide for an assessment of traffic mix both 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, see Table 3-2. 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 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 not included due to data limitations. This analysis was limited to modal activity of passenger vehicles and the data collection was limited to dry daylight conditions. The data was also collected during the evening peak period when most activity is associated with work commute trip. 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

As discussed the relevant operating mode variables from the emission rate models served as the response variables for the statistical analysis. Each of these variables were tested for the conditions described above using the t-test. The t-test will allow for the development of hypotheses testing in order to determine if two observed sample means are likely from the same populations (Neter et al, 1996). For this research the alternative hypothesis that two sample populations are not likely from the same population was of concern. For example if the average proportion of activity grater than 3 mph/sec for force flow conditions is found to be likely from a different population than the average
under free flow conditions, the t-test has indicated that force flow conditions likely influence modal activity differently from free flow conditions. 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 the conclusion that the means are from separate populations is likely, but 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 Five.

3.5 Research Limitations

The goal of this research is to provide sound conclusions regarding the potential air quality impacts of ramp metering systems. This is accomplished through the collection and analysis of vehicle modal 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 will significantly add to the current bank of knowledge. This notwithstanding, there are some limitations within this research and consideration should be given to them.

First, the emissions estimates are the product of a modeling exercise and as with all models certain assumptions can limit the accuracy of the models. The MEASURE model is a detailed model, which takes into consideration numerous factors, which influence vehicle emissions rates. This model is the best tool available for modeling vehicle emissions from a disaggregate perspective and although it may not always produce
precise emissions estimate, it will provide accurate emissions rate that can be used for a comparative analysis. One of the main limitations of the model at this time is the lack of emissions estimate for heavy-duty vehicles. As a result this research will only provide a comparison of emissions estimates for passenger vehicles.

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 in order to completed the analysis. As a result the confidence associated with data subsets is higher for some than others. Where any limitation in the data occurs they were accounted for in the analysis and noted during the presentation of result. The data is therefore presented in varying levels of detail to provide for a comprehensive assessment of an aggregate level and a detailed assessment where warranted by the available data.

Finally, this is an empirical assessment of the modal activity associated with a 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, although the transfer of the data and conclusions to other areas should be conducted with caution and engineering judgment. Variations in travel demand and driver behavior can occur from region to region and over time, limiting the application of the conclusions presented here. In brief the findings presented here are just one step toward final conclusions about the air quality impacts of ramp metering systems and should be used in conjunction with additional information as it becomes available. Despite these limitations this research
provides important information for evaluating ramp metering systems and procedures for evaluating TCMs and other transportation systems.

3.6 Contributions of Research

Not only this work provide a detailed emissions and vehicle modal activity assessment of the Atlanta ramp metering system, but will provide an analysis methodology that can be applied to the evaluation of other TCMs. The goal is to present both a detailed and comprehensive data set, unlike any that has been collected in the past, that will provide new and meaningful information, as well as an underlying research methodology that will contribute and improve upon current analysis procedures in this area.

This research will improve on past ramp metering studies by 1) utilizing a dissagregate modeling approach, 2) analyze a complete ramp metering system not just individual ramps, 3) assess the concurrent mainline activity, and 4) test the impact of ramp design and traffic conditions (LOS) on the vehicle modal activity and emissions rates.
CHAPTER IV

4 RESEARCH PROCEDURES

In order to perform a true evaluation of the air quality impact of a ramp metering system based on a dissaggregate modeling approach as discussed in the previous chapters, it was necessary to collect actual vehicle modal activity data from vehicles operating on the roadway. Empirical information was required to understand system impacts and provide data for driving the models used in the evaluation process. Since this research was concerned with traffic operational impacts as well as air quality implications, both traffic flow and modal activity data was necessary to perform a complete evaluation of a ramp metering system. In addition, ramp metering systems are designed to improve mainline traffic flow and therefore inherently impact both onramp and mainline vehicle operations and instantaneous speed profiles. It was therefore required to design a data collection strategy that included operational and environmental information for the onramp and mainline sections of the ramp metering system. It was also important to evaluate the impacts on a system wide basis and not simply on a ramp or interchange basis. With this in mind, the data collection effort was designed to include the collection of information for a completed system simultaneously to account for fluctuations in the system that might otherwise be overlooked.
On the operations side of the data collection effort, the focus was on the detailed monitoring of the traffic flow conditions in the entire ramp metering system. This would include traffic counts of the mainline, the ramps, and the adjacent arterial system. In order to model the environmental impacts of the system, instantaneous modal activity information was needed for vehicles on the mainline sections of the system and on the onramps, as well as classification and technological information for vehicles operating in the system.

For this research, the five-ramp metering system operating in the northbound direction of I-75 in the city of Atlanta, Georgia was used as the study area. Laser guns and other data collection equipment were employed to collect vehicle operations and activity data on four consecutive ramps and the mainline section of this system for numerous days, under metered and non-metered conditions, during the spring of 1999.

4.1 Data Collection Sites

The I-75 corridor, immediately north of the Atlanta central business district, was selected as the study site for this research as shown in Figure 4-1. This location was selected as the system to be evaluated, as it was the location specified by the Georgia Department of Transportation (GDOT), the sponsor of this study. Indeed, this section of freeway was a natural choice for a ramp metering study, as it is currently the only ramp metering system in the State of Georgia. The proximity of this location to the Georgia Institute of Technology and the GDOT made it the only logical choice of a study of this nature.
4.1.1 Onramp Locations

Only four of the five ramps in the I-75 system were included in this study. The four ramps that were included were the first four in the system as shown in Figure 4-1. The fifth and last (furthest north) ramp was not included, as resources did not allow for the ability to collect data at all five locations concurrently. Therefore, this ramp was excluded from the study completely and the system was evaluated as a four-ramp network. The four ramps in the study area include different geometric designs and configurations allowing for the evaluation of the impact of alternate ramp design on operations and modal activity.
The four ramps included the Northside Drive onramp, which is the first access point on I-75 northbound after it splits from I-85, Howell Mill Road onramp, Moores Mill Road onramp, and West Paces Ferry onramp. All of the ramps are different in terms of design and alignment and all were retrofitted with ramp meters.

The Northside Drive ramp is a loop ramp on a negative grade (-2 to –4 percent) connected to an auxiliary lane that is connected to the Howell Mill Road exit ramp 700 feet downstream.

The Howell Mill Road ramp is a short ramp (1000 feet), which is similar to the Northside Drive ramp, is also on a negative grade (-2 to –7 percent). This ramp is part of an urban diamond interchange and has a straight horizontal alignment until it reached the gore area and merges with the curved alignment of I-75 northbound.

The Moores Mill Road onramp is part of a partial cloverleaf interchange (Parclo). It has a slight curved horizontal alignment, although it is straight from the ramp meter stop bar to the merge area, and is on a positive grade (+3 percent). This ramp is the only ramp that is connected to the arterial system at a non-signalized intersection. As this would indicate, this ramp also carried the lowest traffic volume of the four study area ramps.

The West Paces Ferry onramp is a 1700 foot curved ramp on a positive grade (2 to 5 percent). This ramp is characterized as having the longest acceleration distance (820 feet from ramp meter stop bare to the end of gore) of all the study area onramps. This ramp is the final and furthest north of the ramps in the study area system.
The following Table 4-1 includes a summary of the design and alignment characteristics of each of the four study area onramps.

Table 4-1, Geometric Design Characteristics for the Study Area Onramp Data Collection Locations

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Grade</th>
<th>Ramp Length (feet)</th>
<th>Acceleration Distance (feet), (Stop Bar to End of Gore)</th>
<th>Interchange Design</th>
<th>Loop Ramp</th>
<th>Presence of Auxiliary Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northside Drive Ramp</td>
<td>-4 to 2</td>
<td>1080</td>
<td>550</td>
<td>Parclo</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Howell Mill Road Ramp</td>
<td>-7 to 2</td>
<td>975</td>
<td>450</td>
<td>Diamond</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Moores Mill Road Ramp</td>
<td>-1 to +3</td>
<td>2000</td>
<td>700</td>
<td>Parclo</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>West Paces Ferry Road Ramp</td>
<td>+2 to +5</td>
<td>2000</td>
<td>820</td>
<td>Parclo</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

4.1.2 Mainline Locations

The focus of this study was not limited to the onramp locations. A critical component of this study was to assess the impact of the vehicle activity on the freeway mainline. This research required the collection vehicle operations, modal activity, and classification data for mainline conditions. The study area included a 4.4-mile section of freeway. This section is comprised of one 700-foot weave area between the Northside Drive onramp and the Howell Mill Road off-ramp, three merge areas, and remaining 3.6 miles of basic freeway section. Four primary locations within the study area were chosen for collecting mainline data. The freeway overpasses within the study area were used as the locations for such data collection.
The Northside Drive overpass was used as the primary location for collecting mainline traffic volumes data, and was also used for collecting modal activity data. The Howell Mill Road overpass was also used as a location for collecting vehicle activity data. The Peachtree Battle Road overpass (non-interchange) located between the Howell Mill Road interchange and the Moores Mill Road interchange, was used as a third location for collecting vehicle activity data. Finally, the Moores Mill Road overpass was used as a location to sample vehicle classification and sub-fleet mix information.

4.2 Date Collection Equipment

In order to gather and store the large amounts of vehicle data needed for this research, several mechanical instruments were implemented for the data collection process. Vehicle counts were collected primarily through the use of video cameras, although Nu-Metric detectors placed on roadway and manual counting devices were also implemented during the data collection process. Instantaneous vehicle speed/acceleration profiles were collected on the ramps and mainline primarily through the use of laser guns, with supplemental data coming from probe vehicles, equipped with distance measuring instruments (DMIs).

4.2.1 Laser Rangefinders

The laser gun units used to collect vehicle modal activity for this project were the Advantage laser rangefinder (LRF) manufactured by Laser Atlanta Optics. The LRF units are portable, hand-held devices that measure the distance to an object at a high sampling frequency (238.4 distance measurements per second) with a manufacturer’s
accuracy specification of six inches. Seven laser guns, mounted on tripods for stability, were used for the collection speed profile data for this project. The LRF, or “laser gun” contains an internal algorithm, which can convert the range readings into speeds or merely download every distance measured. The latter was the mode used for this project as it provided the most detailed and disaggregate level of output. Speed and average readings are aggregated by the LRF automatically, resulting in the loss of important and descriptive data points. Collecting simple distance data from the LRF provided a more complete dataset, but required the processing of the output to calculate speed and acceleration rates. The important properties of lasers that allow for measurement of modal activity of vehicles are the wavelength, duration of emission of light, beam divergence, and coherence (Grant, 1999).

Procedural setup, operation, data collection, and data storage at the site using the Advantage LRF is discussed in the following section. Data post processing and analysis is discussed in Chapter Five.

4.2.1.1 Wavelength and Frequency

Wavelength is a fundamental characteristic of light, and each type of laser emits light with a known characteristic wavelength. The value of the wavelength is dependent upon the type of material that emits the laser light, the optical system, and how the light is energized. The wavelengths for most lasers is a range of values, but the range is so narrow that for most purposes it appears to be a single wavelength (Hecht, 1992). Specifications on the Advantage laser rangefinders are a wavelength in the infrared range of 850-950 nm (Laser Atlanta, 1997).
The wavelength of light is a convenient unit for measuring distances. The same principle of radar measurement of distance is used in calculating distances with lasers. An object is targeted with the laser, then a short pulse of light fires from the laser. The time it takes the reflected light to return to the unit is measured by the receiving lens every 35 nanoseconds.

Distance is divided by two because the light actually travels twice the distance to the target, once on its way there and the second time on its return to the receiver. Post-processing of the binary data divides the binary range into a distance of the vehicle from the laser unit. This information was then stored in files on PCMCIA cards inserted into the Advantage LRF unit.

4.2.1.2 Divergence

Observation of a visible laser through air may give the appearance of a thin line, but a closer look would show a beam with a small diameter that grows larger as it travels further from the source as shown in Figure 4-2. This spreading is called divergence, and is typically measured in milliradians. Once a sufficient distance from laser, multiplying the sine of the divergence angle (which equals the value of the angle for small angles measured in radians) by the distance the beam has traveled results in the spot radius of the laser (Hecht, 1992).
Manufacturer specifications on the Advantage are a divergence of 3 milliradians. Thus, after the beam has traveled 100 feet its diameter is 0.6 feet, or 6 feet after traveling 1000 feet. This is the average distance an automobile can be tracked under congested conditions. For heavy-duty vehicles, the rear of the trailer provides a very large surface from which the laser can range. At 2000 feet, the beam of the laser would be 12 feet in diameter, slightly larger than the width of the trailer unit. In sampling with the hand-held laser unit, it is not uncommon to track heavy-duty vehicles for distances twice as long as automobiles at the same location (Grant, 1999). Table 4-2, provides radius/diameter of the LRF beam at various distances from the unit.
Table 4-2, Laser Rangefinder Beam Radius and Diameter Readings

<table>
<thead>
<tr>
<th>Distance (feet)</th>
<th>Spot Radius (feet)</th>
<th>Diameter (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>500</td>
<td>1.5</td>
<td>3.0</td>
</tr>
<tr>
<td>1000</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>1500</td>
<td>4.5</td>
<td>9.0</td>
</tr>
<tr>
<td>2000</td>
<td>6.0</td>
<td>12.0</td>
</tr>
<tr>
<td>2500</td>
<td>7.5</td>
<td>15.0</td>
</tr>
</tbody>
</table>

Divergence of the laser beam places limitations on the LRF to track long distances. The path of the beam must not be impeded by surrounding traffic. As congestion increases, spacing between vehicles decreases, reducing the distance in which the laser is able to track vehicles before interference from surrounding traffic. Observation of the traces will most likely show more seconds of activity under congested regimes due to slower vehicle speeds, but the distance of measurement will likely be less than under free-flow conditions.

Small divergence of the laser units is important for sending the beam distances up to 2500 feet for non-reflectorized distance measurement. High directionality of the beam is an important property allowing the laser to tracking one particular vehicle in a stream of vehicles. Typical radar guns use the Doppler effect of waves to measure the speed of the object. With multiple moving objects in the field of view of a radar gun, the exact object moving cannot be determined precisely. Directionality of laser beams allows use of the heads-up display (HUD) to “aim” the beam at a particular vehicle in the stream and track it as it moves through traffic. A distinction can then be made as to the type of
vehicle (i.e. auto vs. 2-axle 6-tire, etc.) belonging to the data collected and where the vehicle was located with respect to the surrounding traffic (e.g. lane number).

### 4.2.1.3 Distance Uncertainty

Some lasers emit steady beams of light while others emit pulses that can vary in duration and frequency of occurrence. The Advantage emits pulses of laser light to measure distances to objects. The laser pulses beams at high frequency toward an object to measure the location of the object hundreds of times a second. The Advantage emits pulses of laser light at a frequency of 238.4 hertz (238.4 range readings per second). The pulse of the laser should be short for measuring distance accurately using just the return of the beam. Uncertainty in distance measurements can be computed from the formula relating the speed of light and the pulse duration. Reducing the pulse length will reduce the distance uncertainty in laser rangefinders. However, in practice, the uncertainty is strongly affected by the accuracy of pulse-timing and measurement electronics (Hecht, 1992; Landry, 1997).

The pulse duration for the handheld lasers is 35 nanoseconds, with 238.4 pulses occurring over a one-second time period. Given the constant speed of light, the 35-nanosecond pulse equates to each pulse of laser light being approximately 35 feet in length. This ray of light is sent out to the object, and bounced back to the laser unit and received by the lens. The LRF reads the returns and develops the mean time of the beam. The distance uncertainty is equal to the speed of light constant ($3*10^5$ km/sec) multiplied by the pulse duration ($35*10^{-9}$ sec) divided by 2. This gives an uncertainty of 0.00525 km, only taking into account pulse length. The uncertainty is further reduced in the
handheld lasers by varying the time in which the window is open for measuring the laser light, and primarily by measuring the intensity of the returned light to develop the mean travel time of the beam of light.

The time for which the laser unit is open to receive light is a function of the mode of operation. For first return mode, the time “window” in which the laser will range is 4 microseconds, while in last return mode the time is 100 microseconds. The energy of the returned light is measured by the unit, and based on the intensity, time, and mode of operation, a distance is computed which reduces the measurement errors in the unit. First return and last return mode operate by differentiating return sequences with 35 or more feet separation. The LRF unit has trouble when two objects in the line of the beam are closer than 35 feet to each other. When this occurs, the LRF has difficulty measuring distance to an object and most likely will be the average of the two distances (Landry, 1997). However, when the two objects are separated by 35 or more feet, two distinct range readings will be observed by the LRF, and the range returned will depend on mode (first or last) programmed on the gun.

During the data collection process of this project, the LRF units were used in both first and last return. The first return programming provides the most consistent distance readings, but as discussed above, it was not always practical to operate the units under this program. When collecting data from locations with obstructions, such as a cyclone fence, it was necessary to operate the LRF units with the last return program. If the laser beam is partially broken by an obstruction the last return program provides for unit to disregard the beam return from the obstruction. When collecting vehicle traces from an
overpass the last return program was used since there was a fence between the LRF unit and the target vehicles.

Several corrections have to be made for accurate distance measurement. The unit needs to be operated within an appropriate temperature range. The laser units, through the use of an internal thermometer, gauges the outside temperature. The LRF should also only be operated under dry conditions for the best results. In addition, the time from beam return time has to be adjusted for the time of the internal circuitry. All of the adjustments are made by the internal mechanisms of the laser before computing a distance of every reading (Landry, 1997).

4.2.2 Probe Vehicles

The Advantage LRF units were the primary means used to collect vehicle speed/acceleration profile information, although probe vehicles equipped with DMIs were used to collect supplemental information. The DMIs were used to record second-by-second vehicle distance, speed and acceleration information. The DMI equipped probe vehicles were primarily used for two functions that the LRFs were not able to perform. One, they were used to collect vehicle traces along the complete mainline section of the ramp metering system study area (i.e. over four miles). As discussed above, the LRF units operating from a stationary position are only able to track vehicles for up to 1000 feet. The Probe vehicles allowed for the collection of a limited number of traces over the entire freeway section. Two, the probe vehicles were used to collect vehicle modal activity data through curved sections of the onramps in the study. In order for the LRF units to operate effectively they need to be positioned as to track vehicles in
a straight-line trajectory—the probe vehicles allowed for the collection of data where this was not possible. The two locations were this was most critical were the curved sections of the Northside Drive and West Paces Ferry onramp locations. The DMI equipped probe vehicles were effective in collecting data under the above-described circumstance, although the amount of data collected was far less than that which could be gathered through the use of the Advantage LRFs.

The DMI employed for this project was the Nu-metrics Nitestare NS-60. The NS-60 was connected to the probe vehicle transmission and utilized a mechanical sensor to convert electronic pulses into precise distance measurements (i.e. sub-foot accuracy). For example, if the transmission pulses six times per revolution of the internal disk, and the disk revolves 1000 times per mile, approximately 6000 pulses are obtained. Therefore each pulse would represent 0.88 feet (i.e. 5280/6000). The NS-60 was calibrated to each individual vehicle depending on the pulse rate and the disk revolution rate. The accuracy of the data from the NS-60 is only as precise as the calibration process. It was therefore highly important to calibrate each probe vehicle NS-60 unit against an accurate distance measured over an even surface (Nu-Metrics, 1996). The longer the calibration distance or course the more precise the calibration. Therefore, this research utilized the runway at the South Fulton County Airport as the probe vehicle calibration course. This facility provided a 1000-foot calibration distance with minimal grade changes and that was free of curves.

Once the NS-60 units were installed and calibrated, they were ready for data collection. For the purposes of this study, a BASIC program was developed to download
and store second-by-second speed and distance information from the NS-60 to a laptop computer operated by a data collector riding in the probe vehicle. Data from each run was then stored to an individual file, downloaded, and cataloged in the lab at the end of the data collection session. The data collectors were also supplied with a log sheet and were required to manually record information related to each data run, including the data file name.

Two vehicles were equipped with DMIs during the data collection phase of this project. One of the vehicles was a 1993 Dodge Spirit and the other was a 1992 Ford Tempo.

4.3 Data Collection Process

The data collection period was spread over several months during the spring and summer of 1999, with the highest concentration of data collection occurring during a two-month period in the spring. Data collection was planned for the spring as it provided for the best weather, while also allowing for the relatively typical traffic conditions and travel patterns. As called for in the original data collection plan, a total 18 days of comprehensive data collection (i.e. concurrent monitoring at all locations) were performed. This was supplemented by partial data collection deployments during the summer months to collect additional data. During the most intense data collection period, up to 15 data collection personnel were deployed in the field on a given day.

The ramp metering system on I-75 northbound in Atlanta only operates during the evening peak period from 3:15 p.m. to 6:30 p.m. Therefore, the collection of vehicle activity for this project was centered on that same period. Data was collected on
weekdays only. Of the 18 data collection days the most five—occurred on Mondays, while the least two—occurred on Fridays. The following Table 4-3 summarizes the days on which data was collected and the number of data collection days for each day of the week.

Table 4-3, Core Data Collection Activity Summarized by Day of Week

<table>
<thead>
<tr>
<th>Day of Week</th>
<th>Number of Data Collection Days</th>
<th>Dates Data Collection was Performed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monday</td>
<td>Five</td>
<td>May 3, 10, 17, 24, &amp; June 7</td>
</tr>
<tr>
<td>Tuesday</td>
<td>Four</td>
<td>May 4, 11, 25, &amp; July 27</td>
</tr>
<tr>
<td>Wednesday</td>
<td>Four</td>
<td>May 12, 19, June 4, &amp; 9</td>
</tr>
<tr>
<td>Thursday</td>
<td>Three</td>
<td>May 20, 27, &amp; June 10</td>
</tr>
<tr>
<td>Friday</td>
<td>Two</td>
<td>May 28, &amp; June 4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>Eighteen</strong></td>
<td><strong>May 4 to July 27</strong></td>
</tr>
</tbody>
</table>

In addition, data collection was performed under dry weather conditions only. Although the LRFs are durable units designed for field use, it was recommended that they not be used in the rain. Therefore, the LRF units were not deployed under any threat of incumbent weather. Data collection deployment occurred early enough in the afternoon to allow for all data collection equipment and personnel to be in place and ready by 3:15 p.m. on a given data collection day. Data collection efforts were terminated at 7:00 p.m. each day in order to cover the complete peak travel period.
4.3.1 Data Collection Personnel

In total, 25 Georgia Institute of Technology undergraduate students were hired to assist with the data collection process. They were primarily employed to operate the seven Advantage LRFs designed to gather instantaneous vehicle speed/acceleration profiles on the Atlanta ramp metering system. These students were supervised in the field by the senior research staff. In order to gather quality data in a safe and efficient manner, the student data collectors were put through a multi stage training routine. The training schedule included project orientation, equipment training, safety procedures, and trial data collection deployment.

All student workers were hired and introduced to the project during the first week of April 1999. Student data collectors were hired for the entire spring quarter, which ran from March 30 to June 11, 1999. This coincided with the planned data collection period and was convenient for the students. Due to daylight limitations, data collection efforts that required deployment until 7:00 p.m. could not take place until after daylight savings time, which did not start until April 4, 1999. Equipment training and orientation was conducted within the two weeks following the project introduction meeting. Students were identified for a specific task early in the training sessions based on their background and availability. They were then assigned to a deployment location and trained based on the requirements of that location. That is, only those scheduled to work with the LRFs were exposed to the units, while others were trained on the probe vehicles or other data collection equipment. After the initial equipment training session, the students were
deployed in the field for test data collection sessions. Before actual data collection was initiated on May 3, 1999, two “dry” runs were conducted on April 21 and 27, 1999.

Also, before any students were deployed in the field in any capacity they were required to participate in a safety orientation. All data collectors were briefed on the safety concerns for this type of fieldwork and required to follow the following restrictions:

- At no time is a person allowed to enter an active travel way
- Each person will be dropped-off and picked-up at their designated data collections site by the research project shuttle
- They must exit the shuttle on the side of the vehicle that is not adjacent to traffic
- At no time shall anyone leave their designated location without permission from a research staff
- Each person should be alert to arrant vehicles and avoid turning their back completely to traffic
- Do not interfere with existing traffic patterns or take any activity (other than those required for data collection efforts) that may distract drivers or alter driving conditions
- Stay as far from the active travel way as possible
- Do not alter traffic control devices that have been placed at the data collection sites intended to enhance safety.
- All persons must adhere to the dress code, which includes safety vest, hardhat, and long pants.
- Data collection performed in a vehicle must be conducted by teams of two or three. The drivers of the vehicles are not allowed to perform any activity other than operating the vehicle.

In order to assure safe and proficient data collection, the data collection personnel were provided with a field manual. This handbook was provided to each student worker and included detailed data collection instructions for all tasks, and operating and safety procedures. A copy of this manual is provided in Appendix B. The data collection
personnel were mainly involved in the collection of vehicle speed profiles, but were also used to operate probe vehicles and collect vehicle traffic counts.

4.3.2 Collection of Vehicle Modal Activity Data

Vehicle modal activity data, such as speed/acceleration profiles, were collected on all four study area freeway onramps and the entire 4.4-mile study area mainline section. The Advantage LRFs and instrumented probe vehicles were used to collect the vehicle modal activity data. Seven LRFs and two probe vehicles were utilized for the data collection effort. Equipment and field deployment tests started during the end of April with full deployment commencing in May of 1999.

Once the change to daylight savings time occurred in April, sufficient light was available to allow for data collection activities until the required 7:00 p.m. time period. The collection of the vehicle modal activity data was to be center around the p.m. peak period when the ramp meters were in operation. The data collection activities were carried out for approximately four hours per session from 3:15 p.m. to 7:00 p.m. on a typical day. Eighteen days of comprehensive data (i.e. collection of data at all ramps and the mainline simultaneously) and five days of partial data (i.e. one or two locations) were collected during the months of May, June, and July of 1999. The most intensive data collection efforts occurred between, May 3 and June 10, 1999, with seventeen days of full deployment (i.e. six to seven LRFs) taking place during that period. During four of these days, the ramp meters were turned off for the entire peak period. The five additional partial deployments and one full deployment occurred during the end of June
and July to provide supplemental data to the core data collected in May and the beginning of June.

4.3.2.1 Laser Rangefinder Deployment

Advantage LRFs were deployed at eight different northbound onramp and overpass locations in the study area in order to gather appropriate vehicle modal activity data. The LRFs were mounted on tri-pods during data collection. LRFs were positioned on the Northside Drive, Howell Mill Road, and Peachtree Battle Road overpasses to capture mainline vehicle activity. Five LRFs were positioned on all onramp locations in the study area to capture ramp activity. This included one on the Northside Drive onramp, two on the Howell Mill Road onramp, two on the Moores Mill Road onramp, and one on the West Paces Ferry Road onramp.

It was not possible, nor practical, to trace each vehicle that passed each of the LRF locations. Therefore, each location had a sampling routine designed to gather activity data from a sample of vehicles from each site. The data collectors on the onramps were simply instructed to track every fourth vehicle that passed their location. This provided a representative sample of vehicle activity. A similar system was used for the mainline locations, but since the traffic volume did not allow for counting all vehicles, the data collectors were instructed to track every fourth vehicle after their attention had returned to the LRF HUD. Each vehicle that was selected was classified by vehicle type based on the Federal Highway Administration (FHWA) 13-vehicle classification scheme. This study was primarily concerned with typical passenger cars and sports utility vehicles (SUVs). Vehicle classification was tracked through the use of a handheld JAMAR board.
electronic counter. This information was matched back to the vehicle trace during the
data processing phase of the project (Grant, 1997b).

It would have been possible to gather information at a faster rate then every fourth
vehicle, but since the data collectors were required to also fill out a log sheet as a data
quality assurance procedure, the sampling rate had to be slowed. In addition, data
collection sessions were over four hours long and thus, data collection pace was an
important consideration for data collector fatigue. A reasonable data collection pace
provided for consistent data quality throughout the complete data collection session.
Detailed data collector instructions for LRF operations, sampling procedures, vehicle
classification routine, and a sample log sheets are provided in the data collection manual
shown in Appendix B.

Two LRFs were rotated between the three overpass locations during the data
collection period. The Peachtree Battle Road and Howell Mill Road locations were used
extensively to capture mainline activity as they provided the most advantageous sites for
tracking vehicles. The Howell Mill road location recorded vehicle mainline activity in
the merge area while Peachtree Battle location captures activity on the basic section
between the Howell Mill road interchange and the Moores Mill Road interchange. The
Northside Drive location was used to a lesser degree to capture weaving and vehicle
activity on the Northside Drive onramp and Howell Mill Road off ramp weave section.
Approximately 8,000 mainline vehicle tracings were collected from these three locations.

The remaining five LRFs were deployed at the four ramp locations. The Northside
Drive LRF was positioned behind the barrier wall immediately behind the stop bar for the
ramp meter. This LRF captured vehicle activity from the stop bar to the merge area and weave section with the Howell Mill Road off-ramp. A LRF was placed at this location for 17 days during the data collection period recording approximately 68 hours of vehicle activity. Roughly 4,000 vehicles were tracked during this period at this site.

Two LRFs were deployed at the Howell Mill location, one for 18 days and the other for 17 days during the core of the data collection effort. One LRF was placed at the top of the ramp recording activity of vehicles as they approach the ramp meter stop bar. The other LRF was placed just upstream of the ramp meter and recorded vehicle activity from the stop bar through the merge with I-75 northbound. Over 3,800 vehicles were tracked at each of these locations.

One LRF was positioned at the Moores Mill Road onramp approximately 100 feet behind the ramp meter. Twenty days of vehicle activity data were collected at this position from the ramp meter stop bar to the I-75 merge section. Approximately 4,600 vehicle tracings were recorded at this location. For one day during the data collection period, a LRF was placed at the head of the Moores Mill Road Ramp in order to collect data as vehicles approached the meter stop bar. Over 300 vehicles were traced on that day.

The West Paces Ferry Road onramp was the final location for the positioning of an LRF. This LRF was placed in advance of the ramp meter due to physical limitations of the site. The position recorded vehicle activity from approximately 50-75 feet from the stop bar through the merge section with I-75 northbound. Almost 4,000 vehicle tracings
were recorded at this location. The LRF vehicle activity data collected from all of the nine locations is summarized in the following Table 4-4.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Total Days of Data Collection</th>
<th>Days of Data Collection With Metes Off</th>
<th>Total Hours of Data</th>
<th>Number of Usable Vehicle Tracings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northside Drive Ramp</td>
<td>17</td>
<td>4</td>
<td>68</td>
<td>3926</td>
</tr>
<tr>
<td>Howell Mill Road Ramp</td>
<td>17</td>
<td>4</td>
<td>68</td>
<td>3268</td>
</tr>
<tr>
<td>Howell Mill Road Ramp, Advanced</td>
<td>18</td>
<td>4</td>
<td>72</td>
<td>3733</td>
</tr>
<tr>
<td>Moores Mill Road Ramp</td>
<td>20</td>
<td>4</td>
<td>80</td>
<td>4426</td>
</tr>
<tr>
<td>Moores Mill Road Ramp, Approach</td>
<td>1</td>
<td>0</td>
<td>4</td>
<td>307</td>
</tr>
<tr>
<td>West Paces Ferry Road Ramp</td>
<td>18</td>
<td>6</td>
<td>72</td>
<td>3189</td>
</tr>
<tr>
<td>Northside Drive Overpass</td>
<td>4</td>
<td>1</td>
<td>16</td>
<td>804</td>
</tr>
<tr>
<td>Howell Mill Road Overpass</td>
<td>15</td>
<td>3</td>
<td>60</td>
<td>3584</td>
</tr>
<tr>
<td>Peachtree Battle Road Overpass</td>
<td>11</td>
<td>3</td>
<td>44</td>
<td>2790</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>121</strong></td>
<td><strong>31</strong></td>
<td><strong>484</strong></td>
<td><strong>26,027</strong></td>
</tr>
</tbody>
</table>

4.3.2.2 Probe Vehicle Deployment

The probe vehicles instrumented with DMIs were used to supplement the LRF data or fill in where it was not practical to use the LRFs. The primary use of the probe vehicles was to collect comprehensive data for the entire study area mainline section. In addition, the probe vehicles were used to capture vehicle activity on portions of the onramps in which the use of LRFs was not practical, safe, or feasible. For the most part this consisted of curved sections of a ramp where the use of an LRF would be ineffective.
The two primary locations were this occurred was on the Northside Drive onramp and the West Paces Ferry Road onramp, from the top of the ramp to the ramp meter stop bar. The probe vehicles were used on the Moores Mill Road onramp as well.

In order to acquire data with instrumented vehicles, a standard data collection procedure was developed. This procedure was used in the collection of all data using the instrumented vehicles. This procedure was adapted from the procedures developed by Sierra Research during cycle development work (Austin, et al. 1993). The probe vehicle procedure is shown in the following. Complete driver instructions, procedures and sample log sheets can be seen in the data collection manual shown in Appendix B:

1. Enter the freeway at designated location.
2. Driver spots the first white vehicle downstream (in front) of him/her, and enters the lane in which that vehicle is found (when it is safe to do so). Once in the lane, the vehicle immediately in front of the driver is the target vehicle. Driver indicates which vehicle is the target vehicle to the data collector.
3. Follow the target vehicle and mimic its behavior as best as possible, while maintaining a safe distance from the vehicle (headway). This means the driver brakes when it brakes, changes lanes when it changes lanes, speeds up when it speeds up, and maintains the speed at which it travels, including above the speed limit (assumes permission to break speed limits obtained from regulatory authorities).
4. A target vehicle must be acquired before the beginning flag for the run (usually a designated roadside sign, bridge pier, etc.) is reached. A target vehicle must be tracked through the run until the ending flag is reached.

**Target Vehicles:** The target vehicle is the vehicle that the instrumented vehicle is following. The instrumented vehicle is trying to capture the speed and acceleration activity of the target vehicle.

**Following Above Speed Limit:** Target vehicles can travel above the speed limit. On some facilities it is quite common. If runs are aborted because the target vehicle goes above the speed limit, the data sample will be biased due to the lack of vehicles in the sample, which travel above the speed limit. Although for safety purposes, the probe vehicles were not allowed to exceed the design speed of the freeway (approximately 10
mph over the posted speed limit). If this speed was exceeded or a target vehicle was lost for other reasons a new vehicle was chosen.

Changing the Target Vehicle: Each selected target is followed as long as reasonably possible. If a target cannot be followed safely through a lane or speed change, a new target is chosen.

a. If a vehicle gets between driver and the target vehicle, the vehicle immediately in front of the driver becomes the (new) target vehicle. If no vehicle is immediately in front of the driver, a new target vehicle will be acquired using the same procedure used to acquire the initial target.

b. If a vehicle changes lanes in busy traffic (or some other erratic maneuver) and cannot be followed, the driver will duplicate the maneuver safely as soon as possible. Once the maneuver is complete and the driver is in the new lane, the vehicle immediately in front of the driver becomes the (new) target vehicle.

c. If a vehicle exits or obviously is going to exit, a new target is selected. The vehicle immediately in front of the driver becomes the (new) target vehicle.

During the primary data collection phase in May and June, at least one vehicle was in operation collecting mainline activity data for the entire study area. Probe vehicles were not deployed during the last four data collection sessions. On six of the days, there were two vehicles collecting mainline data. Due to ramp data collection needs and mechanical problems, it was not always possible to run both vehicles on every data collection day. On four occasions, one of the vehicles was collecting ramp activity data at one of the above-discussed locations, while the other collected mainline data.

In total, this accounted for 20 vehicle days of data collected on the mainline section over the course of the data collection period. This accounts for 212 complete probe vehicle runs, from the beginning of the study area from the Williams Street onramp to the Mount Pharan Road off-ramp. A complete summary of the mainline probe vehicle data runs is shown in the following Table 4-5.
Table 4-5, Summary of Probe Vehicle Runs for the Mainline Section

<table>
<thead>
<tr>
<th>Run Date</th>
<th>Number of Runs Vehicle 1, (Dodge)</th>
<th>Number of Runs Vehicle 2, (Ford)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 3, 1999</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>May 4, 1999</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>May 10, 1999</td>
<td>12</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>May 11, 1999</td>
<td>9</td>
<td>12</td>
<td>21</td>
</tr>
<tr>
<td>May 12, 1999</td>
<td>15</td>
<td>11</td>
<td>26</td>
</tr>
<tr>
<td>May 17, 1999</td>
<td>12</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td>May 19, 1999</td>
<td>10</td>
<td>13</td>
<td>23</td>
</tr>
<tr>
<td>May 20, 1999</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>May 24, 1999</td>
<td>12</td>
<td>9</td>
<td>21</td>
</tr>
<tr>
<td>May 25, 1999</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>May 27, 1999</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>May 28, 1999</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>June 2, 1999</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>June 4, 1999</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>June 9, 1999</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>June 10, 1999</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>July 27, 1999</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>135</strong></td>
<td><strong>77</strong></td>
<td><strong>212</strong></td>
</tr>
</tbody>
</table>

Eleven vehicle days of data accounting for 276 vehicle runs were performed at the ramp locations, 15 runs at Moores Mill Road onramp, 91 runs at West Paces Ferry Road onramp, and 170 runs at Northside Drive onramp. This data was used to validate and supplement the LRF data. The onramp data collection runs for the probe vehicle are summarized in the following Table 4-6.
<table>
<thead>
<tr>
<th>Run Data and Ramp Location</th>
<th>Number of Runs Vehicle 1, (Dodge)</th>
<th>Number of Runs Vehicle 2, (Ford)</th>
<th>Total Number of Runs</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 13, 1999 Northside Drive</td>
<td>9</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>May 25, 1999 West Paces Ferry Road</td>
<td>0</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>May 26, 1999 Northside Drive</td>
<td>48</td>
<td>0</td>
<td>48</td>
</tr>
<tr>
<td>May 27, 1999 West Paces Ferry Road</td>
<td>29</td>
<td>0</td>
<td>29</td>
</tr>
<tr>
<td>May 28, 1999 Northside Drive</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>June 29, 1999 West Paces Ferry Road</td>
<td>18</td>
<td>0</td>
<td>18</td>
</tr>
<tr>
<td>July 6, 1999 Moores Mill Road</td>
<td>14</td>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>July 13, 1999 Northside Drive</td>
<td>21</td>
<td>0</td>
<td>21</td>
</tr>
<tr>
<td>July 15, 1999 Northside Drive</td>
<td>23</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>July 20, 1999 West Paces Ferry Road</td>
<td>19</td>
<td>0</td>
<td>19</td>
</tr>
<tr>
<td>July 27, 1999 Northside Drive</td>
<td>39</td>
<td>0</td>
<td>39</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>220</strong></td>
<td><strong>55</strong></td>
<td><strong>275</strong></td>
</tr>
</tbody>
</table>

4.3.2.3 Subfleet Characteristics Data

In order to gain fleet characteristic information needed for the MEASURE model, vehicle license plate information was collected for a sample of vehicles in the study. Mainline vehicle license plates were sampled by recording plates from the Moores Mill Road overpass using a spotting scope and an audio recorder. This plate information was
associated with a VIN through registration information and decoded to provide detailed fleet information. Over 5000 mainline vehicle plates were recorded at this location.

Ramp fleet mix data was collected on five days at the Mores Mill Road Ramp concurrent with the collection of the LRF data at that location. This data was used to supplement the data collected by the remote sensing crews deployed at all of the ramps during the data collection period. Remote sensing crews collected two to three days of data at each ramp location providing fleet mix data for over 20,000 vehicles operating on the ramps during the data collection period.

The mainline and ramp data was combined to create a single database representative of the fleet operating in the study area during May and June. This database contained critical information for each vehicle, which was used during the emissions modeling process. This included model year, number of cylinders, emissions control type, weight, and odometer reading from the last inspection maintenance check.

4.3.2.4 Traffic Volume Data

Concurrent with the collection of vehicle modal activity data, traffic volume data was also collected. Video cameras and Nu-Metric devices were used to collect the traffic count data. A combination of GDOT traffic management center (TMC) freeway surveillance cameras and portable School of Civil and Environmental Engineering cameras were used to record the traffic movements during the data collection periods. The Nu-Metric devices were used on some ramp locations when cameras were not available or convenient to employ.
The video cameras were used to record freeway mainline traffic, onramp and off-ramp volumes, and turning movement traffic at all intersections where the arterial system connected with the study area ramp system. This included Northside Drive, Howell Mill Road, Moores Mill Road, and West Paces Ferry Road.

Twelve TCM camera views were used to record most of the mainline and onramp and off-ramp activity. Five portable cameras were used to record turning movement activity on and off of the northbound ramps. Over 500 hours of videotape were recorded during the data collection effort. This data was later reduced in the lab and entered into a database to create a comprehensive traffic count dataset for every day that modal activity data was collected.

### 4.4 DATA REDUCTION

The data reduction procedures included the processing of all the data collection elements, but the focus was on the preparation of the LRF data for analysis. The data reduction process was comprised of several steps including data cleaning (i.e. removing errant data), data transformation (i.e. post processing data into a useable form), data coding, and data storage. Not all steps were required for all data elements. The reduction of the license plate data, traffic count data, and probe vehicle data, which will be discussed first, only required simple processing and manipulation. The LRF data reduction, which will be presented in the final section, required a more sophisticated reduction process.
4.4.1 License Plate Data Reduction

The license plate data used for the subfleet characterization was collected in two different forms and therefore required two reduction procedures. The mainline data was collected manually through the use of audio recorders. The ramp data was collected through the use of video cameras. Both datasets were reduced to digital format, which included the location and date/time stamp. The digital data was then matched with the Georgia Department of Revenue vehicle registration database to match vehicle identification numbers (VINs), model year information, and vehicle type information to the plates. A VIN decoding software was then used to append additional vehicle data to the plate data. These data included make, model, number of engine cylinders, fuel transfer type, emissions control, and vehicle weight. The next step was then to match the VIN to the state inspection and maintenance database and append the final data pieces. These include the odometer reading and transmission type.

The final step was then to combine all the data into a single database so that it could be used to provide the fleet technology and age information necessary for the MEASURE model algorithms. Over 30,000 vehicle plates were recorded during the course of this project, but many of the recorded plates did not lead to complete information. This was the result of several factors. First, many plates were recoded or reduced incorrectly resulting in a mismatch with the registration database. In addition, any out-of-state plates would also not match with the registration database. Secondly, oftentimes-valid VINs will not be decoded nor match the inspection maintenance database. At each step of the process, 10 to 20 percent of the data will not have complete information. As a result, of
the over 30,000 plates collected, complete information was only acquired for approximately 6,000 vehicles. An overall 20 percent match rate may seem low, but the 6,000 complete records and additional partial records provided sufficient data for the MEASURE model. However, it should be noted that the information used to develop the technology group distributions was limited.

4.4.2 Traffic Count Data Reduction

Traffic count data used to assess traffic operations conditions and provide traffic volumes and flow rates was primarily collected through the use of video surveillance. The field videos were viewed and reduced in the lab using TDIP traffic count software. The data reduction process included coding the counts for date, time, vehicle classification, and lane assignment for the mainline vehicles. Once this data was recorded into digital format, it was combined into a single database. This data was then binned in five-minute groups by location, and processed to estimate traffic volumes at location where data was not collected. This provided for a complete traffic count dataset, which was then used to match with the probe vehicle and LRF data for analysis.

4.4.3 Laser Rangefinder Data Reduction

Due to the volume and coarseness of the data, the LRF dataset provided the largest data reduction challenge. As discussed in section 2.4.1, the LRFs were operated in real time range mode in order to collect the most accurate and detailed data. Since the LRF data was collected in this mode, extensive post processing was required. When operating in real time range mode, the output from the LRF unit are simple distance
measurements. The information needed to produce speed/acceleration profiles must be calculated from this field data. The consistency of the LRFs makes this a reasonably easy process for a single trace, but it is complicated when large amounts of data are considered. The LRFs receive precisely 238 readings a second; therefore the time between each distance measurement is always the same. Knowing this, the distance and time information were used to calculate speed and the rate of change in speed (i.e. acceleration).

In the field, each vehicle trace was recorded as a single data file that was stored on a PCMCIA data card inserted into the LRF unit, which was periodically downloaded to a laptop computer for temporary storage. At the end of each data collection day, all of the LRF files along with their accompanying JAMAR vehicle classification files were downloaded and stored in the lab under unique folders indicating the date and location for which the files were associated. On a given day there were hundreds of LRF files from each data collection site, but only one JAMAR file from each site. The single JAMAR file contained the vehicle classification information for all traces from that site. An example of a raw LRF data file is shown in Figure 4-3 and an accompanying JAMAR vehicle classification file can be seen in Figure 4-4.
Figure 4-3, Sample LRF Output File

00223.1f
00223.3f
00223.3f
00223.3f
00224.1f
00223.3f
00224.1f
00224.1f
00224.1f
.

Figure 4-4, Sample JAMAR Vehicle Classification Output File

Jamar Board Count # 1
Site Code #: 00220520

Collection Date: 05-20-99

Start Time: 15:31:0.00
6 axle, multi-unit           Time: 15:31:00.81
2 axle, 6 tire single unit   Time: 15:32:43.17
Car                           Time: 15:33:30.45
Car                           Time: 15:33:50.26
3 axle, single unit           Time: 15:34:31.28
Car                           Time: 15:35:11.37
Car                           Time: 15:35:42.68
Pickup/Van/Motorhome         Time: 15:36:11.45
Pickup/Van/Motorhome         Time: 15:36:33.84
Pickup/Van/Motorhome         Time: 15:37:06.12
Car                           Time: 15:37:42.79
Car                           Time: 15:38:12.82
The LRF data reduction process was divided into four distinct steps. The first was to reconcile the LRF output with the JAMAR vehicle classification file. The second was to process the LRF distance readings into second-by-second vehicle speeds and acceleration rates. The third step was to condense the individual data files into a single database. The fourth step was to group the data into 15-minute bins for analysis. The completion of these four steps resulted in a single convenient dataset that could be used for all the analysis required for this research.

The PCMCIA cards used to store the LRF data, as it is being recorded, held up to 100 data files or vehicle traces. Typically the 2mb data card run out of room before 100 traces could be recorded and only 50 to 60 traces typically fit on a single card. In the field, when a card was filled it was downloaded to a laptop computer and the process was started over. In order to process the LRF files they need to be matched with a JAMAR file so that the vehicle classification of the trace would be known. There needed to be a single JAMAR file for each group (i.e. PCMCIA card) of LRF data. At the end of a given day, there was only one JAMAR file for all the LRF data from a particular site. Therefore, as part of the data processing, the JAMAR file needed to be divided into parts to match the appropriate number of LRF file groups. It was also necessary for each new JAMAR file to contain the same number of vehicles as there are files in the group with which it was matched. For example, if a data collector recorded 10 vehicle traces on a particular PCMCIA card, then its matching JAMAR file needed to contain 10 vehicle classification records. The LRF log sheets were used to reconcile discrepancies between the LRF data and the JAMAR data. On some occasions, data were lost if an
accompanying JAMAR file did not exist or could not be reconciled. Such instances resulted in a loss of approximately 10-15 percent of the LRF traces.

Once the data was matched with a JAMAR file, the second step was performed. A FORTRAN program (RANGE72) was developed that processed the raw LRF data into usable speed and acceleration information for each trace. At the same time this program would extract the vehicle classification, date, time, and metering condition (i.e. meter on or meter off) data from the JAMAR file and append it to the processed LRF data. The program also filtered out errant or inaccurate LRF data points resulting from data collector or LRF error. The conclusion of this step ended with usable data, but it was in flat file form as shown in Figure 4-5. The output of the RANGE72 program assigned each vehicle trace a single record which included a trace number, location code, date, time, metering code, vehicle classification code, trace increment (second), distance, speed (mph), and acceleration rate (mph/sec). The last four data fields (increment, distance, speed, and acceleration rate) were repeated for every second (increment) of the trace. Step three condensed these files and converted the flat file format into a more practical and functioning database.

Figure 4-5, Example of Laser Rangefinder Data File After Being Processed by the RANGE72 Program

<table>
<thead>
<tr>
<th></th>
<th>Trace Number</th>
<th>Date</th>
<th>Time</th>
<th>Metering</th>
<th>Location Code</th>
<th>Speed (mph)</th>
<th>Distance</th>
<th>Acceleration Rate (mph/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:36:04</td>
<td>on</td>
<td>2</td>
<td>71.7</td>
<td>20.5</td>
<td>5.4</td>
</tr>
<tr>
<td>2</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:36:40</td>
<td>on</td>
<td>3</td>
<td>37.9</td>
<td>16.4</td>
<td>5.8</td>
</tr>
<tr>
<td>3</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:37:08</td>
<td>on</td>
<td>3</td>
<td>94.9</td>
<td>25.2</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:37:44</td>
<td>on</td>
<td>2</td>
<td>72.5</td>
<td>20.3</td>
<td>3.2</td>
</tr>
<tr>
<td>5</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:38:19</td>
<td>on</td>
<td>3</td>
<td>22.9</td>
<td>11.8</td>
<td>4.5</td>
</tr>
<tr>
<td>6</td>
<td>00220520,</td>
<td>05-20-99</td>
<td>17:38:48</td>
<td>on</td>
<td>3</td>
<td>12.2</td>
<td>9.6</td>
<td>5.6</td>
</tr>
</tbody>
</table>
As stated, the third step utilized a second procedure to condense the data files into a single database while also transposing the data format. In order to store the data more efficiently, the new database structure stratified the data into two tables: one table containing just the trace information and the other table containing the vehicle and location information. At this time, additional descriptive data (e.g. ramp grade, metering rate, lane number, etc.) was added to another related table in the database. During this process, a final data cleaning procedure was also performed. This included the removal of errant speed and acceleration data not filtered out by the RANGE72 program. Any remaining unrealistic speed or acceleration observations were removed from the dataset.

The fourth and final step was to group the data into bins by date, time (15-min periods), and location. This was a necessary step in order to have the data in a final usable form for analysis. That is, the LRF data had to be normalized before it could be read for analysis. The binning process included normalizing the dataset. During the data collection process the data samples varied by location (i.e. data collection site) and within locations (i.e. at different points along the ramp). Not all vehicles were traced for the same distance along the ramp, which resulted in varying frequency of data points at various points down the ramp. If the data were not normalized by the sample size then any conclusions using the data would be biased by the areas with larger amounts of data. Since it is likely that vehicle modal activity will be different at different points along the ramp section (e.g. at the stop bar versus at the merge area), this was an important process. As a result, the final data analysis consisted of assessing modal activity of vehicles in the aggregate by 15-minutes periods and not as individual vehicle traces. The binned LRF
data was appended to the traffic count data to form a comprehensive database that included ramp and mainline traffic flow information.

The four steps discussed above summarize the process used to reduce the raw LRF data into a usable form. The final process related to the LRF data was to assess any biases that potentially exist within the dataset.

4.4.3.1 Assessing Potential Laser Rangefinder Data Bias

Even under ideal conditions it is difficult collect a perfect dataset. The most effective way to handle any limitations with a dataset is to understand any limitations and account for them appropriately. There are two main areas with this particular dataset where biases might exist. The primary concern was if the data was representative. That is, is the data a random sample of vehicle activity that is representative of the traffic as a whole? Secondary to this is whether or not the sample was constant across day and location and particularly within each location (e.g. across the complete ramp section).

To test for any potential bias in the sampling procedure, the LRF data sample was compared to the observed vehicle count data. The vehicle classification of the LRF sample was compared to the vehicle classification distribution of the total traffic volume. As can be seen in Table 4-7 the control traffic mix distribution closely matched the sampled traffic distribution for the LRF data. This was particularly true for automobiles and SUVs, the vehicles of concern for this research. This showed that the dataset was free of any systematic sampling bias. As a result it was assumed that dataset was truly random and that any bias in the data (e.g. driver behavior) would also be randomly distributed.
Table 4-7, Comparison of Laser Rangefinder Sample with Observed Traffic

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>LRF Sample</th>
<th>Observed Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Cars</td>
<td>% SUVs</td>
</tr>
<tr>
<td>Northside Drive Ramp</td>
<td>65.3</td>
<td>33.6</td>
</tr>
<tr>
<td>Howell Mill Road Ramp</td>
<td>59.6</td>
<td>36.4</td>
</tr>
<tr>
<td>Moores Mill Road Ramp</td>
<td>52.3</td>
<td>44.9</td>
</tr>
<tr>
<td>West Paces Ferry Road Ramp</td>
<td>61.1</td>
<td>36.9</td>
</tr>
<tr>
<td>Mainline</td>
<td>65.9</td>
<td>30.9</td>
</tr>
</tbody>
</table>

Due to the characteristics of the LRFs and the application for this research, there was concern that larger vehicles would be traced for longer distances resulting in a bias toward larger vehicles in the dataset at longer ranges. The primary concern was that larger SUVs might bias the data by being over-represented in certain parts of the dataset. Since SUVs are likely to be operated (i.e. accelerate) differently than typical passenger vehicles, this would not be desirable. Ideally, data with a uniform distribution of vehicles by type by distance from the data collector would be the goal. Therefore, the distribution of SUVs by distance from the LRF collection site was tested to see if it was uniform. The Chi-Squared Goodness-of-fit test was used to evaluate the distribution for each data collection site (Knaji, 1999). For each case, as shown in Table 4-8, the test showed that since the Chi-Squared value (for 16 degrees of freedom) was not exceeded for any case, the distribution over distance was uniform, with a high (i.e. 99.5%) level of confidence.
Table 4-8, Chi Squared Goodness of Fit Test Results for the Sport Utility Vehicle Sample Distribution

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Chi Squared Value</th>
<th>Chi Squared Critical (16df,.005)</th>
<th>Null Hypothesis Accepted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northside Drive Ramp</td>
<td>21.72</td>
<td>34.27</td>
<td>Yes</td>
</tr>
<tr>
<td>Howell Mill Road Ramp</td>
<td>6.02</td>
<td>34.27</td>
<td>Yes</td>
</tr>
<tr>
<td>Moores Mill Road Ramp</td>
<td>7.06</td>
<td>34.27</td>
<td>Yes</td>
</tr>
<tr>
<td>West Paces Ferry Road Ramp</td>
<td>16.12</td>
<td>34.27</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Based on these results, it was concluded that an over-representation of larger vehicles did not exist within the LRF dataset.

4.4.4 Probe Vehicle Data Reduction

Each probe vehicle run, whether it was on the mainline section or a ramp, was saved by the data collector as an individual file on a laptop computer. At the end of each data collection day the files on the laptop were downloaded and stored in the lab. The output from the DMI was in second-by-second speed and distance format, and therefore did not require as much post processing as with the LRF data. A sample of the DMI data output is shown in Figure 4-6. At the end of the data collection period, all the data files were condensed and aggregated into a single summary data file. The probe vehicle data was analyzed separately for each location and stratified by ramp metering condition. It was used for small-scale analysis (i.e. 15-minute bins) in the same way that the LRF data was used. For the ramp locations, this data provided speed/acceleration information for locations where the LRF used was not practical. For the mainline section, this provided
trace data for entire freeway section and was stratified by type of section (i.e. merge, diverge, weave, and basic).

Figure 4-6, Sample Distance Measurement Instrument (DMI) Data Output File

<table>
<thead>
<tr>
<th>Count, Distance,</th>
<th>Change in Distance,</th>
<th>Speed,</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 0</td>
<td>0</td>
<td>0</td>
<td>15:47:09</td>
</tr>
<tr>
<td>2. 0</td>
<td>0</td>
<td>0</td>
<td>15:47:10</td>
</tr>
<tr>
<td>3. 0</td>
<td>0</td>
<td>0</td>
<td>15:47:11</td>
</tr>
<tr>
<td>4. 10</td>
<td>10</td>
<td>20</td>
<td>15:47:12</td>
</tr>
<tr>
<td>5. 34</td>
<td>24</td>
<td>17</td>
<td>15:47:13</td>
</tr>
<tr>
<td>6. 56</td>
<td>22</td>
<td>16</td>
<td>15:47:14</td>
</tr>
<tr>
<td>7. 80</td>
<td>24</td>
<td>17</td>
<td>15:47:15</td>
</tr>
</tbody>
</table>

Once all of the data was collected and reduced to a usable format, the analysis procedures discussed in Chapter Three were implemented. The results of these procedures are presented in the following research findings chapter.
CHAPTER V

5 PRESENTATION OF FINDINGS

One of the objectives of this research was to develop a method to sample representative modal activity on freeway onramps and mainline sections of the Atlanta ramp metering system. This methodology was presented in Chapters Three and Four. The other objectives of this research were to assess the emissions impacts of ramp metering systems and determine the design and traffic conditions that influence modal activity and emissions rates. The analysis findings related to these objectives are presented in this chapter.

First the observed differences in modal activity under metered and non-metered conditions will be presented. This will be followed by a discussion of the emissions estimates for NOx produced using both the MEASURE and MOBILE5b models. The final section will include the findings related to differences in observed modal activity under various design and traffic demand conditions. Conclusions, recommendations, and proposed ramp metering guidelines will be presented in Chapter Six.
5.1 Modal Activity Findings

It is clear that the installation of a ramp metering device that requires all vehicles to come to a complete stop on a freeway will influence modal activity. If nothing else it will decrease the average speed resulting in longer periods of operation for each vehicle traversing the onramp. The question is to what degree is modal activity altered and what are the offsetting factors resulting from improvements to mainline traffic flow. The following Table 5-1 shows the difference in modal activity for all ramps combined and the mainline section based on three measures.

Table 5-1, Average System Wide Modal Activity for Metered and Non-Metered Conditions*

<table>
<thead>
<tr>
<th>Modal Activity Measure</th>
<th>Ramp, Metered</th>
<th>Ramp, Non-Metered</th>
<th>Mainline, Metered</th>
<th>Mainline, Non-Metered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td>32</td>
<td>41</td>
<td>63</td>
<td>62</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>2.2</td>
<td>1.8</td>
<td>0.14</td>
<td>0.12</td>
</tr>
</tbody>
</table>

* From a Combination of Laser Rangefinder and Probe Vehicle Data

As would be expected, the average speeds are slower and the acceleration rates are higher on the onramps under metered conditions. More detailed modal activity findings for each individual location are discussed in the following section. Detailed mainline freeway section modal activity finding are discussed in Section 5.1.2.
5.1.1 Onramp Modal Activity

The LRF data, supplemented by the probe vehicle data, show significant differences in the level of modal activity on the study area onramps, as a function of the metering condition. Several different speed and acceleration measures are presented to illustrate the magnitude of differences in observed modal activity. These include the average speed, average acceleration rate, percent of cycle with acceleration greater than 3 mph/sec, percent of cycle with acceleration greater than 6 mph/sec, percent of cycle with deceleration greater than 2 mph/sec, percent of cycle with inertial power surrogate (IPS) greater than 90 mph²/sec, and percent of cycle with IPS greater than 120 mph²/sec. To show the differences in modal activity for vehicles approaching the ramp meter stop bar and those accelerating from the ramp meter stop bar to the merge area, the data for each ramp location are presented for the deceleration zone (before the stop bar) and the acceleration zone (after the stop bar). The modal activity for each location is also presented in graphical form as a joint acceleration-speed probability density function (JASPROD). The JASPROD summarizes the relative frequency of different combinations of speeds and accelerations and displays it in a three-dimensional format.

The modal activity findings are presented for each location individually. First data from the Northside Drive onramp will be presented followed by Howell Mill Road, Moores Mill Road, and finally West Paces Ferry Road. The Northside Drive and Howell Mill Road location experienced the heaviest traffic volumes each carrying the equivalent of over 400 passenger cars an hour, as can be seen in Figure 5-1. The Moore Mill Road
and West Paces Ferry Road locations experience much lighter traffic carrying the equivalent of 150 to 200 passenger cars over an hourly average.

Figure 5-1, Passenger Car Equivalent, Average Hourly Traffic Volumes by Ramp Location

![Figure 5-1](chart.png)

5.1.1.1 Northside Drive Onramp Modal Activity

An assessment of the modal activity variables shown in Table 5-1 indicates an increase in modal activity that will likely lead to increased occurrence of enrichment and as a result an increase in motor emissions. The exception to this if for the activity associated with the deceleration zone. Modal activity, such as average acceleration rate, in this zone is lower under metered conditions. Any emissions benefit associated with this change in vehicle activity will likely be offset by the change in average speed. That is, even though the model variables are lower in the deceleration zone under metered
conditions the increased engine time associated with the lower travel speed will likely result in an increase in mass emissions. The emissions rate for metered vehicle may be lower on a grams per second basis, but the vehicle will occupy the onramp for a longer period resulting in higher net emissions. The only modal variable that is not lower under metered conditions in the deceleration zone is the percent of cycle with deceleration greater than 2 mph/second. This would be expected, and is consistent across all sites since vehicles are required to come to a stop at the ramp meter location.

Table 5-2, Summary of Modal Activity for the Northside Drive Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Northside Drive Onramp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
</tr>
<tr>
<td></td>
<td>Deceleration Zone</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>12</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-0.3</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>2.2</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.3</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>9.3</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>1.4</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>0.5</td>
</tr>
</tbody>
</table>
The changes in modal activity best illustrated through the use of the graphical JASPROD. By comparing the surface of the JASPROD, the differences in model activity for emissions critical regions can be highlighted. JASPRODs for the metered and non-metered conditions on the deceleration zone for the Northside Drive onramp are shown in Figure 5-2 and Figure 5-3.

Figure 5-2, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone of the Northside Drive Onramp Under Metered Conditions
These figures clearly illustrate the difference in modal activity for these two conditions. When the meter is in operation the modal activity is dispersed and weighted toward the negative acceleration (i.e. deceleration) area due to the slowing and stopping of vehicles. When the meters are not operational the distribution is much more uniform and there is much less activity in the deceleration area. The following Figure 5-4 and Figure 5-5 show the modal activity for the Northside location acceleration zone.
Figure 5-4, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone of the Northside Drive Onramp Under Metered Conditions

Figure 5-5, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone for the Northside Drive Onramp Under Non-Metered Condition
Again a more uniform distribution is evident in the non-metered distribution, Figure 5-3 but the modal activity shift for the metered condition is to the high acceleration area rather than the deceleration area. This shows the induced acceleration activity anticipated on the ramp from ramp meter installation.

A more detailed look at the average speed on the ramp also reveals the impact ramp meters have on vehicle operating mode. The modal variables listed in Table 5-1 include the average vehicle operating speed on the two ramp zones under metered and non-metered conditions. The average speed trace under each condition as shown in Table 5-3 provides a more informative picture of the average vehicle speed at different points along the onramp section.

**Table 5-3, Average Vehicle Speed Profile For Northside Drive Onramp**
The above vehicle speed profiles are illustrated in relation to the stop bar and end of
gore locations. Since all vehicles are required to come to a stop at the ramp meter stop
bar location it would be expected that the speed at this point would close to zero. As can
be seen in Table 5-3 the average speed at the stop bar under metered conditions is
approximately 10 mph. There are several explanations for the observed speed at the stop
bar being higher than expected. The average speed data points for the above trace is an
average over a 50 foot distance bin centered on the stop bar, therefore the actual spot
speed precisely at the stop bar location is less the 10 mph. This notwithstanding, even if
the speed trace was derived using a smaller distance increment (e.g. one foot) the
observed speed at the stop bar would not likely be zero. This due to the fact that many
vehicles “creep” through the stop bar area anticipating a green signal and then proceed
down the ramp without coming to a complete stop. An even smaller number of vehicles
disobey the signal completely and cross the stop bar at speeds similar to those observed
when the ramp meter is not operating. These factors result in average speeds at the stop
bar greater than zero, but ramp meter violations do not appear to be a significant problem
in and of them-selves. The observe violation rate for the Northside Drive onramp during
the course of this research was one percent. As can be seen in Table 5-4, apart from the
Moores Mill location the violation rate was considerably low. The lowest violation rate
was observed on the Howell Mill Road onramp, the modal activity for this ramp is
discussed in the next section.
Table 5-4, Ramp Meter Violation Rate

<table>
<thead>
<tr>
<th>Location</th>
<th>Northside Drive Onramp</th>
<th>Howell Mill Road Onramp</th>
<th>Moores Mill Road Onramp</th>
<th>West Paces Ferry Onramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Violation Rate (%)</td>
<td>1.0</td>
<td>0.7</td>
<td>5.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>

5.1.1.2 Howell Mill Road Onramp Modal Activity

The modal activity observed on the Howell Mill Road onramp revealed even more modal activity extremes than on the Northside Drive onramp. As with the Northside location most all indicators suggest measurable increases in modal activity in the acceleration zone under metered operation, deceleration rates notwithstanding. As can be seen in Table 5-5 the modal activity variables in the deceleration zone are less under metered conditions. Engine load and acceleration rates are reduced as vehicles approach the stop bar, but as explained earlier this will not necessarily lead to a reduction in overall emissions due to change in the average speed. This is also needs to be assess in conjunction with the drastic increase in engine load in the acceleration zone as measured by the changes in percent of cycle with IPS greater than 90 and 120.
Table 5-5, Summary of Modal Activity for the Howell Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Howell Mill Road Onramp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
</tr>
<tr>
<td></td>
<td>Deceleration Zone</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>22</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-0.2</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>6</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.9</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>52</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>3.5</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Figure 5-6, Figure 5-7, Figure 5-8, and Figure 5-9 show the variations in modal activity graphically for this location, in the form of a JASPROD.
Figure 5-6, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone for the Howell Mill Road Onramp Under Metered Conditions

Figure 5-7, Joint Acceleration-Speed Probability Density Function (JASPROD) for the deceleration Zone for the Howell Mill Road Onramp Under Non-Metered Conditions
Figure 5-8, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone for the Howell Mill Road Onramp Under Metered Conditions

Figure 5-9, Joint Acceleration-Speed Probability Density Function (JASPROD) for the deceleration Zone for the Howell Mill Road Onramp Under Non-Metered Conditions
The JASPROD plots for the deceleration zone show the dispersed and heavy deceleration activity under the metered condition. The shift in activity in the deceleration zone from this location is even more extreme than at other sites due to the steep (-7%) grade at the approach to the ramp meter stop bar. The distribution in the acceleration zone is consistent for the two locations, but the shift to higher acceleration activity under metered conditions is clearly evident in Figure 5-9.

The average speed traces shown in Figure 5-10 depict the typical vehicle trajectory down the Howell Mill Road onramp under metered and non-metered conditions.

**Figure 5-10, Average Vehicle Speed Profile For Howell Mill Road Drive Onramp**
5.1.1.3 Moores Mill Road Onramp Modal Activity

The modal activity trends on the Moores Mill onramp were consistent with that observed at the Northside Drive and Howell Mill Location. As can be seen in Table 5-6 under ramp metering the modal activity increased in the acceleration zone for all measures. Modal activity in the deceleration zone decreased along with a sharp (30%) drop in average speed.

Table 5-6, Summary of Modal Activity for the Moores Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Moores Mill Road Onramp</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
<td>Non-Metered</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Deceleration Zone</td>
<td>Acceleration Zone</td>
<td>Deceleration Zone</td>
<td>Acceleration Zone</td>
<td></td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>19</td>
<td>34</td>
<td>27</td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-0.4</td>
<td>2.6</td>
<td>2.2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>6.7</td>
<td>16</td>
<td>12.9</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.3</td>
<td>2.6</td>
<td>0.0</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>19</td>
<td>5</td>
<td>0.0</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>3.8</td>
<td>10.5</td>
<td>39.5</td>
<td>5.9</td>
<td></td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>1.6</td>
<td>5.1</td>
<td>24</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
The average speed traces for this site can be seen in Figure 5-11. The vehicles operating under metered conditions not only have a slower average speed, but do not appear to fully recover from coming to a stop and enter the merge area at a lower average speed than under non-metered conditions.

**Figure 5-11, Average Vehicle Speed Profile For Moores Mill Road Drive Onramp**

The graphical representation of the modal activity for this site also consistent with what has been observed at the other locations. As shown in Figure 5-12 and Figure 5-13 the deceleration zone is associated with extensive deceleration activity under metered conditions and more consistent activity under non-metered conditions. The coarseness of the JASPRODs for the acceleration zone at this site is due to the small dataset and not necessarily due to more inconsistent modal activity.
The modal activity in the acceleration zone for the non-metered case reveals very uniform activity as shown in Figure 5-14. The modal activity in the acceleration zone under metered conditions, is characterized by a wider range of activity and more activity in the “emissions critical” high acceleration area. Similar to the pattern observed at the Howell Mill Road location, there is a significant increase in high accelerations at low speeds, as seen in Figure 5-15.

Figure 5-12, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone for the Moores Mill Road Onramp Under Metered Conditions
Figure 5-13, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone for the Moores Mill Road Onramp Under Non-Metered Conditions

Figure 5-14, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone for the Moores Mill Road Onramp Under Metered Conditions
5.1.1.4 West Paces Ferry Road Onramp Modal Activity

The modal activity observed at the West Paces Ferry Road site was consistent with the other three onramp locations, but the changes were less severe as can be seen in Table 5-7. The activity in the deceleration zone under both metering and non-metering conditions was characterized with noticeable levels of deceleration. This is most likely due to the curved approach design of the ramp requiring braking even if the ramp meter is not operating. The activity in the acceleration zone under metered conditions indicated an increase in modal activity, but to a lesser degree than observed at the other locations.
### Modal Activity Variable

<table>
<thead>
<tr>
<th></th>
<th>West Paces Ferry Road Onramp</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
</tr>
<tr>
<td></td>
<td>Deceleration Zone</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>16</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-0.2</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>5.6</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.0</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>16</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>3.2</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>0.6</td>
</tr>
</tbody>
</table>

A three-dimensional graph showing the relative proportion of vehicle-seconds that vehicles experience at different combined values of speed and acceleration for this location is provided in Figure 5-16, Figure 5-17, Figure 5-18, and Figure 5-19. As can be seen in these graphs both the metered and non-metered conditions experienced high levels of both acceleration and deceleration activity. This explains why the engine load surrogates shown in Table 5-7 are similar for both conditions.

**Figure 5-16, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone for the West Paces Ferry Road Onramp Under Metered Conditions**
Figure 5-17, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Deceleration Zone for the West Paces Ferry Road Onramp Under Non-Metered Conditions
Figure 5-18, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone for the West Paces Ferry Road Onramp Under Metered Conditions

![Figure 5-18](image1.png)

Figure 5-19, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Acceleration Zone for the West Paces Ferry Road Onramp Under Non-Metered Conditions

![Figure 5-19](image2.png)
The average speed trace for the West Paces Ferry onramp is shown in Figure 5-20. This figure shows the average vehicle trajectory on the ramp under metered and non-metered conditions.

**Figure 5-20, Average Vehicle Speed Profile For West Paces Ferry Road Drive Onramp**

It was anticipated that there would be a measurable increase in modal activity under metered conditions simply due to the nature of ramp metering. Therefore the above findings are not surprising, but they do provide quantitative assessment of the impact of ramp metering on onramp activity. One of the key questions of this research is how this change in activity related to changes on the associated mainline sections and what are the
related net air quality impacts. The mainline modal activity will be discussed in the following section and the later question will be answered in section 5.2.

5.1.2 Mainline Modal Activity

The assessment of the freeway mainline activity was performed using the LRF data while also relying heavily on information from the probe vehicles. The approach was to look at the modal activity and the emissions as a function of freeway section. For this analysis the 4.4-mile mainline section was divided based on three criteria that would separate different areas of freeway modal activity. These included basic freeway sections were vehicles operated independent of merging and weaving activity, merge areas approximately 500 feet on either side of each onramp juncture, and weave sections where a merge and diverge area were within close proximity to each other. Based on this the study area freeway was divided into nine sections; one weave (between Northside onramp and Howell Mill off-ramp), three merge, and five basic.

Information from the each of the three LRFs operating on the overpass locations to provided data for assessing the three mainline sections. Data from the Peachtree Battle Road flyover location provided information regarding activity on basic sections, data from the Howell Mill Road overpass provided information related to merge area activity, and data from the Northside Drive overpass provided information related to the merge section activity.

The five mainline basic sections comprised the largest amount of study area freeway, totaling 3.6 miles. As can be seen in Table 5-8 the modal activity variables for the basic section were relatively consistent for each condition. If anything the modal
activity appeared to increase slightly under metered conditions. This is opposite of what would be expected considering the intent of ramp metering is to smooth mainline traffic flow.

**Table 5-8, Summary of Modal Activity for the Mainline Basic Section**

| Modal Activity Variable                  | Mainline Basic Section |   |
|-----------------------------------------|------------------------|
|                                         | Metered | Non-Metered |
| Average Speed (mph)                      | 69.9    | 69.5        |
| Average Acceleration (mph/sec)          | -.52    | -.52        |
| Percent of Cycle Acceleration > 3 (mph/sec) | 0.6    | 0.7        |
| Percent of Cycle with Acceleration > 6 (mph/sec) | 0.1   | .04        |
| Percent of Cycle with Deceleration > 2 (mph/sec) | 6.4   | 4.8        |
| Percent of Cycle with ISP > 90 (mph^2/sec) | 4.5    | 3.3        |
| Percent of Cycle with ISP > 120 (mph^2/sec) | 4.4    | 3.2        |

Although it is not apparent from the modal activity summary statistics the JASPROD for the basic sections reveal the beneficial effects of ramp metering. As can be seen in and the modal activity under non-metered conditions is dispersed and less consistent than under metered conditions.
Figure 5-21, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Mainline Basic Section Under Metered Conditions

Figure 5-22, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Mainline Basic Section Under Non-Metered Conditions
The three merge areas combined to total 0.6 miles of freeway. As with the basic section there does not seem to be a large difference in modal activity between the metered and non-metered conditions. Although, there is was not a large difference in observed activity the differences consistently move toward an increase in modal activity under non-metered conditions as can be seen in Table 5-9. This trend is also apparent in the graphical representation of the modal activity for these sections shown in Figure 5-23 and Figure 5-24. The modal activity is limited to a narrow region of speed and acceleration combinations, but under non-metered conditions a small amount of activity is apparent in both the high acceleration and deceleration regions. This activity is absent from the metered activity plot, and show the relative impact of the slightly higher engine load and acceleration activity in the merge are under non-metered conditions.

### Table 5-9, Summary of Modal Activity for the Mainline Merge Area

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Mainline Merge Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>69.6</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-.28</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>1.2</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>.07</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>4.1</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>6.3</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>6.1</td>
</tr>
</tbody>
</table>
Figure 5-23, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Mainline Merge Area Under Metered Conditions

Figure 5-24, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Mainline Merge Area Under Non-Metered Conditions
The weave section consisted of just one, 1000-foot section between the Northside Drive and Howell Mill interchanges. The modal activity measures indicated the greatest change in activity between metered and non-metered conditions of any of the three mainline sections. Again, assuming that ramp metering would result in smoother mainline operations the finding would be opposite of those observed and presented in Table 5-10. That is, the modal activity in the weave section increased under metered conditions. It is possible that this is due to the reduction of vehicle speeds as they enter the weave under metered conditions.

Table 5-10, Summary of Modal Activity for the Mainline Weave Area

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Mainline Weave Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>58.1</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>-.07</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>1.6</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.2</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>5.4</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph^2/sec)</td>
<td>12.1</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph^2/sec)</td>
<td>7.4</td>
</tr>
</tbody>
</table>
The change in modal activity under each condition can be seen clearly in the JASPRODs for this section shown in Figure 5-25 and Figure 5-26. Again these graphs show the possible impact ramp meters have in the weave area by constraining ramp speeds and creating a wider dispersion of activity through the merge area.

Figure 5-25, Joint Acceleration-Speed Probability Density Function (JASPROD) for the Mainline Weave Section Under Metered Conditions
Information from the probe vehicle runs were used to supplement the LRF mainline data. The probe vehicles provide more comprehensive speed and acceleration data along the mainline section. The following Table 5-11 provides a summary of the probe vehicle runs. For comparative purposes the runs were divided into the same three section types as the LRF data traces.

The probe vehicle data supports the findings from the LRF data discussed above. There appears to be little variation in the level of modal activity between the metered and non-metered conditions. Despite the fact that the difference in modal activity is not large the small changes in average speed could prove beneficial from an air quality standpoint. Although, the changes in average speed are small they are consistent (and significant as discussed in the next section) and suggest a slight increase in travel time in the corridor under metered conditions. There is a potential for greater improvements in travel time
resulting from metering systems under conditions that are more congested that were observed during this research. The decreased travel time will result in fewer seconds of vehicle operations and a possible net reduction in total vehicle emissions.

**Table 5-11, Summary of Average Speed Data From Probe Vehicle Runs**

<table>
<thead>
<tr>
<th></th>
<th>Basic Sections</th>
<th>Merge Areas</th>
<th>Weave Section</th>
<th>Total Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metered, Average Speed (mph)</td>
<td>62.4</td>
<td>63.8</td>
<td>63.2</td>
<td>62</td>
</tr>
<tr>
<td>Non-Metered, Average Speed (mph)</td>
<td>60.7</td>
<td>61.6</td>
<td>64.4</td>
<td>61</td>
</tr>
<tr>
<td>Metered, Average Acceleration (mph/sec)</td>
<td>0.06</td>
<td>0.06</td>
<td>-0.19</td>
<td>0.05</td>
</tr>
<tr>
<td>Non-Metered, Average Acceleration (mph/sec)</td>
<td>0.03</td>
<td>0.06</td>
<td>-0.059</td>
<td>0.02</td>
</tr>
</tbody>
</table>

5.1.3 Significance of Observed Differences in Modal Activity

The observed differences in modal activity under metered and non-metered conditions demonstrate a clear pattern and it appears that ramp metering systems result in measurable changes in modal activity on onramps. Despite this, the LRF data was analyzed to determine if the observed differences were statistically significant or simply due to random variations.

In order to accomplish this, a t-test was used to compare the differences in the means of each of the modal variables for metered and non-metered conditions for each onramp location independently. The test was conducted at the 95 percent confidence level. This analysis was limited to an assessment of the LRF data from the onramp...
acceleration zone locations and an assessment of the average mainline speed measures by the probe vehicles. Although, the probe vehicle data used to provide information for some of the deceleration zone locations did not provide a large enough sample to perform a statistical analysis.

The t-test results for the Northside Drive onramp are presented in Table 5-12. All of the means for the modal variables apart from percent of cycle with deceleration greater than 2 mph/sec were found to be statistically significant based on the t-test results. The t-test results for the Howell Mill location shown in Table 5-13 revealed similar results. For this location all variables were found to be significantly different including percent of cycle with deceleration greater than 2 mph/sec. It should be noted that in the case of this variable the modal activity was greater under non-metered conditions. This is consistent with the results from the Moores Mill location shown in Table 5-14. Again all tests were found to be highly significant with the deceleration rate being higher under non-metered conditions. The test results from the West Paces Ferry location, shown in Table 5-15, were not as conclusive. The means for average speed, average acceleration rate, and percent of cycle with acceleration greater than 3mph/sec were found to be significantly different. Similar conclusions about the other variables could not be made about the other variables. This notwithstanding, the significance of some variables and the strong evidence from the other locations suggest that ramp metering has a significant impact on onramp modal activity in all cases.

The notable exception is related to deceleration rates. There is little evidence that ramp metering will increase deceleration rates in acceleration zones and it could be
argued that deceleration activity is higher under non-metered conditions. It is clear that deceleration activity will increase in the deceleration zone under ramp metering, but it appears that it will also increase in the acceleration zone as well. This could be the result of higher speeds on the ramp under non-metered conditions. When the meters are not operating vehicle will potentially enter the merge area at speeds above the mainline speed necessitating the need to decelerate in order to find a gap in the traffic stream.
Table 5-12, T-Test Results for Significance in Observed Differences in Modal Activity Changes for the Northside Drive Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Metered Mean</th>
<th>Non-Metered Mean</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td>39</td>
<td>40</td>
<td>3.27</td>
<td>1.99</td>
<td>.0016</td>
<td>Yes</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>3.1</td>
<td>2.8</td>
<td>5.94</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>26</td>
<td>11</td>
<td>12.55</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>1.0</td>
<td>0.1</td>
<td>4.97</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>2.2</td>
<td>1.8</td>
<td>1.26</td>
<td>1.99</td>
<td>.2110</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph^2/sec)</td>
<td>30</td>
<td>21</td>
<td>6.35</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph^2/sec)</td>
<td>10.5</td>
<td>6.8</td>
<td>4.99</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 5-13, T-Test Results for Significance in Observed Differences in Modal Activity Changes for the Howell Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Howell Mill Road</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered Mean</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>36</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td>3.2</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td>29</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>2.4</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>2.1</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph$^2$/sec)</td>
<td>26</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph$^2$/sec)</td>
<td>10</td>
</tr>
</tbody>
</table>
Table 5-14, T-Test Results for Significance in Observed Differences in Modal Activity Changes for the Moores Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Moores Mill Road</th>
<th>Metered Mean</th>
<th>Non-Metered Mean</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td></td>
<td>34</td>
<td>45</td>
<td>21.48</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td></td>
<td>2.6</td>
<td>1.4</td>
<td>16.45</td>
<td>1.97</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td></td>
<td>16</td>
<td>3.0</td>
<td>16.765</td>
<td>1.97</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td></td>
<td>2.6</td>
<td>0.2</td>
<td>4.60</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td></td>
<td>5.2</td>
<td>8.4</td>
<td>4.39</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td></td>
<td>10.5</td>
<td>5.9</td>
<td>5.21</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td></td>
<td>5.1</td>
<td>3.0</td>
<td>3.03</td>
<td>1.97</td>
<td>.0028</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Table 5-15, T-Test Results for Significance in Observed Differences in Modal Activity Changes for the West Paces Ferry Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>West Paces Ferry Road</th>
<th>Metered Mean</th>
<th>Non-Metered Mean</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td></td>
<td>37</td>
<td>44</td>
<td>12.29</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Average Acceleration (mph/sec)</td>
<td></td>
<td>1.9</td>
<td>1.4</td>
<td>7.16</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle Acceleration &gt; 3 (mph/sec)</td>
<td></td>
<td>9</td>
<td>4.2</td>
<td>6.78</td>
<td>1.98</td>
<td>.0000</td>
<td>Yes</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td></td>
<td>0.7</td>
<td>0.2</td>
<td>1.79</td>
<td>1.98</td>
<td>.0763</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td></td>
<td>10.9</td>
<td>10.2</td>
<td>0.53</td>
<td>1.98</td>
<td>.5985</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td></td>
<td>9.2</td>
<td>7.8</td>
<td>1.80</td>
<td>1.99</td>
<td>.0749</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td></td>
<td>4.3</td>
<td>3.5</td>
<td>1.39</td>
<td>1.98</td>
<td>.1664</td>
<td>No</td>
</tr>
</tbody>
</table>
One test was performed to assess the differences in modal activity observed on the mainline section. The means for the average speed on the mainline under metered and non-metered conditions as measured by the probe vehicles were tested. The observed difference in average speed over the 4.4-mile section was only one mph. As shown in the average metered condition speed was 62 mph and for the non-metered condition was 61 mph. The t-test found that the two means were statistically significantly different at 99.5 percent confidence level.

The question that remains is whether these significant differences in modal activity on the onramps and mainline will result in an estimated emissions reduction or increase. The emissions modeling estimates for the Atlanta ramp metering system are discussed in the following section.

5.2 Emissions Estimates

It has been shown that ramp metering systems have a significant impact on vehicle modal activity variables and in most cases result in an increase in modal activity. It is clear that the potential for effecting vehicle emissions exists, but the true air quality impact cannot be assessed without estimating the emissions from the system under alternate metered conditions.

As discussed in Chapter Two, changes modal activity and related engine operations influence emissions differently for different pollutants. In general carbon monoxide (CO) and hydrocarbon (HC) emissions are more sensitive to enrichment and changes in modal activity, but Oxides of Nitrogen (NOx) are the more critical pollutant in the Atlanta
Region due to their role in ground level ozone formation. Emissions estimates presented here will therefore focus on NOx. The emissions estimates presented here were produced using the MEASURE model algorithm and the MOBILE5b average speed emissions rate model.

Emissions analyses were conducted at two levels (ramp-related emissions rates and mass emissions under various operating and ramp metering conditions, and mainline emissions rates and mass emissions). This is important because the expected influences of metered flows can also impact mainline operating profiles (and change travel demand) resulting in different mass emissions levels. Changes in average speeds will also result in different mass emission levels even if the gram/second emissions rates remain the same because slower travel speeds yield longer travel times to traverse the segment.

5.2.1 MEASURE Model Estimates

Emissions estimates were produced from the MEASURE modal by applying observed speed/acceleration activity and vehicle fleet technology information from each ramp and mainline location to the MEASURE algorithm for NOx. The emissions estimates were produced for each 15-minute period of each data collection day. The mass emissions estimated and emissions rates were then aggregated and averaged to provide emissions estimates for typical metered and non-metered conditions.

The MEASURE grams per second emissions rates for NOx are shown in Figure 5-27. The NOx emissions rates for the onramp location are consistently lower under metered conditions, but slightly higher for the mainline location. Emissions rates are an
important factor in an air quality analysis providing a standard measure for comparing different locations. Although the emissions rates are only part of the equation as the traffic volume and average speed will ultimately determine the net emissions impact. When the emissions rates were applied to the traffic conditions observed in the field mass emissions estimates were produced for the metered and non-metered conditions. The mass emissions are based on the total estimated emissions for an average day over a 2.75-hour peak period. The mass emissions estimates for the onramp locations for NOx are shown in Figure 5-28.

Figure 5-27, MEASURE Emissions Rates for Oxides of Nitrogen by Location

![Bar chart showing emissions rates for different locations under metered and non-metered conditions.]

NOx emissions estimates were lower under metered conditions at all but one location. The onramp emissions estimates are important, but the mainline emissions have a greater impact on the overall system evaluation (accounting for 96 to 98 percent of the
system wide emissions). The NOx emissions estimates for the mainline and system total are presented in Figure 5-29.

Figure 5-28, MEASURE Oxides of Nitrogen Mass Emissions Estimates for Onramp Locations

![Bar chart showing NOx emissions estimates for metered and non-metered conditions at different locations.]

The emissions estimates for NOx showed an increase on the mainline and in total for metered conditions. These estimates are based on actual vehicle activity and volume observed during the data collection period and as a result the traffic volumes were lower during the non-metered days. Since the mass emissions estimates are a function of not only the emissions rates, but also the number of vehicles to which the rates are applied. In order to produce a more accurate comparison of metered and non-metered conditions a second set of mass emissions estimates were produced with the traffic volume on the
onramps and the mainline held constant. The result was an emission analysis that isolated the changes in modal activity and average speed resulting from the ramp metering system. The NOx mass emissions estimates on the onramps for this second analysis are shown in Figure 5-30. This graph shows the consistent trend of lower NOx emissions at the onramp locations under ramp metering conditions.

Figure 5-29, MEASURE Oxides of Nitrogen Mass Emissions Estimates for Mainline Traffic and System Total
The mainline and system NOx mass emissions estimates for metered and non-metered conditions when the traffic volume is held constant are shown in Figure 5-31. As with the first estimates the total NOx emissions estimates were higher under metered conditions. NOx emissions rates are typically higher as average speed increases and as a result increase as mainline traffic conditions and average speed improvements with ramp metering. The traffic flow benefit observed during this study was very slight, but if greater traffic flow improvements are realized the result could be a net reduction in NOx emissions under metered conditions due to decrease in average seconds of vehicle operation.
A complete summary of the emissions rates and mass emissions estimates are provide in the following Table 5-16 and Table 5-17. The mass emissions are based on the total estimated emissions for an average day over a 2.75-hour peak period. The emissions estimates from the MOBILE5b analysis are presented in section 5.2.2.
Table 5-16, Summary of MEASURE Oxides of Nitrogen Emissions Rates

<table>
<thead>
<tr>
<th>Location</th>
<th>NOx Emissions Rates Metered Conditions (grams/sec)</th>
<th>Emissions Rates Under Non-Metered Conditions (grams/sec)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northside Drive</td>
<td>.00931</td>
<td>.01341</td>
<td>-31</td>
</tr>
<tr>
<td>Howell Mill Road</td>
<td>.01065</td>
<td>.01906</td>
<td>-44</td>
</tr>
<tr>
<td>Moores Mill Road</td>
<td>.01044</td>
<td>.01776</td>
<td>-41</td>
</tr>
<tr>
<td>West Paces Ferry Road</td>
<td>.01068</td>
<td>.01566</td>
<td>-32</td>
</tr>
<tr>
<td>Mainline</td>
<td>.05839</td>
<td>.05642</td>
<td>4</td>
</tr>
</tbody>
</table>
Table 5-17, Summary of MEASURE Mass Oxides of Nitrogen Emissions Estimates, Traffic Volume Held Constant

<table>
<thead>
<tr>
<th>Location</th>
<th>Mass NOx Emissions Under Metered Conditions (grams)</th>
<th>Mass NOx Emissions Under Non-Metered Conditions (grams)</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northside Drive</td>
<td>664</td>
<td>680</td>
<td>-2</td>
</tr>
<tr>
<td>Howell Mill Road</td>
<td>420</td>
<td>533</td>
<td>-21</td>
</tr>
<tr>
<td>Moores Mill Road</td>
<td>379</td>
<td>489</td>
<td>-22</td>
</tr>
<tr>
<td>West Paces Ferry Road</td>
<td>288</td>
<td>327</td>
<td>-12</td>
</tr>
<tr>
<td>Mainline</td>
<td>272,517</td>
<td>261,614</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>274,268</td>
<td>263,643</td>
<td>4</td>
</tr>
</tbody>
</table>

Although the ramp-related g/second emission rates under metered conditions decrease by 31 to 44 percent at the four ramps, the vehicle time spent in each metered zone also increases under metered conditions. Thus, the total onramp related NOx emissions under metered conditions decrease by only 14%. Note, however, that the improved traffic flow on the mainline results in a predicted increase in mainline emission rate by approximately 3%. Because onramp traffic volume is low, the emissions from the ramps are two orders of magnitude lower than the emissions from the mainline. Hence, the net emissions impact of the system change is almost exclusively experienced on the mainline segment. The NOx emissions reduction associated with onramp operation is
completely overwhelmed by the increase in mainline emissions. The net increase in system NOx emissions along this corridor from ramp metering is approximately 4%. Since this is strongly influenced by the mainline activity, the length of the metered corridor will directly determine the level of emissions impact.

It is important to note that the emissions results reported for the Atlanta metered system are for a series of freeway segments that seldom experience forced flow conditions. A bottleneck on the freeway system upstream from the metered section prevents the area at the meters from reaching capacity during peak periods. While the metering of the onramp demand does improve mainline traffic flow, the mainline demand is never sufficient for the ramps to actually serve their intended function - preventing or delaying the onset of force flow conditions. Continued research and simulation analyses is needed to determine the expected emissions effects that would occur under conditions of increased entry volumes into the metered section. Given the emissions relationships described earlier, it is likely that under some conditions ramp metering can serve to reduce system emissions. That is, under traffic conditions where ramp metering would be most effective the resulting traffic flow improvements would result in travel-time savings that could result in a net NOx emissions decrease. This notwithstanding, under certain traffic conditions there appears to be a tradeoff between NOx emissions and travel-time savings.
5.2.2 MOBILE5b Model Estimates

In order to produce emissions estimates that would be directly comparable with the MEASURE analysis the same parameters were used for the MOBILE5b analysis. As with the second set of MEASURE estimates, the traffic volumes were held constant for this analysis. The MOBILE5b emissions rates and mass emissions estimates for NOx for the onramp locations are shown in Figure 5-32 and Figure 5-33. As can be seen in these figures the estimated NOx emissions decrease under metered conditions, a trend that is consistent with what was indicated by the MEASURE analysis.

Figure 5-32, MOBILE5b Oxides of Nitrogen Emissions Rates by Location
The NOx mass emissions estimates for the mainline section and the total system are shown in Figure 5-34. The mainline emissions increase under metered conditions resulting in a net increase in system wide emissions levels.
Figure 5-34, MOBILE5b Oxides of Nitrogen Mass Emissions Estimates for Mainline Traffic and System Total, Traffic Volume Held Constant

5.2.3 Comparison Of MEASURE and MOBILE5b

As compared to the MEASURE emissions estimates the MOBILE5b modal consistently under predicted emissions for NOx. A comparison of MOBILE5b and MEASURE emissions estimates for the onramp locations, the mainline, and the system total are shown in Figure 5-35, Figure 5-36, and Figure 5-37.
Figure 5-35, Comparison of MOBILE5b and MAESURE Mass Emissions Estimates for the Onramp Locations for Metered and Non-Metered Conditions

Figure 5-36, Comparison of MOBILE5b and MAESURE Mass Emissions Estimates for the Mainline Location for Metered and Non-Metered Conditions
5.3 **Findings on the Influence of Ramp Design and Prevailing Traffic Conditions**

The information presented in section 5.1 showed that there was a clear and significant difference in the average level of modal activity between metered and non-metered conditions. It was also evident that there are also differences in activity between locations and under different traffic conditions. Part of this research is concerned with attempting to identify the parameters that influence modal activity on freeway onramps under metered conditions. Four parameters that were felt to have a potential for influencing onramp modal activity were chosen for analysis. These included mainline traffic flow conditions, onramp grade, onramp acceleration distance, and the influence of trucks in the traffic mix. There are additional factors that could potentially impact modal
activity, but not all factors were considered due to data limitations or the inability to isolate certain factors.

5.3.1 Traffic Volume Effects

As traffic volume on the freeway mainline increases, the ability of vehicles entering the freeway to merge becomes compromised. Indeed, this is one of the main reasons for implementing ramp metering systems. The issue is whether varying traffic conditions influence the level of modal activity at the merge area. To test to see if this was the case the onramp modal activity in merge area (i.e. the acceleration zone) was compared under different traffic condition operating levels or level of service (LOS). Again the t-test was used as a statistical method to test the means of the modal activity variables under different levels of service.

Ideally testing the completed range of traffic conditions (LOS A to F) for differences in modal activity, but not all levels of traffic operations were not experienced during the data collection phase of this research. The vast majority of traffic conditions observed were at LOS C or D. Some LOS B and E conditions were experienced, but not enough to support a statistical analysis. Therefore, for this analysis changes in modal activity between LOS C and LOS D were tested for each onramp location separately. The locations were tested independently to control for secondary factors such as grade and acceleration distance, which will be discussed in the following sections.
The t-test results for the changes in modal activity between LOS C and D for the Northside Drive Location is presented in Table 5-18. As can be seen none of the observed differences in modal activity under different LOS were found to be significant for any of the modal variables. This is likely due to the similarity of traffic operations under LOS C and LOS D conditions and not the fact that traffic flow conditions is not an important factor in modal activity. Since this dataset was associated with a narrow band of traffic conditions with little data associated with light or alternatively highly congested traffic conditions a complete picture of the LOS influences were not detectable. As can be seen in Table 5-19, Table 5-20, and Table 5-21 these findings were consistent for all onramp locations.
Table 5-18, T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Northside Drive Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Northside Drive</th>
<th>Mean LOS C</th>
<th>Mean LOS D</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td></td>
<td>39</td>
<td>39</td>
<td>0.25</td>
<td>1.99</td>
<td>.8073</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle</td>
<td></td>
<td>28.2</td>
<td>25.8</td>
<td>1.21</td>
<td>1.99</td>
<td>.2299</td>
<td>No</td>
</tr>
<tr>
<td>Acceleration &gt; 3</td>
<td></td>
<td>0.8</td>
<td>0.6</td>
<td>0.72</td>
<td>1.99</td>
<td>.4725</td>
<td>No</td>
</tr>
<tr>
<td>(mph/sec)</td>
<td></td>
<td>1.9</td>
<td>1.9</td>
<td>0.007</td>
<td>1.99</td>
<td>.9940</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle</td>
<td></td>
<td>32</td>
<td>29</td>
<td>1.53</td>
<td>1.99</td>
<td>.1302</td>
<td>No</td>
</tr>
<tr>
<td>Deceleration &gt; 2</td>
<td></td>
<td>10.4</td>
<td>10.0</td>
<td>1.18</td>
<td>1.99</td>
<td>.2424</td>
<td>No</td>
</tr>
<tr>
<td>(mph/sec)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 5-19, T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Howell Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Howell Mill Road</th>
<th>Mean LOS C</th>
<th>Mean LOS D</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Speed (mph)</td>
<td></td>
<td>36</td>
<td>36</td>
<td>0.54</td>
<td>1.98</td>
<td>.5861</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 3 (mph/sec)</td>
<td></td>
<td>28</td>
<td>29</td>
<td>0.70</td>
<td>1.98</td>
<td>.4855</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td></td>
<td>2.6</td>
<td>2.1</td>
<td>1.56</td>
<td>1.98</td>
<td>.1226</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td></td>
<td>2.0</td>
<td>2.2</td>
<td>0.36</td>
<td>1.98</td>
<td>.7129</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td></td>
<td>26</td>
<td>26</td>
<td>0.06</td>
<td>1.98</td>
<td>.9470</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td></td>
<td>9.9</td>
<td>10.1</td>
<td>0.22</td>
<td>1.98</td>
<td>.8230</td>
<td>No</td>
</tr>
</tbody>
</table>
Table 5-20, T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the Moores Mill Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Moores Mill Road</th>
<th></th>
<th></th>
<th></th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean LOS C</td>
<td>Mean LOS D</td>
<td>t-Statistic</td>
<td>Critical t-Value (.05)</td>
<td>t-statistic Probability</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>32.5</td>
<td>33.8</td>
<td>2.03</td>
<td>1.99</td>
<td>.0453</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 3 (mph/sec)</td>
<td>15.3</td>
<td>16.5</td>
<td>0.74</td>
<td>1.99</td>
<td>.4588</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>1.2</td>
<td>0.82</td>
<td>1.07</td>
<td>1.99</td>
<td>.2846</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>7.9</td>
<td>4.5</td>
<td>2.52</td>
<td>2.01</td>
<td>.0149</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph$^2$/sec)</td>
<td>8.6</td>
<td>9.0</td>
<td>0.43</td>
<td>1.99</td>
<td>.6619</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph$^2$/sec)</td>
<td>3.1</td>
<td>3.3</td>
<td>0.43</td>
<td>1.99</td>
<td>.6676</td>
</tr>
</tbody>
</table>
Table 5-21, T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Level of Service (LOS) for the West Paces Ferry Road Onramp

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>West Paces Ferry Road</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean LOS C</td>
<td>Mean LOS D</td>
<td>t-Statistic</td>
<td>Critical t-Value (.05)</td>
<td>t-statistic Probability</td>
<td>Accept Alternative Hypotheses that Means are Different</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>35.8</td>
<td>36.3</td>
<td>0.31</td>
<td>2.13</td>
<td>.7629</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 3 (mph/sec)</td>
<td>9.4</td>
<td>13.0</td>
<td>0.90</td>
<td>2.31</td>
<td>.3937</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>0.4</td>
<td>0.4</td>
<td>1.00</td>
<td>2.44</td>
<td>.3548</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>13.9</td>
<td>5.5</td>
<td>1.94</td>
<td>2.11</td>
<td>.0687</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>8.8</td>
<td>12.9</td>
<td>1.27</td>
<td>2.31</td>
<td>.2403</td>
<td>No</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>3.8</td>
<td>7.5</td>
<td>1.14</td>
<td>2.36</td>
<td>.2902</td>
<td>No</td>
</tr>
</tbody>
</table>

5.3.2 Grade Effects

Grade is known to increase engine load that can lead to enrichment and elevated emissions levels. When possible freeway onramps are designed with a negative grade so that vehicles entering the freeway can more easily achieve freeway speed. For this same
reason positive grades on freeway onramps are avoided and therefore onramps are
typically designed to minimized grade induced enrichment. Despite this two of the ramps
in the study area were designed with a positive grade. In an attempt to test and see if
grade influenced vehicle modal activity the speed/acceleration data from the two positive
grade locations was compared with the two negative grade locations under metered
conditions. To the degree possible secondary influences, such as trucks, were controlled
for in this analysis.

Similar to the other statistical test used for this research the t-test was utilized to test
the means of the modal activity variables for the positive and negative grade ramps. In
all cases the t-test failed to identify any significant differences in the variable means.
This suggests that ramp grade does not have a significant influence on the modal activity
of vehicles operating on freeway onramps. This is not to say the grade is not an
important consideration for onramp design, but that grade does not accentuate the
problem by increasing the level of modal activity.

5.3.3 Acceleration Distance Effects

As with grade, the ideal ramp design includes sufficient acceleration distance so that
vehicle can make a smooth transition from the arterial system to the freeway system. If
the acceleration distance is not sufficient drivers will be inclined to accelerate at a rapid
rate so that they can reach the necessary speed for merging. Ramp metering systems can
compromise the acceleration length or in other cases physical constraints do not allow for
the optimal acceleration distance. It was hypothesized that modal activity would increase
on ramps with short acceleration differences due to the need (or perceived need) to accelerate at a higher rate.

To test for this the data from the short Howell Mill Road onramp (975 feet) was compared with data from the longer Moores Mill Road and West Paces Ferry Road onramps (2000 feet). The acceleration distance for the Howell Mill Ramp is 450 feet. The acceleration distance for the Moores Mill Road and West Paces Ferry Road ramps are approximately 700 to 800 feet. The t-test results for the comparison of the means for the modal variables are presented in Table 5-22. As can be seen all of the modal variable except one were found to be significantly different between short and long ramps. This provides indication that a short acceleration distance may lead to increased levels of modal activity under cretin conditions. These conclusions are highly limited since it is representative of only three onramp locations. In order to develop more conclusive findings the assessment of more ramp locations would be necessary.
Table 5-22, T-Test Results for Significance in Observed Differences in Modal Activity Changes Resulting from Onramp Acceleration Distance

<table>
<thead>
<tr>
<th>Modal Activity Variable</th>
<th>Acceleration Distance</th>
<th>t-Statistic</th>
<th>Critical t-Value (.05)</th>
<th>t-statistic Probability</th>
<th>Accept Alternative Hypotheses that Means are Different</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Short Ramp (975 feet)</td>
<td>Mean Long Ramps (2000 feet)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>37.5</td>
<td>35.5</td>
<td>5.45</td>
<td>1.97</td>
<td>.0000</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 3 (mph/sec)</td>
<td>27.3</td>
<td>12.9</td>
<td>18.18</td>
<td>1.97</td>
<td>.0000</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration &gt; 6 (mph/sec)</td>
<td>1.5</td>
<td>1.8</td>
<td>0.70</td>
<td>1.97</td>
<td>.4846</td>
</tr>
<tr>
<td>Percent of Cycle with Deceleration &gt; 2 (mph/sec)</td>
<td>2.2</td>
<td>7.7</td>
<td>9.48</td>
<td>1.97</td>
<td>.0000</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 90 (mph²/sec)</td>
<td>27.9</td>
<td>9.9</td>
<td>22.78</td>
<td>1.97</td>
<td>.0000</td>
</tr>
<tr>
<td>Percent of Cycle with ISP &gt; 120 (mph²/sec)</td>
<td>10.2</td>
<td>4.8</td>
<td>11.12</td>
<td>1.97</td>
<td>.0000</td>
</tr>
</tbody>
</table>
5.3.4 Effects of Trucks

In many cases, the modal activity of vehicles on ramps is not independent of the other vehicles in the traffic stream. Of particular concern is the presence of trucks and potential for large truck volumes to influence the modal activity of vehicles on the freeway onramps. To test for this, the modal activity for each location was assessed based on the percentage of trucks in the traffic mix.

Again, the t-test was used to determine if the mean modal activity was significantly different when trucks were present compared to when they were not. Modal activity for traffic mix with less than one percent trucks with modal activity for traffic mix greater then two percent trucks. Each site was assessed independently to control for secondary influences. The t-test did not indicate any significant findings regarding modal activity and the presence of trucks. In most all cases, the means under the two conditions were not found to be different.
CHAPTER VI

6  RECOMMENDATIONS AND CONCLUSIONS

The Clean Air Act Amendments of 1990 and the Transportation Equity Act for the 21st Century encourage the use of traffic flow improvements, such as ramp metering, as a means to improve air quality based on the fact that they mitigate traffic congestion. However, emissions from motor vehicles are not in direct proportion to traffic congestion and vehicle delay. Research has demonstrated that emissions are not a function of delay measures (e.g. average speed), as inferred by the current US Environmental Protection Agency (USEPA) MOBILE emission rate model, but rather a function of the modal operation of the vehicle (associated with speed/acceleration profile). As a result the current version of the USEPA model (MOBILE5b) does not produce accurate emission rate estimates under certain applications (Gertler et al., 1997; Pierson et al., 1990; NRC 1991). The MOBILE5b mode utilizes speed correction factors to adjust emissions, measured using the federal test procedure (FTP) to account for average speeds that are different from the average speed of the FTP drive cycle. Although, the FTP drive cycle does not adequately represent the range of driving conditions encountered under most typical driving scenarios. To date, modeling techniques have not been capable of capturing off-cycle conditions and in turn unable to analyze the true air quality impacts of
many traffic management strategies, including ramp metering systems. A modeling approach that takes into account the operating mode of the vehicle provides a method for assessing the impacts of a ramp metering system.

Ramp metering and other traffic flow improvement projects are often implemented with the intent of improving air quality through the smoothing of traffic operations. This is done without fully understanding the modal activity and emissions impacts of such projects. This research has attempted to add to the understanding of the complete impacts of transportation control measures (TCMs), especially those that influence vehicle operating mode. This was accomplished through the analysis of the Atlanta ramp metering system as a case study.

The improvement of air quality through the implementation of traffic flow improvement projects is not as simple as developing projects that simply improve travel speeds. From a traffic operations stand point it may seem as simple as this, but when air quality issues are considered it becomes increasingly more complex. There are numerous factors that influence the level of vehicle emissions and under some conditions a tradeoff between travel speed and emissions can exist. In addition, a tradeoff between different pollutants (e.g. NOx and HC) can also exist.
6.1 **Ramp Metering and Air Quality**

The assessment of the Atlanta ramp metering system indicated that the installation of ramp meters resulted in a net increase in NOx emissions. It is important to consider that these conclusions apply only to the study corridor and extrapolation of these findings to other areas should only be performed in the context of this study. The conclusions of this research indicate that ramp metering in the study corridor is not recommended, due to the fact that little travel time benefit is realized along with a marginal NOx emissions increase. This is not to say that the same conclusion would be reached for every ramp metering system corridor. Indeed, under certain congested traffic conditions ramp metering system can delay the onset of force flow conditions and greatly improve travel time in the given corridor. Under such conditions the tradeoff between travel time and NOx emissions could be reversed resulting in a net NOx emissions reduction.

In addition, the consideration of HC emissions could also lead to different conclusions. HC emissions are more sensitive to enrichment conditions and would likely increase on the onramps under metered conditions. Similarly, the HC emissions associated with the mainline traffic under metered conditions would likely decrease due to traffic smoothing and travel-time savings. This research did not assess the HC emissions impacts associated with the study system, but the existing dataset could be applied to the current statistical based emissions modeling regimes to produce a HC emissions estimates.

Whether the emissions differences for HC or NOx under metered versus non-metered conditions are positive or negative it is important to consider the potential
impacts in a regional context. As shown in Chapter Five the estimated net NOx emissions differential metered versus non-metered conditions is 10,624 grams per day, which is equivalent to 0.0117 tons per day. The daily NOx emissions budget for the Atlanta Region is approximately 245 tons per day (ARC, 1999). Therefore the estimated emissions increase due to ramp metering accounts for 0.005 percent of the daily regional budget. This is for a reasonably small, four ramp system. As systems increase in size the relative impact would be also increase. Nonetheless, it is apparent that even an extensive ramp metering system would not result in a large emissions change when compared to the regional budget. It is therefore important to keep in mind the current local emissions issues when evaluating the impacts of ramp metering and assessing the traffic congestion and operations tradeoffs in light of these emissions impacts.

Ramp metering has been and will likely continue to be a popular cost effective traffic management tool with a high potential for improving freeway traffic flow. It is also clear that ramp metering systems will impact the modal vehicle activity within the implemented corridor and in turn have the potential for marginal air quality impacts. Ultimately the decisions to implement a ramp metering system will be a function of the specific traffic operations and air quality issues associated with the area under consideration. Based on this research it is not clear if the implementation of ramp metering systems as a TCM is appropriate.
6.2 Future Research

The findings of this research are limited to the scope of the case study and simply provide an assessment of the NOx emissions associated with a single ramp metering system in Atlanta. In order to provide a more complete picture of the potential air quality impacts of ramp metering further research is required. This research has provided two critical elements to that will allow for more effective ramp metering and air quality research in the future. First this research has provided for the development of an analysis framework that can be applied to future studies. The data collection and analysis methodologies developed for this research establish a tested method for this type of study. Second, the research methodology that has been established has resulted in a comprehensive dataset that can be used for continued analysis.

One of the critical areas, which requires further research, is the assessment of the ramp metering system under force flow conditions and during the build up to force flow conditions. Due to a bottleneck downstream from the study area, force flow traffic conditions rarely occur in the study corridor. As a result it was not possible to assess the impact of force flow conditions on modal activity. Of particular importance is the assessment of mainline activity under metered versus non-metered conditions during the development of force flow or jam density operations. Apart from studying a new corridor the analysis of force flow conditions could be accomplished with the current dataset through the use of computer simulation. The data collected as part of this research could be used to calibrate a traffic simulation model, which could than be used to simulate increased traffic volumes. The output from these simulation runs could than
be used to assess the change in modal activity and emissions estimates under traffic conditions that were not observed during the data collection process. Through the development of an analysis process that will allow for the assessment of a ramp metering system under a wide range of traffic conditions a more complete understanding of the air quality impacts of ramp metering will be possible.
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APPENDIX A

MOBILE5b Control File
PROMPT
1999 (Jan. 2000), Atlanta (03naa-2.txt)(ramps.txt)
1 TAMFLG
1 SPDFLG
1 VMFLAG
3 MYMRFG
2 NEWFLG
6 IMFLAG - Enter I/M control flag record.
1 ALHFLG
5 ATPFLG - ATP and Pressure, no Purge
2 RLFLAG
2 LOCFLG - LAP record appears once, in One-Time data section.
1 TEMFLG
4 OUTFMT - 80-column
4 PRTFLG - Print exhaust HC, CO and NOx results.
1 IDLFLG
3 NMHFLG - Calculate emissions for volatile organic hydrocarbons.
1 HCFLAG - print HC totals, no components

0.067 0.065 0.072 0.074 0.072 0.068 0.062 0.056 0.046 0.033 JUMLYR.LDGV..my ages 1-10
0.032 0.074 0.065 0.051 0.033 0.026 0.019 0.021 0.015 0.011 .LDGV..my ages 11-20
0.008 0.007 0.005 0.004 0.014 .LDGV..my ages 21-25
0.058 0.066 0.078 0.083 0.078 0.082 0.069 0.057 0.045 0.026 .LDGT1.my ages 1-10
0.024 0.065 0.068 0.040 0.031 0.024 0.015 0.019 0.015 0.012 .LDGT1.my ages 11-20
0.007 0.006 0.007 0.005 0.020 .LDGT1.my ages 21-25
0.058 0.066 0.078 0.083 0.078 0.082 0.069 0.057 0.045 0.026 .LDGT2.my ages 1-10
0.024 0.065 0.068 0.040 0.031 0.024 0.015 0.019 0.015 0.012 .LDGT2.my ages 11-20
0.007 0.006 0.007 0.005 0.020 .LDGT2.my ages 21-25
0.064 0.062 0.071 0.089 0.071 0.069 0.057 0.051 0.043 0.023 .HDGV..my ages 1-10
0.020 0.040 0.034 0.036 0.032 0.024 0.027 0.026 0.022 0.018 .HDGV..my ages 11-20
0.013 0.014 0.014 0.009 0.071 .HDGV..my ages 21-25
0.067 0.065 0.072 0.074 0.072 0.068 0.062 0.056 0.046 0.033 LDDV..my ages 1-10
0.032 0.074 0.065 0.051 0.033 0.026 0.019 0.021 0.015 0.011 LDDV..my ages 11-20
0.008 0.007 0.005 0.004 0.014 LDDV..my ages 21-25
0.058 0.066 0.078 0.083 0.078 0.082 0.069 0.057 0.045 0.026 LDDT..my ages 1-10
0.024 0.065 0.068 0.040 0.031 0.024 0.015 0.019 0.015 0.012 LDDT..my ages 11-20
0.007 0.006 0.007 0.005 0.020 LDDT..my ages 21-25
0.076 0.077 0.113 0.113 0.090 0.078 0.081 0.068 0.029 0.026 HDDV..my ages 1-10
0.022 0.039 0.033 0.034 0.027 0.011 0.014 0.017 0.014 0.010 HDDV..my ages 11-20
0.007 0.005 0.004 0.003 0.009 HDDV..my ages 21-25
0.008 0.009 0.010 0.013 0.017 0.030 0.030 0.025 0.036 0.055 MC....my ages 1-10
0.037 0.730 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 MC....my ages 11-20
0.0 0.0 0.0 0.0 0.0 MC....my ages 21-25

004
1 7 3 90 90 05.639 00.000
1 7 3 91 97 04.598 00.000
1 7 3 98 03 03.679 00.000
1 7 3 04 50 01.840 00.000
2 1 2 1 # I/M programs=2,TIER1=no,TTC=yes,RSD=no
82 20 94 98 03 03 097 222 2221 2211 2211 220. 1.20 999. 2500/Idle test
82 20 75 93 03 03 097 222 2221 5211 25.0 25.0 2.00 ASM 2525, phase-in cutpoints
1.00 1.00 1.00 1.00 0.40 Alternate effectiveness
82 75 98 2221 22 097. 12111111 ATP
82 75 98 2221 22 097. Pressure
Stage II

Local Area Parameter record

400 02.5 87.0 20.6 27.3 20.6 01
400 05.0 87.0 20.6 27.3 20.6 01
400 10.0 87.0 20.6 27.3 20.6 01
400 15.0 87.0 20.6 27.3 20.6 01
400 19.6 87.0 20.6 27.3 20.6 01
400 20.0 87.0 20.6 27.3 20.6 01
400 25.0 87.0 20.6 27.3 20.6 01
400 30.0 87.0 20.6 27.3 20.6 01
400 35.0 87.0 20.6 27.3 20.6 01
400 40.0 87.0 20.6 27.3 20.6 01
400 45.0 87.0 20.6 27.3 20.6 01
400 50.0 87.0 20.6 27.3 20.6 01
400 55.0 87.0 20.6 27.3 20.6 01
400 60.0 87.0 20.6 27.3 20.6 01
400 65.0 87.0 20.6 27.3 20.6 01

FTP average speed
APPENDIX B

Data Collection Operating Procedures
HANDBOOK
For
DATA COLLECTORS

Ramp Metering Project

Version One

Georgia Institute of Technology
School of Civil and Environmental Engineering
Spring 1999
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<td>CAMERA OPERATIONS</td>
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<td>Section 9</td>
<td>LICENSE PLATE SURVEY OPERATIONS</td>
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<td>Section 10</td>
<td>PROBE VEHICLE DRIVING AND DATA COLLECTION PROCEDURES</td>
<td>14</td>
</tr>
</tbody>
</table>
SECTION 1

DAILY OPERATING PROCEDURE

1. Check Web Site for Cancellations and to Confirm Schedule and Assignment
   - http://transaq.ce.gatech.edu/ramps
   - Weather Cancellations will be Posted by 9:00 AM Each Morning

2. Meet in Room 305 SEB to Checkout Equipment by 2:50 PM

3. Meet in the Parking Lot on the West Side of the SEB for Shuttle to Field Sites
   - Shuttles will Leave at 3:00 PM

4. Setup Equipment and Start Data Collection at 3:15 PM

5. Stop Data Collection at 7:00 PM and Break Down Equipment

6. Wait for Shuttle Pickup by 7:15 PM
   - Do not Leave Site or Leave Equipment Unattended

7. Return to Campus and Check in Equipment
   - Report any Problems
   - Report Time on Time Sheet
SECTION 2
REQUIRED SAFETY CRITERIA

Style of Dress:

All data collectors must wear long pants (i.e. shorts are not acceptable). Each data collector (person) located adjacent to or in the proximity of a road must also wear a safety vest and hard hat. Individuals positioned in moving vehicles are not required to wear the vest and hat while inside the vehicle. The use of headphones or portable radios will not be permitted.

Safety precautions at the Data Collection Site:

1. At no time will a person assigned to collect data enter the active traveled way (the region between edges of road dedicated to vehicle activity).

2. Each person will be dropped-off and picked-up at his or her specific data collection location (unless other arrangements are made with either Dr. Daniel, Dr. Guensler, or Dr. Dixon prior to the day of data collection). When the transportation shuttle delivers individuals to a site, they must exit the shuttle on the side of the vehicle that is not adjacent to traffic. At no time should anyone leave the site without permission from the designated team leader. If an individual needs to leave his or her data collection post for personal reasons, he or she is to contact the team leader via radio or telephone and arrangements will be made for a vehicle to pick-up the person and transport them safely away from the site.

3. Each person should stay alert to errant vehicles. Avoid turning your back completely to traffic.

4. Do not interfere with existing traffic patterns or take any activity (other than those required for the data collection efforts) that may distract drivers or alter driver conditions.

5. Stay as far from the active traveled way as possible.

6. At certain sites, traffic control devices such as parked cars or cones will be positioned to enhance the safety of team members. At no time alter the configuration of these devices.
7. Each data collection site will have data collection zones indicated (generally using surveyor tape or paint). Each person must remain within this zone during the data collection efforts as well as during the intervals before and after collection when the transportation shuttle is not available.

8. If any team member is confronted or threatened during data collection by someone who wants the data collection equipment, do not resist -- surrender the equipment and then immediately report the loss to the team leader and then the police.

**Data Collection within a Moving Vehicle:**

1. When performing moving data collection studies, allow the driver of the vehicle to collect data only if the activity does not detract from his or her ability to drive.

2. When in a vehicle collecting data in the traffic stream, keep seat belts buckled and do not block the vision of or distract the driver.
SECTION 3

COMMUNICATIONS

Communications between the field workers and the senior staff on the project will be maintained through two-way radios and site visits. One senior staff member will also be equipped with a cellular phone during all data collection sessions. It is encouraged that all data collectors who own a cellular phone bring it with them to their field locations.

If the need to contact a senior staff member arises, they should be contacted with the two-way radio or a cellular phone directly or have another individual with such capabilities make contact them for you. If you are unable to make communications, wait at your site until a staff member reaches your location. Only leave your location in the case of an emergency.

CELL PHONE CONTACT NUMBER

404.822.8258
SECTION 4

VEHICEL CLASSIFICATION CODES

1. MOTORCYCLE
2. CARS
3. PICKUPS, VANS, SPORTS UTILITY VEHICLES
4. BUSES
5. 2 AXLE, 6 TIRE SINGLE UNIT TRUCK
6. 3 AXLE SINGLE UNIT TRUCK
7. 4 AXLE SINGLE UNIT TRUCK
8. 4 OR LESS AXLE, DOUBLE
9. AXLE, DOUBLE
10. 6 OR MORE AXLE, DOUBLE
11. 5 OR LESS AXLE, MULTI-UNIT
12. 6 AXLE, MULTI-UNIT
13. 7 OR MORE AKLE, MULTI-UNIT
## SECTION 5

### LOCATION CODES

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<thead>
<tr>
<th>Location Code</th>
<th>Equipment Type</th>
<th>Code</th>
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<tbody>
<tr>
<td>Northside Drive</td>
<td>Laser Range Finder-Ramp</td>
<td>NSR-LRF 10</td>
</tr>
<tr>
<td></td>
<td>Laser Range Finder-Overpass</td>
<td>NSO-LRF 11</td>
</tr>
<tr>
<td></td>
<td>Camera</td>
<td>NSO-CAM 13</td>
</tr>
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<td>Howell Mill Road</td>
<td>Laser Range Finder-Ramp</td>
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<tr>
<td></td>
<td>Laser Range Finder-Advanced</td>
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<td></td>
<td>Laser Range Finder-Overpass</td>
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<td>License Plate</td>
<td>HMO-PLT 24</td>
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<td>Mores Mill Road</td>
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<td>MMR-LRF 30</td>
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<tr>
<td></td>
<td>Laser Range Finder-Behind</td>
<td>MMB-LRF 31</td>
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<tr>
<td></td>
<td>License Plate</td>
<td>MMO-PLT 32</td>
</tr>
<tr>
<td>West Paces Ferry</td>
<td>Laser Range Finder-Ramp</td>
<td>WPR-LRF 40</td>
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<tr>
<td>Peachtree Battle</td>
<td>Laser Range Finder-Overpass</td>
<td>MLO-LRF 50</td>
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<td></td>
<td>License Plate</td>
<td>MLO-PLT 51</td>
</tr>
<tr>
<td>Probe Vehicle One (Dodge)</td>
<td>Distance Measuring Device One</td>
<td>DMI-1DC 01</td>
</tr>
<tr>
<td>Probe Vehicle Two (Ford)</td>
<td>Distance Measuring Device Two</td>
<td>DMI-2DC 02</td>
</tr>
</tbody>
</table>
SECTION 6

LASER RANGE FINDER (LRF) GENERAL OPERATIONS

At the data collection site, the following steps should be taken.

1. Setup tripod at specified data collection location--make sure that the tripod is stable.

2. Connect battery handle to LRF.

3. Mount LRFs on surveying tripods with disc and yoke attachment or on a camera tripod directly to battery handle base, before operation. Use of the LRFs in conjunction with the tripods produces the best results.

4. Power on LRF.

5. Test battery and LRF operation. LRFs will default to appropriate RTR mode when powered up. There is no need to adjust the LRF configuration during any portion of this project.

6. Power off LRF.

7. Insert formatted SRAM card with 100 null files (data.000, data.001, etc.) into PCMCIA card slot on gun; remember SRAM cards are inserted upside down when gun is in the off position.

8. Power on LRF.

9. Power on and set JAMAR board (see JAMAR operations).

10. Start data collection:

   - For ramp locations track every fourth vehicle. For overpass locations track the fourth vehicle that passes under after your focus has returned back to the HUD.

   - Fix LRF cross hairs in heads up display (HUD) on a location on the rear of a vehicle (e.g. the license plate).

   - Track vehicle for as long as possible. The LRFs can take reading from distances of over 2000 feet. The distance from the gun to the vehicle will be
shown in the HUD. Use these readings as an indication for if the gun is storing readings.

- Keep trigger pulled continuously for each vehicle being tracked.

- Stop distance measurement once a vehicle is out of sight or a fix is lost (i.e. flat line in HUD).

- Record vehicle type on JAMAR board after each trigger pull, manually record vehicle type, LRF P=xxxxxx value and time on JAMAR board on log sheet for approximately every fifth vehicle.

- Before removing the SRAM card, always record the last vehicle tracking on the field log, along with the notation “SRAM card changed” on the next line along with the time from the JAMAR board. After installing the a new SRAM card always record the first vehicle tracked on the field log along with the two digit SRAM card number. For overpass locations also record the lane number for which that data on the card coincides.

13. Avoid squeezing the LRF trigger with the SRAM card installed except when ready to actually collect sample data. Every time the trigger is depressed and released, a separate file on the SRAM card is created. If the trigger is depressed unintentionally, the number of readings (P=xxxxxx) should be recorded on the vehicle log along with the JAMAR board time. A button should be depressed on the JAMAR board as a placeholder for the error file.

12. After approximately half an hour or 60-70 trigger pulls (i.e. vehicles) power off LRF and Remove SRAM card.

- Insert and remove SRAM cards only when LRFs are in the off position.

- Insert SRAM card into PCMCIA card slot (usually the top slot) on the site assigned laptop.

- Down load SRAM card to site assigned laptop using DOWNLOAD program. Initiate the program by clicking on the DOWNLOAD icon on the laptop. You will be prompted for the location and SRAM card number.

- Insert SRAM card with new null files into the LRF and repeat data collection process (step 10), there is no need to begin a new JAMAR file.

13. Continue until end of data collection period at 7:00 PM.
14. Power off LRF.

15. Remove LRF from tripod and brake down equipment.

**CAUTION:**
Do not insert or remove SRAM cards when LRF is in the on position.
Do not open the case under any circumstances.
Do not point the LRF directly at the sun.
Do not place the LRF on an unstable surface.
Always transport the LRF in the yellow carrying case.
SECTION 7

JAMAR BOARD GENERAL OPERATIONS

At the data collection site, the following steps should be taken in conjunction with LRF readings.

1. Power on JAMAR board.

2. Make sure that the FHWA scheme F classification template is on the board.

3. Start a new count in saturation flow mode (SF) and enter a six digit numeric code (two digit site ID and four digit date, e.g. 210704 (site twenty-one April seventh)) for the count. JAMAR sequence (COUNT>NEW>SF>8-DIGIT>sitecode).

4. The screen will say “Sat Flow Study, Any Key to Start”, however when you are ready to start data collection, button 12 must first be pressed to start the data collection process.

5. The Board should be located near the LRF, preferably within arms length for quick pressing of button following release of trigger.

6. After release of the trigger on the LRF, immediately press the button on the JAMAR board that corresponds to the type of vehicle tracked.

NOTE: Change the JAMAR board batteries with the provided AA-batteries if a BATT: LOW message is received.
SECTION 8
CAMERA OPERATIONS

At the data collection site, the following steps should be taken to record the traffic entering the study area on northbound I-75 or at designated intersections.

1. Set up tripod at designated location. Pick a location that will capture the target movements and is free from obstructions.

2. Mount camera on tripod.

3. Connect camera to 8-hour battery pack.

4. Power on camera and insert blank videotape.

5. Slide the [CAMERA/VCR] selector to “CAMERA”.

6. Slide the [S-VHS ON/AUTO/OFF] selector to “OFF”.

7. Remove lens cap.

8. Before recording make sure of the following:
   - Adjust the field of view so that all traffic lanes are captured on tape--use zoom to adjust.
   - Press the [DATE/TIME] button and verify that the correct date and time can be seen in the viewfinder.

9. Press Start/Stop button to initiate recording.

10. During the data collection session use the viewfinder to check the following:
    - Power supply (a 2-hour backup battery is provided although it should not be needed).
    - Field of view (make sure camera has not been moved from original position).
    - The camera is in recording mode (i.e. not on pause).

11. Press Start/Stop button to stop recording at 7:00 PM.
12. Disconnect Battery and put camera back in case.
SECTION 9
LICENSE PLATE SURVEY OPERATIONS

At the data collection site, the following steps should be taken. On most days the license plate survey will take place on either the Howell Mill Road overpass or the Mores Mill Road overpass.

1. Locate a position on the overpass above lane one (inside lane)

2. Once your recorder and binoculars are ready start data collection.

3. First record the survey location, date, and start time.

4. Start collecting license plate State and number. Remember to speak clearly and loudly into the recorder microphone.

5. After a plate is recorded, let three vehicles pass and record the license number of the fourth vehicle.

6. Continue this cycle for 15 minutes and then rotate to lane two. Continue to rotate survey from lane to lane every 15 minutes.

7. Change tapes as necessary. Write location and data on tape labels.

8. At 7:00 PM stop collecting license plate numbers.
SECTION 10

PROBE VEHICLE DRIVING AND
DATA COLLECTION PROCEDURE

Directions for Driver:

1. After leaving Georgia Tech, drop off data collectors assigned to vehicle for drop-off/pickup at their respective sites in the field. If you do not have passenger proceed to step five (5).
2. After dropping off last passenger, return south via Interstate-75.
3. Travel I-75 south to Exit 102 – 14th and 10th Streets.
4. At 14th Street intersection, turn left and cross I-75, remaining in left lane.
5. Turn left at intersection of Williams Street and 14th Street (immediate next light) and continue onto I-75 Northbound on-ramp.
6. Enter and drive along I-75 as per Car Following Procedure, which follows.
7. Exit the freeway at Exit 108 – Mt. Paran Road and turn left at the light, onto Mt. Paran Road.
8. Turn left at next light (U.S. 41) and return to 14th Street via I-75.
9. Repeat steps 3-9 as many times as possible before 7:00 P.M. On final southbound trip, pickup data collectors assigned to you.
Data Collection:

In order to acquire data with instrumented vehicles, a procedure was developed. This procedure was used in the collection of all data using instrumented vehicles. It was adapted from the procedures Sierra Research, Inc. developed in its work (Austin, DiGenova, et al. 1993).

Car Following Procedure:
1. Enter the freeway.
2. Driver spots the first white vehicle downstream (in front) of him/her, and enters the lane in which that vehicle is found (when it is safe to do so). Once in the lane, the vehicle immediately in front of the driver is the target vehicle. Driver indicates which vehicle is the target vehicle to the instrument person(s).
3. Follow the target vehicle and mimic its behavior as best as possible, while maintaining a safe distance from the vehicle (headway). This means the driver brakes when it brakes, changes lanes when it changes lanes, speeds up when it speeds up, and maintains the speed at which it travels, including above the speed limit (vehicles should not exceed the general flow of traffic).
4. A target vehicle must be acquired before the beginning mark for the run (a designated roadside sign) is reached. A target vehicle must be tracked through the run until the ending sign is reached.

Target Vehicles: The target vehicle is the vehicle that the instrumented vehicle is following. The instrumented vehicle is trying to capture the speed and acceleration activity of the target vehicle.

Following Above Speed Limit: Target vehicles can travel above the speed limit. On some facilities it is quite common. If runs are aborted because the target vehicle goes above the speed limit, the data sample will be biased due to the lack of vehicles in the sample which travel above the speed limit. Permissions must be obtained from the appropriate regulatory authorities to exceed speed limits for purposes of data collection. For this project, since permission has not been obtained, vehicles shall not exceed speeds above the general flow of traffic.
Changing the Target Vehicle: Each selected target is followed as long as reasonably possible. If a target cannot be followed safely through a lane or speed change, a new target is chosen.

a. If a vehicle gets between driver and the target vehicle, the vehicle immediately in front of the driver becomes the [new] target vehicle. If no vehicle is immediately in front of the driver, a new target vehicle will be acquired using the same procedure used to acquire the initial target.

b. If a vehicle changes lanes in busy traffic [or some other erratic maneuver] and cannot be followed, the driver will duplicate the maneuver safely as soon as possible. Once the maneuver is complete and the driver is in the new lane, the vehicle immediately in front of the driver becomes the [new] target vehicle.

c. If a vehicle exits or obviously is going to exit, a new target is selected. The vehicle immediately in front of the driver becomes the [new] target vehicle.

d. If a target vehicle is changed during a run, the change and the point at which it occurs should be noted in the vehicle log. The distance from the start of the run to the location of the change should be noted in the vehicle log by pressing the DISP/HOLD button on the NS-60 and recording the number.

Instrumented Car Travel at Other Times: At all times when the instrumented car is not following a target (e.g., while trying to acquire a new target in busy traffic), the instrumented car will match the general flow of through traffic around it.
Directions for DMI Operator:
The DMI (distance measurement instrument) operator will ride along in probe vehicle and run the Nitestar NS-60 device as well as the laptop used for downloading of data while the driver completes a prescribed circuit on I-75. The procedure to be used follows:

1. Setup computer while driver drops off passengers and returns to start of course (14th/Williams St. on-ramp).
   a. Plug adapter into serial port of laptop computer and connect computer to the NS-60 with provided cable.
   b. Turn on computer and NS-60. Allow computer to boot up.
   c. Open Windows Explorer and open the DMI directory.
2. Make sure the NS-60 is in COUNT HOLD mode, and units in feet.
3. Run a test of the data collection program to verify that data is being transferred to the laptop.
   a. Run the application entitled QBasic, which will open a DOS window.
   b. Press Esc or click on <escape> to start program.
   c. Press Alt-F, then O, to open a file. Select DMIRUN.BAS and press Enter.
   d. Press Shift-F5 to begin collecting data from the NS-60. The display on the laptop should be a string of timestamps with three columns of zeros.
   e. Press RUN/HOLD on the NS-60 to begin counting. The display should begin counting with columns for timestamp, distance travelled, delta distance, and speed.
   f. Press RUN/HOLD to stop counting.
   g. Press Ctrl-Break on the laptop to close the data window.
   h. Press Alt-F, then X, to exit the DOS window
   i. Press CLEAR to clear memory of the NS-60.
   j. Open the file testout.dat with a word processor to verify that data was written during the previous steps. If not, check connections and or reboot, then repeat steps 3a through 3i until data is written to the test file.
   k. Close data file.
4. When driver re-enters freeway at Williams St., be prepared to begin counting.
5. Repeat steps 3a-3d and collect a few seconds of blank test data to delineate “real” distance data.
6. Press **RUN/HOLD** exactly when the vehicle passes the Northside Drive exit sign to begin collecting “real” data. Try not to disturb the device while collection is in progress.

7. Target vehicles should be identified before reaching Northside Drive sign. Record vehicle information for each run on the log sheet.

8. If the target vehicle is changed during the run the new vehicle should be noted in the log along with the distance from the beginning of the run at which the change occurred. The distance from the beginning of the run can be noted by pressing **DISP/HOLD** on the NS-60. Pressing **DISP/HOLD** again sets the counter to the current distance.

9. Press **RUN/HOLD** exactly when the vehicle passes the second mark at Mt Paran Road ½ mile exit sign.

10. Repeat steps 3g-3i.

11. While driver is returning to 14th Street, verify that data was written to the file **testout.dat**.

12. Rename the file **testout.dat** using the following naming scheme:
    
    Filename = **VMMDDRR.dmi**, where \(V\) is the vehicle designation (1 or 2), **MM** is the two digit month designation, **DD** is the two digit day designation, and **RR** is the two digit number of the run just performed (i.e., the first run of the day is 01).

13. Fill out log sheets for each run.

14. Repeat steps 4-13 until approximately 7:00 P.M.

15. Return to campus after picking up any passenger that were dropped off at the beginning of the session.