Emissions Impacts of Ramp Metering Strategies on the Atlanta Freeway System

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Abstract:

The goal of the study is to collect a comprehensive set of freeway and on-ramp operational data for the assessment of ramp metering systems. This paper is a presentation of a subset of data and initial findings from this larger project. The results reported here focus on the changes in modal activity (e.g. speed/acceleration) and oxides of nitrogen (NOx) and carbon monoxide (CO) emissions estimates that occurred on two of the study area locations as a function of meter operation. Data from one ramp and one associated mainline location are presented here.

The study showed that vehicles on the freeway and on-ramp assessed in this paper displayed increase levels of modal activity that resulted in associated increased levels of vehicle CO emissions. Although the extension of these results to other freeway on-ramps or to the evaluation of ramp metering systems as whole may be limited. This study does provide initial evidence that ramp metering will impact vehicle activity on ramps and that the activity within each condition (metered versus non-metered) is reasonably consistent. This also provides the initial steps for developing a ramp drive cycle for use in the detailed modeling of freeway on-ramp emissions. Continuing research in the area will assess the specific emissions impacts and the system wide air quality effects.

Key Words:
Vehicle Emissions
Freeway Ramp Operations
Ramp Metering
Drive Cycles
Introduction

In October of 1998, the Georgia Institute of Technology, School of Civil and Environmental Engineering began a 16-month comprehensive study of the Atlanta ramp meter system for the Georgia Department of transportation (GaDOT). The goal of the study is to collect a comprehensive set of freeway and on-ramp operational data and develop a traffic simulation model for these ramps. The simulation model will then be used to examine the effects of ramp meter operation and design policies on vehicle pollutant emissions. As will be discussed in some detail later, vehicle emissions are a function of both speed and acceleration characteristics of vehicle operations. Although the TRAF series of models typically provide good traffic flow data, previous Georgia Tech studies have identified deficiencies in the ability of the models to accurately simulate speed/acceleration profiles (Hallmark, et al., 1999). Hence, a primary goal of the study is to develop a calibrated model that accurately predicts not only the traffic flows on the links, but the speed/acceleration profiles for these vehicles. Ultimately, the simulation model will be linked to advance motor vehicle emission rate models for estimating the impacts of ramp meter operation as a function of ramp meter design and operation.

For 18 days, vehicle speed/acceleration profiles were collected on ramp and mainline segments using laser range finders and probe vehicles. The focus of this study is on the data collected by the laser range finders on ramp and one mainline section in the study.

The results reported here focus on the changes in modal activity that occurred on two of the study area data collection sites as a function of meter operation. These results are initial findings from a much larger study on the impacts of ramp metering and management strategies. Once the analyses of vehicle activity data are completed for the freeway segments, the simulation model will be developed and comprehensive changes in modal operations for the entire system and fleet will be predicted. This study is a look at a small subset of the overall data collected as part of this project.

Background

For years, ramp metering has proven to be a popular and effective means for major urban areas to reduce freeway traffic congestion. Ramp metering is an example of a transportation control measure designed to reduce congestion by improving traffic flow. Ramp meters restrict the rate and number of vehicles entering a freeway network from on-ramps, so that the induced congestion on the freeway is minimized. Without ramp metering, freeway on-ramp demand is usually accommodated at the expense of traffic already on the network. That is, the vehicles coming down the ramp force their way onto the system, reducing the available freeway capacity to handle the upstream traffic. When the freeway is operating under congested conditions (at lower levels of service), heavy on-ramp demand can force the upstream sections of the freeway into an unstable mode of operation, and upstream queues of very slow moving traffic can develop. The concept of ramp metering is to restrict on-ramp access in such a manner that the formation of unstable upstream flow is minimized. Vehicles are metered onto the system such that large groups of vehicles do not significantly disrupt existing flow patterns.
Ramp metering results in stop delay and higher fuel consumption for vehicles waiting for freeway access and accelerating to freeway speeds. However, because unstable flow on the freeway is avoided, fuel consumption is minimized for the very large numbers of vehicles on the freeway. Usually, traffic flow improvement measures result in concurrent motor vehicle emissions reductions. When traffic flow becomes more steady, motor vehicle emissions usually decline. However, ramp metering is an example where there is still a great deal of uncertainty in estimating the trade-off between increased fuel consumption and emissions on the ramps and decreased fuel consumption and emissions on the freeway.

Recent vehicle emissions studies demonstrate that motor vehicle emissions under hard acceleration and high-speed moderate-acceleration conditions can lead to order-of-magnitude increases in vehicle emissions for some vehicle technologies (Kelly and Groblicki, 1993; LeBlanc, et al., 1994; LeBlanc, et al., 1995; Barth, 1996b; An, 1998; Guensler, et al., 1998; Fomunung, et al., 1999). Hard deceleration conditions also yield statistically significant carbon monoxide (CO), oxides of nitrogen (NOx), and hydrocarbon (HC) emissions increases (An, 1998; Fomunung, et al., 1999). The extreme non-linear relationships are particularly important for ramp meters, where traffic stops at the on-ramp and then accelerates to freeway speeds (sometimes over short distances). For the last few years, various representatives of federal and state agencies have advocated against ramp meter implementation due to the large expected increases in emissions on the ramps.

To analyze the net emissions effects of ramp meters and other flow-smoothing strategies detailed observations or accurate simulation models must be coupled with modal emissions and fuel consumption models. The analytical results can vary significantly as a function of network characteristics. Geometric parameters such as ramp length, grade, gore length, weave section characteristics, etc., can also significantly affect modal operations and therefore emissions.

Modal models are more complex than traditional emission rate modeling approaches. These models account for the interactions between vehicle technology characteristics and the vehicle operating modes. To apply a modal emissions model to such a ramp metering analyses, a variety of non-traditional data must be made available for analysis. That is, some vehicle technology groups experience significant increases in emissions under certain operating conditions, while others do not. Hence, to model the impacts of ramp metering where changes in operating modes are expected, modelers need roadway grade estimates, vehicle fleet characteristics, and speed/acceleration profile data for each scenario (Guensler, et al., 1998; Bachman, 1998).

As discussed earlier, the goal of the Georgia Tech/GaDOT ramp metering study was to collect a comprehensive data set that could be used in estimating the impacts of ramp metering through the application of the Mobile Emissions Assessment System for Urban and Regional Evaluation (MEASURE) modal model. The MEASURE model is a GIS based model emissions model developed at Georgia Tech. Road grade information for
the study area is available through the Atlanta GIS system. Detailed vehicle fleet characteristics were collected by sampling vehicle license plates, translating plate numbers to vehicle identification numbers using a registration database, and decoding the VINs to provide vehicle technology group data. The speed/acceleration profiles were collected using laser rangefinders and probe vehicles. The results presented here focus on the changes in modal activity and related emissions levels that occurred on one of the four study area ramps as a function of meter operation. Laser rangefinders were used to collect data for the following analysis. Once vehicle activity analyses are completed for the other three study area segments, the comprehensive changes in modal operations for the entire system and fleet will be predicted using the MESURE model. The following are initial findings.

Data Collection Methodology

Laser Rangefinders
Laser rangefinders were used for this study, as a means to collects precise modal activity data for a large sample of the vehicle fleet. The laser instruments record vehicle distance measurements at a rate of 236 readings per second. This allows for the accumulation of highly detailed information for each vehicle trace. Once the distance information was collected, a post processing routine was applied in order to produce more descriptive modal activity information such as speed and acceleration.

Equipment and field deployment tests started during the end of April with full deployment commencing in May and June of 1999. The collection of the vehicle modal activity data was centered around the PM peak period when the ramp meters were in operation and under clear weather conditions. The data collection activities were carried out for approximately four hours per session from 3:15 PM to 7:00 PM on a typical day. The ramp meters were in operation from 3:45 PM to 6:30 PM. Data was collected for the locations presented here occurred on seventeen different days between May and July of 1999. During four of these days, the ramp meters were turned off during the entire peak period. A summary of the data collection activity for the locations reported here is provided in the following table.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Days of Data Collection</th>
<th>Hours of Data Collection</th>
<th>Approximate Number of Vehicle Traces</th>
<th>Metered Traces</th>
<th>Non-Metered Traces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howell Mill Ramp</td>
<td>18</td>
<td>72</td>
<td>3300</td>
<td>2525</td>
<td>775</td>
</tr>
<tr>
<td>Mainline, near Howell Mill Ramp merge area</td>
<td>16</td>
<td>60</td>
<td>3500</td>
<td>2625</td>
<td>875</td>
</tr>
</tbody>
</table>
Site Selection
The data presented here is from the Howell Mill Road ramp, which is one of four locations in the study area as shown in Figure 1. The design of this on-ramp includes a negative grade which is steep at times (~7 percent). This data set also includes vehicle modal activity from an adjacent mainline freeway section. The mainline data was collected from the Howell Mill Road overpass and is representative of vehicle activity near the merge area of the Howell Mill Road on-ramp. This site was chosen as it currently provided the most complete and uniform data set available. This data set allowed for an initial assessment of the modal activity and related vehicle emissions impacts of ramp metering for an entire ramp and mainline system. There are currently only five ramp meters in operation in the Atlanta area.

Sub-Fleet Mix Data
In order to characterize the fleet in the study area vehicle license plate information was collected for a sample of vehicles during the data collection period. Vehicle license plates were recorded by the data collector and enter on the field log. Additional plate data was collected at the two ramp locations by a remote sensing crew collecting vehicle emissions data as a related part of this project. This plate information will be associated with a VIN and decoded to provide detailed fleet information. The resulting vehicle technology data was used as an input to the MEASURE emissions rate model.

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 GaDOT TMC freeway surveillance cameras and portable Georgia Tech 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.

Study Findings
The essential findings are centered on the comparison of activity when the ramp meter was on versus when the ramp meter was off, and the estimated emissions differences. Since the ramp meters were turned off during a portion of this study direct comparisons of emissions estimates and activity during critical peak period times can be made on a location by location basis.

The findings are summarized by vehicle speed and acceleration, and other vehicle activity measures that lead to enrichment or enleament, and are important to the level of vehicle emissions. Moreover, since the Atlanta region is an ozone nonattainment area with a focus on NOx reduction, NOx emissions were also analyzed. To provide a comparison CO emissions were also analyzed, which also tend to parallel the relative level of hydrocarbon emissions. The modal activity measures analyzed were: acceleration greater than 3 mph per second$^2$, acceleration greater than 6 mph per second$^2$,
deceleration greater than 2 mph per second², and inertial power surrogate (IPS: measured as velocity * acceleration) greater than 45 mph²/sec, and greater than 90 mph²/sec.

The following table shows general information and descriptive findings for the two locations examined in this study. The ramp cycle length for the ramp location was 1300 feet and the mainline cycle length was 2100 feet.

<table>
<thead>
<tr>
<th>MEASURE</th>
<th>Howell Mill Road Ramp</th>
<th>Mainline, Near Howell Mill Road Ramp Merge Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
<td>Non-Metered</td>
</tr>
<tr>
<td>Cycle Length (feet)</td>
<td>1,300</td>
<td>1,300</td>
</tr>
<tr>
<td>Average Speed (mph)</td>
<td>30.2</td>
<td>42.9</td>
</tr>
<tr>
<td>Maximum Speed (mph)</td>
<td>72.7</td>
<td>70.8</td>
</tr>
<tr>
<td>Maximum Acceleration (mph/sec²)</td>
<td>14.4</td>
<td>11.8</td>
</tr>
<tr>
<td>Maximum Deceleration (mph/sec²)</td>
<td>7.6</td>
<td>8.8</td>
</tr>
</tbody>
</table>

As would be expected the average ramp cycle speed was lower under metered versus non-metered conditions. Higher maximum acceleration rates were also observed for metered versus non-metered ramp conditions. The following figures 2 shows the average speed traces over the ramp cycle for the Howell Mill location. Note that the average speed at the stop bar under metered conditions was approximately 8 mph. The expected value for this condition should be close to zero. The 8-mph figure is a result of the fact that few queues formed during the data collection period, some vehicles received a green signal upon approaching the stop bar, and not all vehicles obeyed the ramp meter signal. Figures 3 and 4 show the distribution of actual speed observations over all points down the ramp location under metered and non-metered conditions respectively. These figures show the spread of speed observations at different locations and how the variability in speed activity is greater under metered operations. In addition, these figures show the impact of vehicle queues on vehicle speeds through the ramp cycle. The individual speed data points observed at the beginning of the ramp vary as a result of the presence of a vehicle queue.

Figures 5 through 8 show the joint frequency distribution over speed and acceleration for the ramp location under metered versus non-metered conditions. In order to show the variability in modal activity on the ramp, these figures show ramp conditions in two segments, one for data before the stop bar and one for data after the stop bar. In separating these figure in to two parts the primary deceleration and acceleration activity is separated to provide a clearer picture of ramp activity. These figures show the variability in acceleration for the metered conditions on the on-ramp. In addition, the non-metered conditions reveal a much narrower distribution compared to the metered
conditions. These figures also show the higher level of zero velocity activity (i.e. idle under the metered conditions). Figures 9 and 10 show the joint frequency distributions for the mainline location. As can be seen, at least for this particular mainline section, the modal activity if consistent under both metered and non-metered conditions.

It has been shown that specific modal activity is important for estimating the level of various exhaust emissions. The percent of time a vehicle is operating in certain acceleration ranges and power demand ranges influence the level of NOx and CO emissions—specifically acceleration rates greater than 3 mph per second, acceleration rates greater than 6 mph per second, deceleration greater than 2 mph per second, and IPS (i.e. change in positive kinetic energy measured as power, acceleration * velocity) greater than 60 mph^2/second (Fomunung, 1999). The following table shows the estimated NOx and CO emissions and the percent of the cycle spent in each of the above mentioned modes of operation. The ramp cycle length for the ramp location was 1300 feet and was divided into two sections, one before the ramp meter stop bar and one after the stop bar.

<table>
<thead>
<tr>
<th>POLLUTANT EMISSIONS and MODAL ACTIVITY</th>
<th>Howell Mill Road Ramp Approach to Stop Bar</th>
<th>Howell Mill Road Ramp After Stop Bar</th>
<th>Mainline, Near Howell Mill Road Ramp Merge Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metered</td>
<td>Non-Metered</td>
<td>Metered</td>
</tr>
<tr>
<td>NOx Emissions (grams/peak period (2.75 hours))/Rate (grams/sec)</td>
<td>37/ .00157</td>
<td>47/ .00337</td>
<td>62/ .00448</td>
</tr>
<tr>
<td>CO Emissions (grams/peak period (2.75 hours))/ Rate (grams/sec)</td>
<td>1086/ .04573</td>
<td>753/ .05419</td>
<td>920/ .06664</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration Greater than 3 mph/sec</td>
<td>13.1</td>
<td>28.5</td>
<td>54.9</td>
</tr>
<tr>
<td>Percent of Cycle with Acceleration Greater than 6 mph/sec</td>
<td>2.37</td>
<td>1.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Percent of Cycle with deceleration Greater than 2 mph/sec</td>
<td>24.7</td>
<td>2.5</td>
<td>.4</td>
</tr>
<tr>
<td>Percent of Cycle with IPS Greater than 45 mph^2/sec</td>
<td>23.3</td>
<td>68.6</td>
<td>93.0</td>
</tr>
<tr>
<td>Percent of Cycle with IPS Greater than 90 mph^2/sec</td>
<td>10.4</td>
<td>37.2</td>
<td>70.5</td>
</tr>
</tbody>
</table>

The above table shows that most of the variables found to be important to predicting vehicle emissions are measurably different for both parts of the ramp locations. The
mainline activity was roughly consistent for both conditions. Based on the related emissions estimates the impact of this change in activity is most significant for CO emissions. The emissions estimates for these locations indicate that NOx emissions would decrease with ramp metering and CO emissions would increase on the ramp and decrease on the mainline with ramp metering. Acceleration and deceleration activity and related power demand surrogates have been found to be the most significant modal activity variables for predicting vehicle emissions. Based on these initial findings and the varying levels of modal activity observed under the metered versus non-metered conditions there is indication that vehicle CO emissions may be higher under metered conditions ramps sections.

This study provides strong initial evidence that ramp metering will impact vehicle activity on ramps and that the activity within each condition (metered versus non-metered) is reasonably consistent. This also provides the initial steps for developing a ramp drive cycle for use in the detailed modeling of freeway on-ramp emissions.

**Summary of Findings**
The following is a summary list of the results of this study. These results are from data collected at the two study locations and caution should be used when extending the findings to other freeway on-ramps.

- Average speed on ramps decreased under metered conditions
- The percent of ramp cycle under “hard” acceleration (greater than 3 and 6 mph/sec) or enrichment conditions increased under metered conditions as vehicles accelerate from the meter stop bar.
- The percent of ramp cycle under rapid deceleration (greater than 2 mph/sec) increased under metered conditions as vehicles approach the meter stop bar
- The maximum ramp acceleration rate increased under metered conditions
- The maximum ramp deceleration rate was consistent for both conditions
- The average and maximum speed was higher on the mainline under metered conditions.
- The percent of ramp cycle under IPS greater than 45 and 90 (change in kinetic energy measured as power) increased under metered conditions for the mainline and ramp acceleration zone (after meter stop bar).
- CO Emissions on the ramp increased and on the mainline decreased under metered conditions
- NOx Emissions on the ramp and mainline decreased under metered conditions
• It is evident that ramp meters influence driving behavior even when they are not in operation (i.e. some individuals stop or slow down at the ramp meter stop bar even if the meter is off). That is, there is likely a difference between a non-metered ramp and a metered ramp with the meter off.

Limitations of the Data and Results
The study showed that vehicles on the freeway and on-ramps assessed in this paper displayed increase levels of modal activity that result in associated increased levels of CO emissions. This analysis was limited to activity associated with only two locations with in a five ramp system. Therefore, the extension of these results to other freeway on-ramps or to the evaluation of ramp metering systems as whole is also limited. Continuing research in the are will assess the specific emissions impacts and the system wide air quality effects.

Future and Forthcoming Research
Currently the Georgia Institute of Technology, School of Civil and Environmental Engineering is collecting and analyzing additional vehicle modal activity on other freeway on-ramps in the system and mainline sections. This fourth coming data will provide a more comprehensive and conclusive assessment of the emissions impact of ramp metering systems. The findings here are an initial look at a subset of the overall system activity. The expansion of the scope in both study locations and data collection intensity will provide for a much richer data set than is provided here. Future research will include not only more data, but simulation and validation studies.
Figure 2
Average Speed Over Distance
Relative to Ramp Meter Stop Bar

![Graph showing the average speed over distance relative to the ramp meter stop bar, with speed in mph on the y-axis and distance in feet on the x-axis. The graph includes two lines: one for metered conditions and another for non-metered conditions. The line for metered conditions shows a peak and a trough around the middle of the distance range.]
Figure 6: Howell Mill, Before Stop Bar
Non-Metered

Speed (mph)

Acceleration (mph/sec^2)

Frequency

Legend:
- 6%-7%
- 5%-6%
- 4%-5%
- 3%-4%
- 2%-3%
- 1%-2%
- 0%-1%
Figure 7
Howell Mill, After Stop Bar Metered
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