Applications of Freeway Ramp Metering in Alabama

By

Virginia P. Sisiopiku, Ph.D.
Anirban Das, M.S.
Andrew Sullivan, P.E.

Department of Civil and Environmental Engineering
The University of Alabama at Birmingham
Birmingham, Alabama

Prepared by

UTCA

University Transportation Center for Alabama
The University of Alabama, The University of Alabama in Birmingham,
And The University of Alabama in Huntsville

UTCA Report 04203
March, 2005

Technical Report Documentation Page

1. Report No **FHWA/CA/OR-**	**2. Government Accession No.**	**3. Recipient Catalog No.**
4. Title and Subtitle Applications of Freeway Ramp Metering in Alabama	**5. Report Date** January 2005 **6. Performing Organization Code**	
7. Authors Virginia P. Sisiopiku, Anirban Das, and Andrew J. Sullivan	**8. Performing Organization Report No.** UTCA Report 04203	
9. Performing Organization Name and Address Department of Civil & Environmental Engineering The University of Alabama at Birmingham 1075 13th Street South Birmingham, AL 35294-4440	**10. Work Unit No.** **11. Contract or Grant No.** DTSR0023424	
12. Sponsoring Agency Name and Address University Transportation Center for Alabama The University of Alabama P.O. Box 870205 Tuscaloosa, AL 35487-0205	**13. Type of Report and Period Covered** Final Report 1/1/04-12/31/04 **14. Sponsoring Agency Code**	
15. Supplementary Notes		

16. Abstract

Freeway ramp metering systems have been successfully used in U.S. cities since the 1960s, to improve traffic flow on urban freeways, increase freeway speeds, reduce overall travel times, and improve travel time consistency. These systems improve freeway flow by regulating the rate at which vehicles are allowed to enter the freeway at the entrance ramps. By monitoring flow conditions on the freeway in real-time, these systems can continually adjust the entrance ramp flows to maintain optimum flow on the freeway. However, ramp metering options are not without drawbacks. While they can reduce delays on the freeway, they typically increase delays on the ramps and can adversely impact traffic flow on arterial operations. Moreover, they typically reduce air pollution and emissions, but often increase system-wide fuel consumption due to increased ramp delays. Also, some public opposition has been observed in several areas where ramp metering strategies were first introduced.

This project assessed the applicability of various ramp metering strategies to congested freeway segments in Alabama. The report contains a comprehensive review of ramp metering practices, a synthesis of best practices based on experiences in other states, identification of Birmingham Interstate corridors that may benefit from ramp metering, and evaluation of impacts of various ramp metering options on selected corridors through a simulation study and a cost-benefit analysis. The simulation study was performed using the CORSIM microsimulation model and the cost-benefit analysis was based on the IDAS software
.

17. Key Words Ramp metering, traffic management, metering options, traffic simulation, cost-benefit analysis.		**18. Distribution Statement**	
19. Security Classif. (of this report) Unclassified	**20. Security Classif. (of this page)** Unclassified	**21. No of Pages** 81 pages	**22. Price**

Form DOT F 1700.7 (8-72)

Contents

Contents.. iii
List of Tables v
List of Figures vi
Executive Summary vii

CHAPTER 1 INTRODUCTION..1
1.1 Study Objective..3
1.2 Physical Components of Ramp Metering Systems..3
1.3 Evolution of Ramp Metering in the U.S. 5
1.3.1 Case Studies 6

CHAPTER 2 SURVEY OF THE STATE OF PRACTICE..10
2.1 Approach..10
2.2 Summary of Findings..11
2.2.1 Public Perception..11
2.2.2 Metering Algorithms Used 12
2.2.3 Implementation Criteria 12
2.2.4 Installation Costs..13
2.2.5 Maintenance Costs 13
2.2.6 Impact Studies..13
2.2.7 Enforcement Issues 13
2.2.8 Problems with Meters/Removed Meters..14

CHAPTER 3 RAMP METERING IMPLEMENTATION..16
3.1 Ramp Metering Operational Options 16
3.2 Ramp Metering Strategies..17
3.3 Design Considerations 19
3.4 Implementation Process 25

CHAPTER 4 METHODOLOGY 31
4.1 The Role of Simulation in Traffic Modeling 32
4.2 Simulation Model Selection..32
4.3 Development of the Simulation Test Bed 34
4.3.1 Building the Network..34
4.3.2 Data Collection..35
4.4 Ramp Metering Options Analyzed 36
4.4.1 No Metering..36
4.4.2 Clock Time Control..36
4.4.3 Demand/Capacity Meter 40
4.4.4 Multiple Threshold Occupancy Meter 41
4.4.5 ALINEA Meter..42

Contents (Continued)

CHAPTER 5 SIMULATION STUDY RESULTS 45

CHAPTER 6 IMPLEMENTATION OF FINDINGS 53
6.1 Implementation of Simulation Findings to the Birmingham Region..............53
6.2 Analysis of Benefits and Costs 57

CHAPTER 7 SUMMARY AND CONCLUSIONS 61

CHAPTER 8 LIST OF REFERENCES 63

APPENDIX A
Summary of Agency Survey Response...66

List of Tables

Number **Page**

Table 1-1 Benefits of ramp metering 3
Table 1-2 Ramp metering in the U.S.A 5
Table 2-1 Summary of Agency Survey Responses 15
Table 3-1 Recommended widths for metered ramps 19
Table 3-2 Acceleration distance from meter to merge point 23
Table 3-3 Ramp meter configurations 29
Table 4-1 Data needed for CORSIM simulation model 34
Table 4-2 Clock time ramp metering with time headway 5 secs 37
Table 4-3 Clock time ramp metering with time headway 5 secs and 10 secs 38
Table 5-1 Mainline speed comparison-upstream of ramp 45
Table 5-2 Mainline speed comparison-downstream of ramp 46
Table 5-3 Speed comparison-on ramp 46
Table 5-4 Mainline density comparison-upstream of ramp 49
Table 5-5 Mainline density comparison-downstream of ramp 49
Table 5-6 Mainline density comparison-on ramp 50
Table 6-1 Mainline speed comparison 54
Table 6-2 Ramp speed comparison 55
Table 6-3 Travel time and delay time comparison 56

List of Figures

Number		Page
Figure 1-1	Schematic diagram of ramp meter	1
Figure 1-2	Metered freeway ramp	4
Figure 2-1	Ramp metering state of practice survey instrument	10
Figure 3-1	Single lane ramp meter	18
Figure 3-2	Dual lane ramp meter	19
Figure 3-3	Distance requirements for ramp meters	20
Figure 3-4	Queue distance to ramp meter	21
Figure 3-5	Acceleration length from meter to merge point	22
Figure 3-6	Cross section at a metered location	24
Figure 3-7	Flow chart for ramp meter design process	27
Figure 3-8	Quality of ramp metering	30
Figure 4-1	Criteria for selection of micro-simulation tool	33
Figure 4-2	Study test bed: Birmingham area network	35
Figure 4-3	Clock time meter properties	37
Figure 4-4	Speed comparison of clocktime headways on mainline, upstream	38
Figure 4-5	Speed comparison of clocktime headways on mainline, downstream	39
Figure 4-6	Speed comparison of clocktime headways on ramp	39
Figure 4-7	Demand/capacity ramp meter input table	40
Figure 4-8	Multiple threshold occupancy meter input table	41
Figure 4-9	Default metering rate values in multiple threshold occupancy meter	42
Figure 4-10	ALINEA ramp meter input parameters	44
Figure 5-1	Mainline freeway speed comparison-upstream of ramp	47
Figure 5-2	Mainline freeway speed comparison-downstream of ramp	47
Figure 5-3	Speed comparison-on ramp	48
Figure 5-4	Mainline freeway density comparison-upstream of ramp	50
Figure 5-5	Mainline freeway density comparison-downstream of ramp	51
Figure 5-6	Density comparison-on ramp	51
Figure 6-1	CORSIM simulation of MT occupancy ramp meter	55
Figure 6-2	CORSIM simulation of ALINEA ramp meter	56
Figure 6-3	Benefit/cost summary in IDAS	59
Figure 6-4	Birmingham region coded in IDAS	60
Figure 6-5	IDAS preparing the Benefits Module	60

Executive Summary

Freeway ramp metering systems have been successfully used in the U.S. since the 1960s to improve traffic flow on urban freeways, increase freeway speeds, reduce overall travel times, and improve travel time consistency. These systems improve freeway flow by regulating the rate at which vehicles are allowed to enter the freeway at the entrance ramps. By monitoring flow conditions on the freeway in real-time, ramp metering systems can continually adjust the entrance ramp flows to maintain optimum flow on the highway.

While the basic components of ramp metering systems are similar across the U.S., there is considerable variation in the algorithms used to monitor and control ramp flows. Some systems do not explicitly monitor traffic conditions on the ramps, and therefore can create longer delays. Others incorporate data on ramp conditions into the overall metering algorithms, reducing ramp delays but often at the expense of mainline flows. Determining which control algorithms are best suited to a particular corridor is therefore critical to the success of a ramp metering system.

Ramp metering systems are not currently deployed in the State of Alabama, although there are a number of congested interstate corridors, particularly in the Birmingham region, that could be potential implementation sites.

One of the goals of this project is to review the experiences of other state agencies with ramp meters and develop a set of best practices for their use and implementation in Alabama. To meet this goal an extensive literature review was conducted along with a state-of-the-practice review involving interviews of transportation officials across the nation with experience in ramp metering operations. The report provides an overview of different ramp metering strategies, criteria for determining under what conditions different types of ramp metering strategies are warranted, and documentation of experiences (both positive and negative) from other agencies with ramp metering.

Moreover, the study identifies Interstate corridors in the Birmingham region that may be candidates for ramp metering strategies. The test bed was modeled using the CORSIM software to provide a more detailed analysis of impacts on travel speeds, travel times, and delays with and without ramp metering. Moreover, the IDAS software was used to develop estimates of benefits and costs from ramp metering implementation. The report compares the impacts of various ramp metering strategies on the freeway and ramp operations for various demand levels on the mainline and ramp and identifies conditions under which ramp metering is justified. The report also summarizes benefits and costs that are expected to result if ramp metering is implemented at selected ramps along major Birmingham corridors.

CHAPTER 1
INTRODUCTION

Many urban freeways today operate with peak traffic demands in excess of capacity. This results in congestion, delays, and low vehicle throughput. In order to improve freeway operations two options typically exist. The first option involves increase of the supply and the second one involves control of the demand. Increasing the supply is often an undesirable alternative due to physical constraints, cost considerations and potential environmental impacts. Controlling the demand and spreading it over time and space is often a better alternative (Johnston 1995). There are many ways to control traffic demand. One of those is the implementation of a ramp metering strategy.

Ramp meters are traffic signals that control traffic at entrances to freeways. The purpose of ramp meters is to regulate the rate at which vehicles are allowed to enter the freeway at entrance ramps. Ramp metering attempts to smooth the merging process between vehicles approaching from the entrance ramp and the mainline freeway traffic (University of Minnesota 2004).

Figure 1-1 presents a schematic diagram of a basic ramp metering highway merge area.

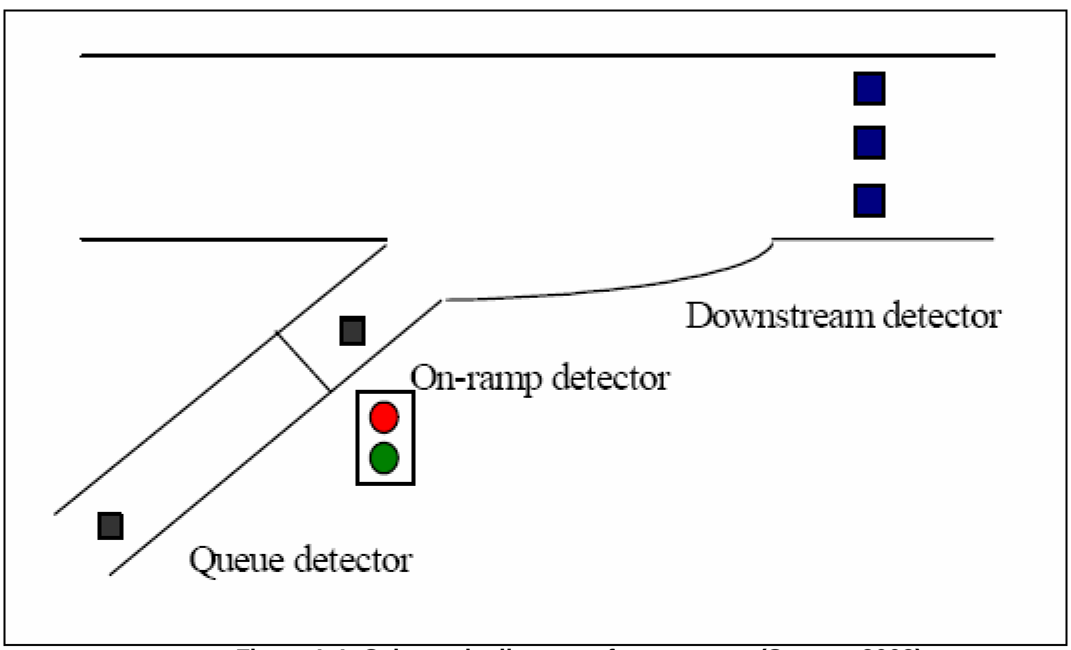

Figure 1-1: Schematic diagram of ramp meter (Stewart 2003)

Ramp meters are installed to address two primary objectives:

1. Control the number of vehicles that are allowed to enter the freeway, and
2. Break up the platoons of vehicles entering the freeway from an upstream traffic signal.

The purpose of the first objective is to ensure that the total traffic entering the freeway section remains below its operational capacity. The second objective supports a safe merge operation at the freeway entrance. A secondary objective of ramp metering is to introduce controlled delay (cost) to vehicles wishing to enter the freeway, and as a result, reduce the incentive to use the freeway for short trips.

Traffic signals on ramps regulate the amount of traffic allowed to enter freeways. Responding to freeway or ramp gaps and queues, they redistribute demand over time by storing the excess demand on ramps instead of the mainline. Real-time adaptive ramp meters capture the dynamic traffic characteristics and respond to them accordingly. Implementation of real-time ramp metering requires area traffic sensors and control algorithms for determining the time-varying metering rates. Ramp metering control systems may also turn off ramp meters when not needed and automatically balance queues at the ramps by prioritizing consecutive ramps along the freeway (Tian 2002).

When properly installed, ramp metering has the potential to achieve increased freeway productivity, higher moving speeds, safer operation on both the freeway and its entrances and decreased fuel consumption and vehicular emissions (European Commission 2001). Additionally, ramp metering can affect driver route choice and can be used to encourage alternative routes in corridor networks, particularly where complimentary measures such as alternative route signing are applied. The potential benefits of adaptive ramp meters are summarized in Table 1-1.

But the implementation of ramp metering is not simple. There are many hurdles which ramp metering must overcome to become a successful solution. The main challenge to the implementation of ramp metering is public opposition (Alkadri 2001). If the public has not had any exposure to the benefits of ramp metering, they may not be able to see beyond the additional waiting time at the ramps to understand potential ramp metering advantages. In addition, ramp metering takes time to produce benefits, and often must be adjusted after installation to respond to actual results, further increasing the likelihood of public frustration during the adjustment period.

In addition to initial public opposition, issues of equity may arise. Ramp metering on a system wide level may favor the drivers who live the farthest from the central business district (CBD). Drivers attempting to access the freeway closer to the CBD may find their metering rates extremely restrictive because mainline capacity has already been filled by the drivers entering further upstream. Equity issues can be addressed by adjusting the metering rates (Dudek 1992).

Finally, ramps must have the capacity to handle queues at meters without causing undesirable spillover onto the arterial network. Ramp metering usually works better if the arterial network has some extra capacity to accommodate the small portion of traffic that is diverted.

Table 1-1: Benefits of Ramp Metering (Pearsons 2001)

Benefits	Description
Efficient Use of Capacity	If there is excess capacity on surface streets, it may be worthwhile to divert traffic from congested freeways to surface streets, and discourage trip paths with high societal costs. If insufficient capacity exists, metering can have adverse effects. Ramp metering can also result in temporal diversion, where drivers change ramp arrival time. Flow peaks are thus spread out over a longer period resulting in better freeway capacity utilization.
Improved Safety	Reduced turbulence in merge zones can lead to reduced sideswipe and rear-end accidents which are associated with unmetered areas. Such turbulence is generated by platoons of entering vehicles which disrupt mainline flow. Similarly, if metering prevents a bottleneck, one can also expect safer conditions through the reduced variance in speed distributions.
Reduced Vehicle Emissions	Smoother traffic flow resulting in less speed variation on a metered freeway can lead to substantial reduction in emissions and fuel savings.
Travel Time Savings	If properly implemented, ramp metering can significantly increase peak speeds and reduce travel times. While ramp delays increase, system wide delay reductions can be large and positive.

1.1 Study Objective

Hence, the implementation of ramp metering is a controversial issue and special attention has to be given to local conditions and priorities before it is actually implemented. The main objective of this project to study if local traffic conditions justify implementation of ramp meters in Alabama. There are a number of congested Interstate corridors, particularly in the Birmingham region, which can be potential implementation sites. One of the goals of this project was to review the experiences of other state agencies with ramp meters and to develop guidelines for their use and implementation in Alabama. The study overviewed different ramp metering strategies and design considerations. Moreover, it developed criteria for determining under what conditions different types of ramp metering strategies are warranted. Using these criteria, a number of ramps were selected for ramp metering in the Birmingham region and an analysis was performed to demonstrate the impacts of ramp metering on network operations.

1.2 Physical Components of Ramp Metering Systems

Figure 1-2 below shows the different physical components that can be present in a metered ramp. As shown in Figure 1-2, a ramp metering system consists of various physical components, which are often elements of the freeway management architecture. These components are:

- **Ramp Metering Signal and Controller** - The signal is typically located to the drivers left, or on both sides of the ramp. Each ramp meter typically has one nearby weatherproof control cabinet which houses the controller, modem(s) and inputs for each loop. A multi-lane ramp meter is served with a single cabinet. The controller is set to a specified algorithm, which controls the ramp metering rate. A widely used controller is the Type 170 Controller developed jointly by the states of New York and California (to be upgraded in the future to the Type 2070 Controller).

- **Advance Warning Signage -** The Manual of Uniform Traffic Control Devices (MUTCD 2003) recommends one or two advance warning signs with flashing beacons indicating that ramp metering is active.
-

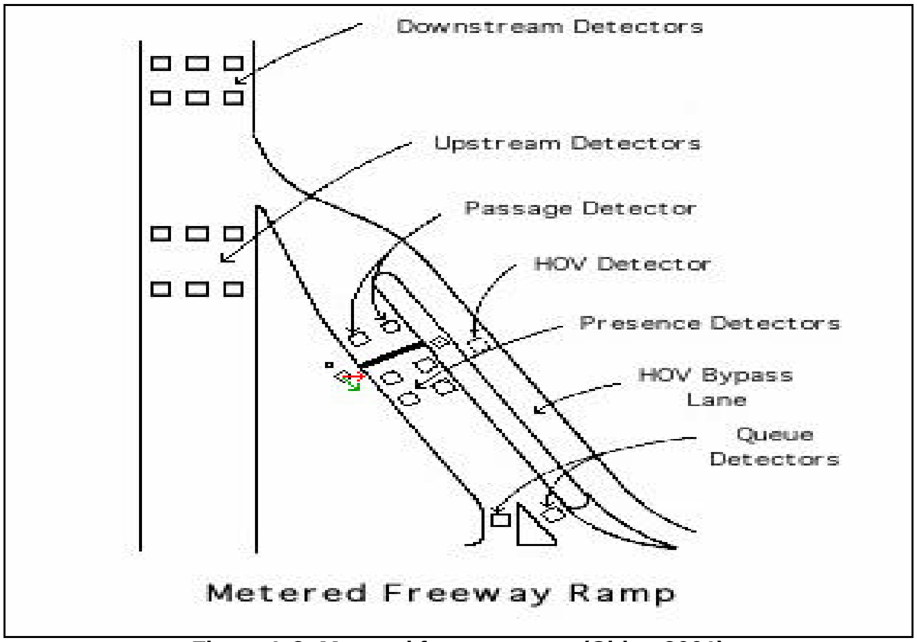

Figure 1-2: Metered freeway ramp (Chien 2001)

- **Check-In Detector -** The check-in, or demand detector, is located upstream of the ramp metering cordon line. The check-in detector notifies the controller that a vehicle is approaching in order to activate the green interval. It is common to use two or more demand detectors per lane to avoid situations where a vehicle that stops just upstream of the detector is not recognized by the controller and the ramp meter fails to switch to green.
- **Check-Out Detector -** The check-out or passage detector is located downstream of the ramp metering cordon line. The check-out detector notifies the controller that a vehicle has passed through the ramp meter and that the signal should be returned to red. In this manner, one vehicle passes per green interval when it is a Single-Car per green type of metering system.
- **Merge Detector -** The merge detector is an optional component that senses the presence of vehicles in the primary merging area of the ramp. To prevent queuing in the primary merging area, the controller holds a red indication when the merge detector indicates a vehicle within this area. This prevents vehicles from having to merge onto the freeway from a stopped position, requiring additional acceleration distance on the mainline and disrupting mainline vehicle speeds. This typically occurs when a timid motorist hesitates, and impacts subsequent ramps vehicles. In

the case of single-entry metering, subsequent green intervals are preempted until the vehicle merges.

- **Queue Detector** - The queue detector is located on the ramp, upstream of the check-in detector. The queue detector prevents spillover onto the surface street network. Continued actuation of the queue detector with no actuation of the check -in detector indicates that the first queued vehicle has stopped in advance of the check-in detector, and the ramp metering signal should be turned to green to allow this vehicle to proceed. Once ramp queues reach the queue detector and queues begin to spill onto the surface street, the metering rate is reduced or metering is terminated. This is also prevented with multiple check-in detectors, as already discussed.
- **Mainline Detectors** - Mainline detectors are located on the freeway upstream and downstream of the on-ramp. For isolated ramp metering applications, only the occupancy/flow registered from upstream detectors influences the ramp metering rate if the metering is adaptive (not preset). For ramp metering systems, data from both upstream and downstream detectors influence the metering rate.

1.3 Evolution of Ramp Metering in the U.S

The ramp metering technique was first introduced in the early 1960s in experiments conducted in Detroit, New York and St. Louis (Bogenberger & May 1999). Since then, the ramp meter has spread across the United States and to other countries providing some relief to the problem of freeway congestion. Currently, ramps meters are used in 12 states and 20 cities in the U.S., as well as oversees in several countries including the U.K and Australia. Locations where ramp meters are now successfully used in the U.S are given in Table 1-2.

Table 1-2: Ramp Metering in the U.S.A (Banks 1988)

Metropolitan Area	Location	No. of Meters
Arizona	Phoenix	65
California	Fresno	15
	Los Angeles	808
	Orange County	278
	Sacramento	19
	San Bernardino	51
	San Diego	134
	San Francisco	96
Illinois	Chicago	109
Michigan	Detroit	49
Minnesota	Minneapolis	367
New York	Long Island	75
Virginia	Arlington	26
Washington	Seattle	54
Wisconsin	Milwaukee	43

In the following paragraphs, selected case studies involving ramp metering are reviewed and results from evaluations are presented.

1.3.1 Case Studies

Portland, Oregon: Portland was the first city to install ramp meters in the Pacific Northwest in the late 1960s (Piotrowicz & Robinson 1995). Sixteen ramp meters were installed along a 10-kilometer stretch of the Interstate 5 to help alleviate congestion and increase the average speed during the PM peak. Before the installment of the ramp meters the PM peak speed between downtown Portland and the Washington state line was an average of 16.3 mph. The following list illustrates the benefits that Portland has seen since the installment of the metered ramps:

- PM peak speed increased from 16.3 mph to 41.3 mph in 14 months
- Travel time was reduced from 23 minutes to about 9 minutes
- Fuel consumption caused by ramp delay was reduced by 2,040 liters (540 gallons) of gasoline per weekly
- Overall accident rates during the peak period were reduced by 43 percent.

Portland has seen a dramatic change in the way traffic flows around I-5. Because of the success of ramp meters, Portland has installed more ramp meters around the city and neighboring cities. Currently there are over 50 ramp meters in and around Portland (Piotrowicz & Robinson 1995).

San Diego, California: The first ramp metering system in San Diego was initiated in 1968. The system, run by the California Department of Transportation (Cal Trans), includes over 130 ramp meters along 69 miles of freeway. A noteworthy aspect of the system is the metering of the freeway-to-freeway connector ramps. Metering freeway-to- freeway connectors requires many important considerations, such as storage space, advanced warning and sight distance. This was very successful and presently the state of California uses the maximum number of ramp meters.

Minneapolis/St. Paul, Minnesota: The Twin Cities Metropolitan Area first installed ramp meters in 1969. As of the year 2000, the Minnesota Department of Transportation (MnDot) used approximately 430 ramp meters to manage freeway access on approximately 210 miles of freeways in the Twin Cities metropolitan area (Cambridge Systematics et al. 2001). The first two ramp meters were put in on I-35 E north of downtown St. Paul. Others were later added on a 5-mile stretch of I-35 E and I-35 W, and they are evaluated periodically. Since the installation of the ramp meters, the Twin Cities have benefited in the following ways (Hourdakis and Michalopoulos 2002):

- Speeds on I-35 E increased by 16 percent from 37 to 43.1 mph
- Peak period accidents decreased by 24 percent and peak period accident rates decreased by 38 percent (on I-35 E)
- Speed on I-35 W increased by 35 percent from 34.4 to 46.3 mph
- Peak period accidents decreased by 27 percent and peak period accident rates decreased by 38 percent (on I-35 W)
- Peak period pollutant emissions decreased to just under 4.4 million pounds

Austin, Texas: Texas first installed ramp meters in the late 1970s along northbound I-35. The initial system consisted of three metered ramps set for the AM peak period. Evaluation studies showed that (Piotrowicz & Robinson 1995):

- Metering increased vehicle throughput by about 7.9 percent and increased
- Average mainline speed by 60 percent

Seattle, Washington: The Washington Department of Transportation (WSDOT) employed its first ramp metering system in the fall of 1981 along I-5 north of Seattle Central Business District (Piotrowicz & Robinson 1995). The system, named FLOW, initially included 17 southbound metered ramps during the AM peak and 5 northbound metered ramps in the PM peak. By 1994, there were more than 50 ramp meters in use and more meters were planned for implementation. Since the meters were installed, Seattle has experienced the following benefits:

- Travel time dropped approximately 22 min to 11.5 min
- Accident rates decreased by 39 percent, and
- Traffic on surrounding routes decreased by 43 percent due to increased accessibility

Denver, Colorado: The Colorado Department of Transportation ran a pilot project to test the usefulness of the ramp metering system along I-25 in the spring of 1981 (Piotrowicz & Robinson 1995). The system in place consisted of five metered ramps that operated during the AM peak along the stretch of 2.5 miles of the interstate. The DOT tested the area for about 18 months and concluded the following:

- Average peak period driving speed increased by 57 percent
- Average travel time decreased by 37 percent, and
- Accidents declined by 5 percent

Detroit, Michigan: The Michigan Department of Transportation (MDOT) installed some of its first meters in 1982. The system has since grown to over 40 metered ramps across the state (Piotrowicz & Robinson 1995). Michigan State University conducted an evaluation of the metered system and concluded the following:

- Speed increased by 8 percent
- Peak hour volume increased to 6400 vph from (5600 vph)
- Accident rates decreased by 50 percent
- Injury accidents decreased by 71 percent

The evaluation showed the positive impact of the metered ramps. Eventually, MDOT decided to install more ramp meters.

Long Island, New York: In 1989, Long Island Expressway's ramp meter system was evaluated after two months in operation to determine its effectiveness (Piotrowicz & Robinson 1995). The following are the results of that evaluation:

- Peak period mainline travel time decreased by 20 percent from 26 to 21 mins.
- Average speed increased by 16 percent from 29.3 to 35.0 mph
- Motorists entering the system experienced an increase in average speed from 23.1 to 28.1 mph
- 6.7 percent reduction in fuel consumption
- 17.4 percent reduction in carbon monoxide emissions, and
- 13.1 percent reduction in hydrocarbons

The metering system in Long Island has brought about significant changes since its implementation in the area. It has improved the way the traffic flows and has reduced the amount of pollutants in the air.

These case studies demonstrate some of the many benefits associated with ramp metering implementation. It should be noted that proper design and placement of ramp meters is important in order to maximize the benefits achieved.

A national study (SIAS 2003) indicates that most states in the U.S use some recommended guidelines for installing and operating ramp meters, but there are no nationally accepted standards. Despite this fact there is a consensus that ramp metering can be successfully implemented by careful selection of some design features. These include, but are not limited to:

- Adequate storage space at the ramp, and
- Adequate acceleration distance from the stop-bar to the merge location.

Within the framework of the stated objectives of ramp metering, an agency can adapt a policy that lies somewhere within the following two extreme cases:

- Give highest priority to vehicles on the freeway, or
- Give highest priority to vehicles on the ramp

The objective of the first policy is to keep the freeway traffic moving at all times, including times when there is an incident on the freeway. This policy is implemented by operating the controller in a traffic responsive mode. In this mode, freeway detectors are used to assess traffic conditions at the freeway, and metering rates are adjusted to accommodate only the amount of ramp traffic that can be handled while keeping the freeway level of service below a specified value. Traffic responsive metering can be implemented in an isolated mode or a system mode. In an isolated mode, the controller takes into account freeway conditions in the vicinity of a specific ramp only. In the systems mode, sophisticated algorithms and a central computer are used to take into account traffic conditions along a freeway section consisting of many metered on-ramps.

The objective of the second policy is to ensure that the upstream signal is kept free of any queues at all cost. This policy is implemented by using queue detectors at the ramp entrance and suspending the metering operations when a queue is detected and for as long as it is present. Sometimes this policy is based on a maximum allowable delay value for the ramp traffic. Like the traffic responsive mode, this policy can be implemented in an isolated or system mode using a central computer. Regardless, queue clearance at the ramp overrides the isolated or central operation.

The ramp-metering operations in Minnesota and Texas are examples of first and second extremes respectively. All other states that employ ramp metering utilize policies resulting from a compromise between the above two extremes and, in many cases, closer to the first extreme.

Hence, it is important to develop a set of best practices for their use and implementation in the state of Alabama. One of the goals of this project is to review the experiences of other state agencies with ramp meters. The guidelines would include an overview of the different ramp metering strategies, criteria for determining under what conditions different types of ramp metering strategies are warranted, document experiences (both positive and negative) in other agencies and provide estimates of the benefits and costs that could be expected. To address these needs, a survey was conducted involving the state agencies which operate ramp meters. The results of this survey are discussed in the next chapter.

CHAPTER 2
SURVEY OF THE STATE OF PRACTICE

2.1 Approach

The survey involved contacting selected transportation agencies across the U.S. that operate ramp meters to gain insights into the state of the practice as well as practical considerations such as public reception, enforcement issues, and maintenance costs. A survey form was developed and was e-mailed to contact persons at a total of nine designated agencies. A copy of the survey form is shown in Figure 2-1. Because initial response to the e-mail questionnaire was poor (one out of nine), follow up telephone calls were made. The following agencies were contacted and provided valuable input on their experiences with ramp metering operations:

Ramp Metering Survey Questions **Agency: ___________**

1. How many ramp meters does your agency operate?
2. In what situations are they used? What types are used (fixed or adaptive)?
3. What are the criteria for implementation?
4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
5. What has been public reaction to the ramp meters? Enforcement problems?
6. What have been your average installation costs? Annual maintenance costs?
7. Have you removed any meters? Had major problems with them?
8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?

Figure 2-1: Ramp metering state of practice survey instrument

- Arizona DOT (Phoenix area)
- California DOT (CalTrans – statewide)
- Michigan DOT (Detroit area)
- Minnesota DOT (Minneapolis area)
- New York DOT (Long Island INFORM program)
- Virginia DOT (Northern Virginia area)
- Washington DOT (Seattle area)
- Wisconsin DOT (Milwaukee area)

The summary of some of the key findings follows. Detailed responses of all interviewed agencies are available in Appendix A.

2.2 Summary Findings

2.2.1 Public Perception

There were a range of responses to this question. Some agencies felt that public perception to ramp meters was generally good, with the majority of people accepting if not supporting their operation. The Michigan DOT felt that the public generally accepted ramp meters, and the Washington DOT said that the public had actually embraced ramp meters and in some instances requested meters at new locations. Other agencies, notably Virginia DOT, said that the public was generally hostile to ramp meters but because they provided a benefit to freeway operations VDOT continued to operate them. It should be noted that in almost all cases the people who were most likely to complain about ramp meters were those who were delayed on the ramps. Drivers who entered the freeway farther upstream (where there were no meters) were generally positive toward ramp meters.

One factor that may play into these varying public perceptions is the amount of delay created on the ramps. In Detroit, where MDOT's strategy is to disperse platoons rather than detain motorists on the ramps for significant periods, delays due to ramp meters are typically small and public perception was generally felt to be positive. In Seattle, where the WDOT carefully restricts ramp meter use to short periods during the peaks, the public perception was also felt to be positive. In Minnesota, where the ramp metering was seen to be more aggressive, ramp delays could be significant and public/political attitudes were sometimes less positive. After completing a study of its ramp metering system, the Minnesota DOT is modifying its metering algorithms to reduce ramp delays to a maximum of 4 minutes.

Public education was also felt to be important in creating positive attitudes. The Michigan DOT stressed the importance of demonstrating to the public that there are benefits to all parties, both those who are delayed on ramps and those who access the freeway farther upstream. The Arizona DOT likewise stated that while initial public reaction to ramp meters in usually negative, if the public can be shown that there are tangible benefits the meters will become accepted. Caltrans issues press statements prior to turning on new ramp meters and has a web site and available literature that explain the purposes and benefits of ramp metering. One effective form of public education can be a before and after demonstration. The Michigan DOT addressed complaints from a large manufacturing plant by turning off the adjacent ramp meter for several days to demonstrate that traffic conditions were actually worse without the meter. Several agencies stressed the need for the public to understand that ramp meters by definition operate in congested corridors and that it is easy for the public to blame some of that congestion on the meters themselves. Before and after demonstrations can be very effective at getting that point across. Large scale evaluations, like that done by the Minnesota DOT, are effective but may not be practical for most agencies.

One interesting point related to public perceptions was raised by the Michigan DOT, which operates all of its meters within the city limits of Detroit. Because the City is predominantly black while the surrounding suburbs are predominantly white, some felt that the ramp metering system delayed urban (black) residents at the expense of suburban (white) commuters. This is really a common criticism that is levied against ramp meters, that they favor long distance extra-urban trips over shorter in-town trips, but with a racial dimension added.

2.2.2 Metering Algorithms Used

Phoenix was the only region still using primarily fixed-time meters. The remaining agencies said they were using adaptive metering algorithms, and even the Arizona DOT said it was in the process of switching its meters to adaptive operation. Interestingly, Phoenix has begun to use dual-lane metering systems wherever possible because this gives them added storage space and capacity.

Several agencies stated that the type of metering algorithm used has an impact on public perception and acceptance. The Washington DOT recently adopted fuzzy logic metering algorithms which take into account speed, delays, and queue and felt that it had benefited flow significantly. The Michigan DOT uses its meters primarily to disperse platoons entering the freeway, so its discharge algorithms are simpler and rates typically vary between 5 to 15 veh/min.

All states stressed the importance of restricting the times of operation for ramp meters. Several states said they were able to deal with the majority of public complaints about the meters by simply restricting the times of operation to the very peak times and making sure they are turned off as soon as they are not needed.

2.2.3 Implementation Criteria

There was a surprising lack of fixed criteria for the implementation of ramp meters. All agencies more or less deploy ramp meters corridor-wide, since metered interchanges can drive traffic to un-metered interchanges. It also reflects the system-wide approach to managing congestion represented by ramp metering. The Arizona DOT recently completed a very comprehensive implementation study, while other agencies such as the Michigan DOT seem to base implementation more on operational observation.

The Virginia and California DOT's both placed importance not just on traffic volumes but also on the ability of interchange geometrics to accept ramp meters. Virginia has minimum ramp storage requirements before meters will be considered, ensuring that meters will not cause congestion on adjacent arterials. California has a comprehensive design manual to ensure that ramp meters will operate safely and efficiently.

2.2.4 Installation Costs

Installation costs varied widely and depended in large part on the existing communication infrastructure and the extent of ramp modifications required to accept ramp metering. Washington, California, and Wisconsin, for instance, provide HOV bypass lanes at most of their ramp meters. Those modifications can be quite expensive and require additional hardware.

For this reason it is difficult to compare installation costs because each agency includes different costs in their estimates. Washington, for example, often considers the communications infrastructure a separate ITS entity from the ramp meter itself, and therefore the incremental cost of installing metering hardware may be on the order of only $5,000 - $10,000. If communications costs are included, this figure jumps to $30 - $50k per installation. Virginia reported metering hardware itself is on the order of $10k - $15k, but again that does not include communications. New York reported an average installation cost of about $80k per meter including all communications, and this is consistent with Arizona DOT's estimate of approximately $90k for an isolated installation.

2.2.5 Maintenance Costs

Maintenance costs were fairly consistently reported to be on the order of a few thousand dollars per year, with loop detectors and knocked over signal heads the most common maintenance problems.

2.2.6 Impact Studies

There were surprisingly few impact studies available. The Minnesota DOT has conducted perhaps the most comprehensive study of ramp meters and their impacts on freeway speeds, travel time, and delays. CalTrans has also performed a number of studies, although many are now 15-20 years old. The Arizona DOT recently commissioned a study which found that their ramp meters were effective in maintaining freeway speeds. The NYDOT performed a small scale study in 1990 which found that ramp meters in the Long Island Inform system did improve freeway speeds significantly. Other agencies reported that no formal studies or assessments of any kind had been done.

2.2.7 Enforcement Issues

None of the agencies surveyed reported major enforcement problems. Where they existed, many of the enforcement problems seemed to be tied to abuses of HOV bypass lanes. Other agencies suggested that major compliance problems may indicate excessive delays and a need to modify the ramp metering algorithms. Where ramp delays were reasonable, compliance was generally felt to be good.

2.2.8 Problems with Meters/Removed Meters

Only rarely were meters removed due to public complaints. In some cases, meters were removed after detailed study showed they were not warranted or effective (Minnesota). A more common response was to restrict meter use in the face of public complaints.

The overall survey results are summarized in Table 2-1. The table allows quick review and comparison of responses from state to state.

Table 2-1: Summary of Agency Survey Responses

	Number of Meters	Metering Type	Criteria for Implementation?	Impact Study Available?	Average Installation Costs	Average Maintenace Costs (yr)	Public Reception/ Support	General Comments
Arizona DOT (Phoenix)	65	Fixed time, converting to adaptive	Yes, variable	Yes	$50k - $90k	$2k - $3k	Good	Seeking to expand coverage in Phoenix and into Tucson. Overall effectiveness and public reaction has been very good.
CalTrans (statewide)	>1,000	Adaptive	Yes	Yes, though dated	varies	$3,000	Good	Operates largest system of ramp meters in the U.S. Coverage is expanding. Overall very effective.
Michigan DOT (Detroit)	60	Adaptive	No	No	n/a	$2,500	Good	System is currently down. MDOT hopes to have it operational again in 2-4 years. Overall experience has been good, though there has been resistance to expanding coverage outside of Detroit.
Minnesota DOT (Minneapolis)	416	Adaptive	Yes	Yes, 2002	$10k[a]	$1,000	Mixed	As a result of extensive evaluation, have removed some ramps and modified ramp discharge algorithms to reduce ramp delays.
New York DOT (Long Island)	99	Adaptive	Yes	Yes, 1990	$80k per ramp	$2,000	Good	Meters confined to Long Island with no immediate plans to expand outside of current area.
Virginia DOT (Northern Virginia)	26	Adaptive	Some	No	$10k - $15k[a]	$5,000	Poor	Overall effectiveness seen as good, but no plans to expand outside of current coverage. It was felt ramp meters would not be accepted in other parts of the D.C area.
Washington DOT (Seattle)	>100	Adaptive	No	Yes	$30k - $50k	$3,000	Very Good	Public acceptance is very good. Recent switch to fuzzy logic control has improved operation. Compliance good. May expand into Tacoma region.
Wisconsin DOT (Milwaukee)	110	Adaptive	No	No	$30k - $50k	$2,000	Good	

CHAPTER 3
RAMP METERING IMPLEMENTATION

Proper design and placement of a ramp metering system is essential to its success. The engineer should decide on the type of ramp metering operation (fixed time versus traffic responsive), type of metering strategy (one car per green versus multiple cars per green, single lane or dual lane operation) and related design considerations (Bellemans 2004). Most states use basic implementation guidelines provided in the *Manual on Uniform Traffic Control Devices* (MUTCD, 2003). A discussion on ramp metering operation options and design consideration follows:

3.1 Ramp Metering Operation Options

The sophistication and size of a ramp metering system should reflect the amount of desired improvement and existing conditions (ITE Technical Committee 1984). Ramp metering strategies can be based on fixed metering rates that reflect historical data, or traffic adaptive metering systems based on real-time traffic data, or predicted traffic demand. Strategies can be implemented to optimize conditions locally or system-wide. Each control mode has an associated hardware configuration. Distinguished by their responsiveness to prevailing traffic conditions, metering systems fall into three categories, namely fixed-time operations, local traffic responsive operations and system-wide traffic responsive operations (Taiwan Area National Freeway Bureau 2004).

Fixed Time Operation

Fixed time or preset operation is the simplest form of metering which breaks up platoons of entering vehicles into single-vehicle entries. This strategy is typically used where traffic conditions are predictable. Although detectors are installed onto the ramp to actuate and terminate the metering cycle, the metering rate is predetermined, based on historically averaged traffic demand conditions. Fixed time meters can provide benefits associated with accident reductions from merging conflicts, but are less effective in regulating mainline conditions. The main criticism of preset strategies is that they may result in over restrictive metering rates if congestion dissipates sooner than anticipated, resulting in unnecessary ramp queuing and delays. On the other hand, the hardware configuration for fixed timed ramp metering is the simplest option available.

Local Traffic Responsive Operation

For local traffic responsive operation, the metering rate is based on prevailing traffic conditions in the vicinity of the ramp. Controller electronics and software algorithms select an appropriate metering rate by analyzing occupancy or flow data gathered from ramp and mainline detectors. Traffic responsive systems are more expensive to install and maintain; but have the ability to deal with unusual and unanticipated traffic changes, and to deliver better results compared to fixed metering systems. The hardware requirements for local traffic responsive operation are similar to the pre timed operation, with the addition of required mainline detectors upstream of the ramp. The main criticism of traffic responsive algorithms is that they are reactive, and adjust metering rates after mainline congestion has already occurred. To address this issue, traffic predictive algorithms such as ALINEA have been developed to anticipate operational problems before they occur.

System – Wide Traffic Responsive Operation

System wide traffic responsive ramp metering operation seeks to optimize a multiple-ramp section of highway, often with the control of a bottleneck as the ultimate goal. Typically a centralized computer supervises numerous ramps and implements control features which override local metering instructions. This centralized configuration allows the metering rate at any ramp to be influenced by conditions at other locations within the network. In addition to recurring congestion, system wide ramp metering can also manage freeway incidents, with more restrictive metering rates upstream and less restrictive metering downstream of the incident. Authorities can monitor and control the entire system from a traffic operations center, and can remotely override or reprogram controllers. The hardware requirements for this mode of operation are the most complex of the three, requiring detectors upstream and downstream of the ramp, as well as a communication medium and central computer linked to the ramps. In this type, a few ramps are linked together to a central computer and the signal timings are adjusted according to traffic on all ramps that are linked to the central computer.

3.2 Ramp Metering Strategies

When merge capacity is not the bottleneck, an uncontrolled single – lane freeway entrance ramp may have a throughout capacity of 1,800 to 2,200 vehicles per hour (VPH). The same ramp will have lower capacity when metered (Saito and Hernandez 2003). The maximum theoretical metering capacity depends on the type of strategy used. There are three ramp metering strategies, which are described in the following sub-sections (Bhat and Guo 2001).

Single – Lane One Car per Green

This strategy allows one car to enter the freeway during each signal cycle. Typically, each signal cycle has green, yellow and red signal indications. The lengths of green plus yellow indications are set to ensure sufficient time for one vehicle to cross the stop line. The length of red interval should be sufficient to ensure that the following vehicle completely stops before proceeding. From a practical point of view, the smallest possible cycle is 4 seconds with 1 second green, 1 second yellow and 2 seconds red. This produces a meter capacity of 900 VPH. However, field observations have shown that a 4-second cycle is too short to achieve the vehicle stopping requirement. Also, any hesitation on the part of a driver may cause the consumption of two cycles per vehicle. A more reasonable cycle is around 4.5 seconds, obtained by increasing the red time to 2.5 seconds. This increase results in a meter capacity of 800 VPH. A single lane ramp meter is shown in Figure 3-1:

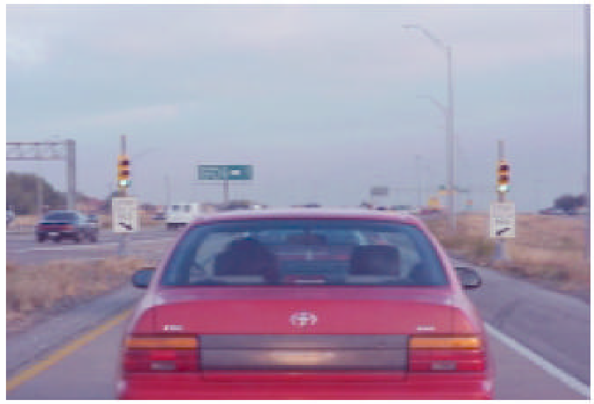

Figure 3-1: Single lane ramp meter (Chaudhary and Messer 2000a)

According to the Ramp Meter Design Manual (California DOT 2000), geometrics for a single lane ramp meter should be provided for volumes up to 900 VPH. When truck volumes (3-axle or more) are 5 percent or greater on ascending entrance ramps to freeways with sustained upgrades exceeding 3 percent (i.e. at least throughout the merge area), a minimum length of 150 m of auxiliary lane should be provided beyond the ramp convergence point.

Single Lane Multiple Cars per Green

This strategy, also known as bulk metering, allows two or more vehicles to enter the freeway during each green indication. The most common form of this strategy is to allow two cars per green. Three or more cars can be allowed; however, this will conflict with one of the ramp metering objectives, i.e., breaking up platoons of merging traffic. Furthermore, contrary to what one might think, bulk metering does not produce a drastic increase in capacity over the single-lane one-car-per-green operation. This is because this strategy requires more green and yellow times as ramp speed increases, resulting in a longer cycle length. Consequently, there are fewer cycles in one hour. For instance, two cars per green strategy require cycle lengths between 6 to 6.5 seconds and results in metering capacity of 1,100 to 1,200 VPH.

Dual - Lane Metering

Dual-lane metering implementation requires two lanes on a ramp in the vicinity of the meter. In this strategy, the controller operates by alternating the green-yellow-red cycle for each lane. Depending on the controller being used, the cycle may or may not be synchronized between the two ramp lanes. When synchronized, the green indications are timed to allow a constant headway between vehicles from both lanes. Dual-lane metering can provide metering capacity of 1,600 to 1,700 VPH and more storage space for queued vehicles. The only problem is that most existing ramps do not have room to provide dual-lane operation. The two ramp lanes before merging with the freeway merge into a single lane. This single lane merges with the freeway. A ramp with dual lane metering is shown in Figure 3-2.

Figure 3-2: Dual Lane Ramp Meter (Chaudhary and Messer 2000a)

When entrance ramp volumes exceed 900 VPH and/or when an HOV lane is determined to be necessary, a two lane ramp segment should be provided. On two-lane loop ramps, normally only the right lane needs to be widened to accommodate design vehicle off-tracking.

Three-lane metered ramps are sometimes needed to serve peak hour traffic along urban and suburban freeway corridors. The adverse effects of bus and truck traffic on the operation of these ramps (i.e. off-tracking, sight restriction, acceleration characteristics on upgrades, etc.) is minimized when the ramp alignment is tangential or consists of curve radii not less than 90 meters. The recommended widths for metered ramps are given in Table 3-1.

Table 3-1: Recommended widths for metered ramps (Caltrans 2000)

Metered Ramp	Pavement Widths		
	Traveled Way	Shoulder	
		Inside	Outside
1-lane	3.6 m	1.2 m	2.4 m
2-lanes	7.2 m	1.2 m	2.4 m
3-lanes	10.8 m	0.6 m	0.6 m

3.3 Design Considerations

Installation of a ramp meter to achieve the desired objectives requires sufficient room at the entrance ramp. The determination of minimum ramp length to provide safe, efficient and desirable operation requires careful consideration of several elements described below:

1. Sufficient room must be provided for a stopped vehicle at the meter to accelerate and attain safe merge speeds.

2. Sufficient space must be provided to store the resulting cyclic queue of vehicles without blocking an upstream signalized intersection, and
3. Sufficient room must be provided for vehicles discharged from the upstream signal to safely stop behind the queue of vehicles being metered.

The ability to provide certain storage space for ramp metering depends on the length of the ramp and the location of ramp signals. Figure 3-3 illustrates the distance requirements for ramp meters. In this figure, the dotted line shows the ramp length. The queue detector controls the maximum queue length in real-time. Thus, the distance between the meter and the queue detector defines the storage space.

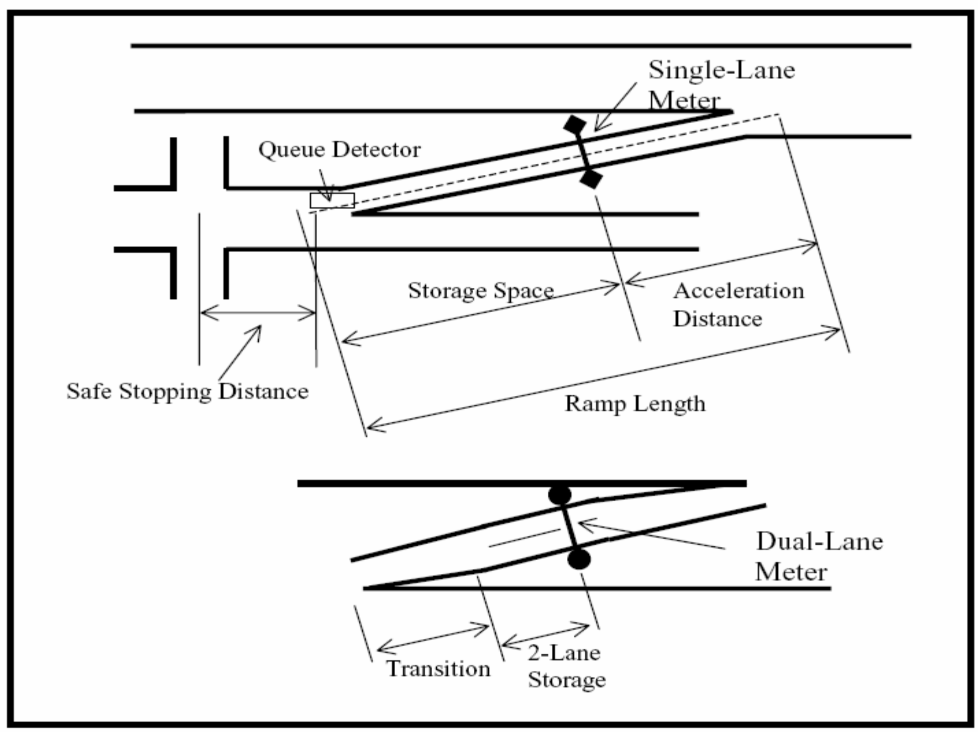

Figure 3-3: Distance requirements for ramp meters (Chaudhary and Messer 2000b)

For dual-lane ramps, the ramp storage area (lower part of the figure) should also consider the transition from one lane to two lanes and dual-lane storage space. The transition zone should be at least 23 meters long, and the length of dual-lane storage should be sufficient to store a minimum of four cars per lane (approximately 31 meters).

Storage Length

To minimize the impact of local street operation, every effort should be made to meet the recommended storage length. Wherever feasible, ramp metering storage should be contained on the ramp by either widening the ramp or lengthening it. Improvements to the local street system in the vicinity of the ramp should be thoroughly investigated where there is insufficient storage length on the ramp and the ramp queue is expected to adversely affect local queue operation. These improvements can include widening or restriping streets or intersections to provide additional storage or capacity. Also, signal timing revisions along the corridor feeding the ramp can enhance the storage capability. These will require coordination with the local agency consistent with the regional traffic operations strategy. Ultimately, system-wide adaptive ramp metering will coordinate with local street and arterial signal systems. It is recommended that a minimum vehicle spacing of nine m be considered for locations where there are significant percentages of trucks, buses or recreational vehicles.

Figure 3-4 provides the maximum queue length distribution for locating the excessive queue detector based on 95 percentile criteria. This figure shows the requirements for three metering strategies: (1) single-lane with single vehicle release per cycle, (2) single-lane with bulk metering and (3) dual-lane metering assuming single-line storage. For each strategy, the graph terminates when demand volume exceeds meter capacity.

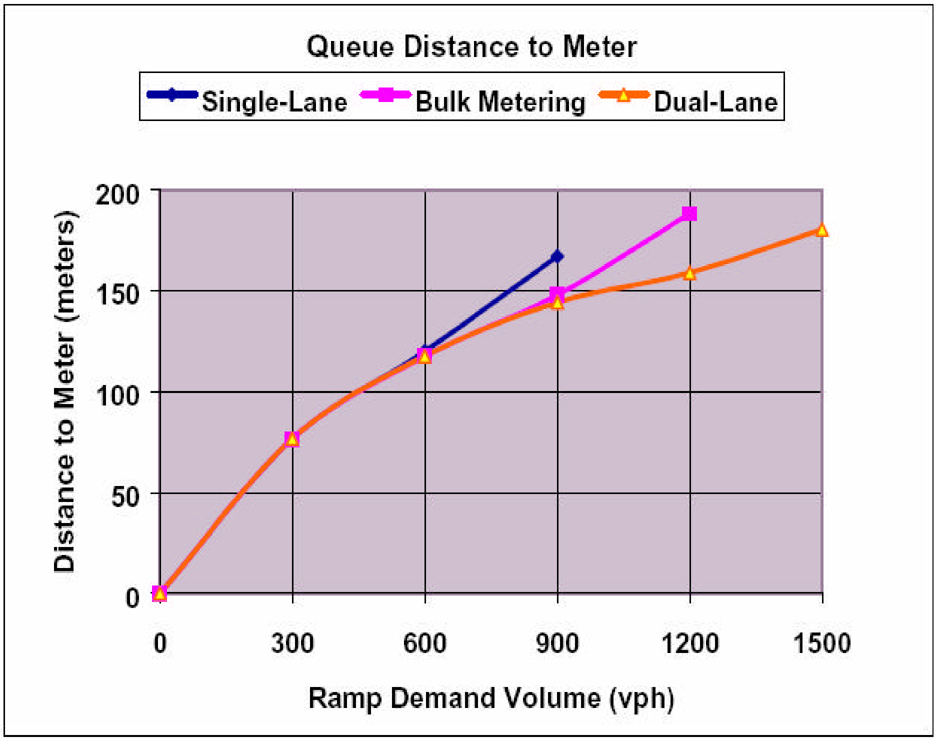

Figure 3-4: Queue distance to ramp meter (Chaudhary and Messer 2000b)

The figure illustrates that the minimum single-lane storage length is approximately 170 meters. If the storage length of design vehicles is 7.72 meters, this distance will be sufficient for storing 22 vehicles. The actual storage distance for a dual-lane meter will depend on the dual-lane storage distance provided in the design. For instance, if half of the 22 vehicles are stored in a dual-lane storage area, the total storage distance will be reduced to 126 (84 plus 42) meters.

Distance from Meter to Merge

AASHTO provides speed-distance profiles for various classes of vehicles as they accelerate from a stop to speed for various ramp grades. Figure 3-5 provides similar acceleration distances needed to attain various freeway merging speeds based on AASHTO design criteria. The desired distance to merge increases with the increasing freeway merge speed and ramp grade.

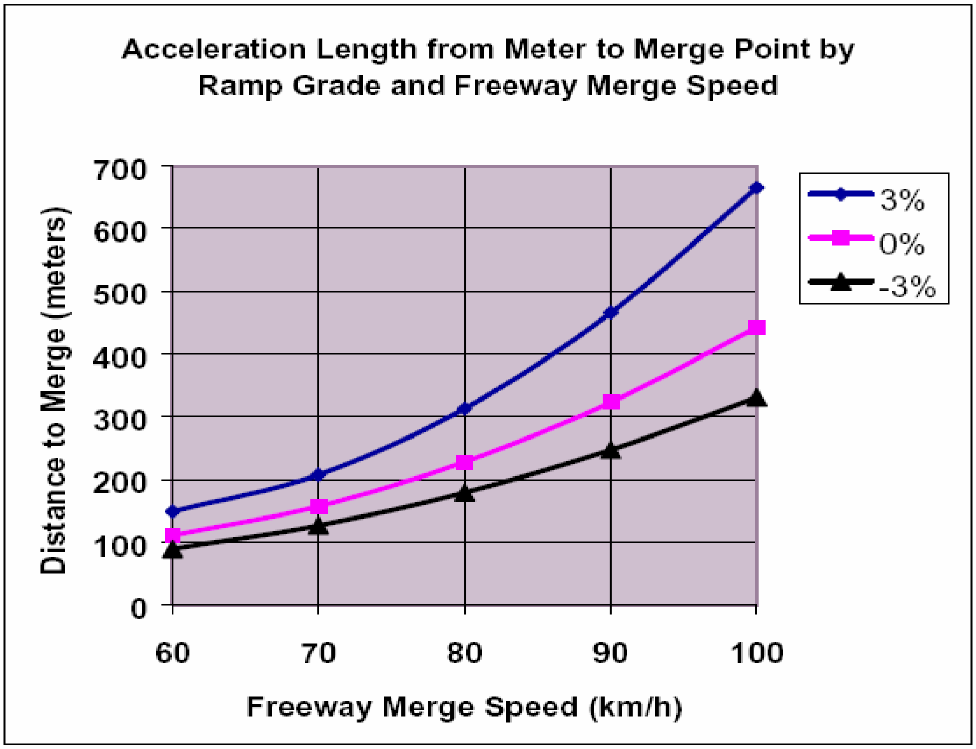

Figure 3-5: Acceleration length from meter to merge point (Chaudhury 2000b)

For easy reference, Table 3-2 gives the numerical values for Figure 3-5.

Minimum Stopping Distance to the Back of Queue

Motorists leaving an upstream signalized interchange will likely encounter the rear end of a queue as they proceed towards the meter. Adequate maneuvering and stopping distances should be provided for both turning and frontage road traffic. Frontage road (ramp) speeds are usually higher than left-or right-turn speeds leaving the upstream traffic signal. Frontage road traffic speeds may be 55 km/h or higher. Left turn speeds are usually no higher than 30 km/h. Right-turn vehicles, in particular, should be able to make lane changes to the metered queue, presumably located downstream on the left side of the frontage road.

Table 3-2: Acceleration distance from meter to merge point (Chaudhury 2000b)

Merge Speed (km/h)	Ramp Grade (%)		
	-3	0	+3
60	90	112	150
70	127	158	208
80	180	228	313
90	248	323	466
100	331	442	665

For a 55 km/h frontage road design speed, the minimum separation distance is calculated to be 73 m from the basic AASHTO stopping sight distance equation (AASHTO 2001):

$$X = 0.278vT + v^2/(254f_v) = 0.278 * 55 * 2.5 + 55^2/(254*0.34) = 73 \text{ m} \qquad \text{Equation (1).}$$

where:

X = stopping sight distance, meters;
v = traffic speed, km/h;
T = perception-reaction time (2.5 sec), seconds, and
f_v = coefficient of deceleration braking friction as related to speed.

Here, the stopping sight distance (X) is measured from the centerline of the cross street in the interchange. For a 40 km/h left-turn speed, the AASHTO stopping distance is 44.4 meters as measured from the centerline of the cross street.

Right-turn vehicles must also weave across one or more frontage road lanes before stopping at the back of the queue, assuming that the queue being metered is positioned along the inside lane(s) of a two or three-lane frontage road. For right-turn speeds of 30 km/h, a lane change distance of 25 meters is assumed plus an added stopping distance of 29.6 meters. Adding a half of the street width, or 14 meters, produces a distance from the centerline of the cross street of 68.6 meters. The distance to the back of the queue should also be some distance downstream of any turnaround lane entrance, which may be nearly 30 meters from the cross street curb line.

The minimum desired distance from the centerline of the cross street to the back of the design queue should be about 75 meters. A more desirable distance would be about 100 meters permitting two lane changes for right-turn vehicles from the cross street and higher ramp approach speeds.

The placement of signal poles must take into consideration the following:

- Minimum setback to prevent drivers from reaching the signal head
- Storage space between the upstream signal and the meter, and
- Distance from meter to merge point on the freeway to provide room for vehicles stopped at the signal to attain merge speed

Figure 3-6 provides an illustration of a cross section where ramp metering is present.

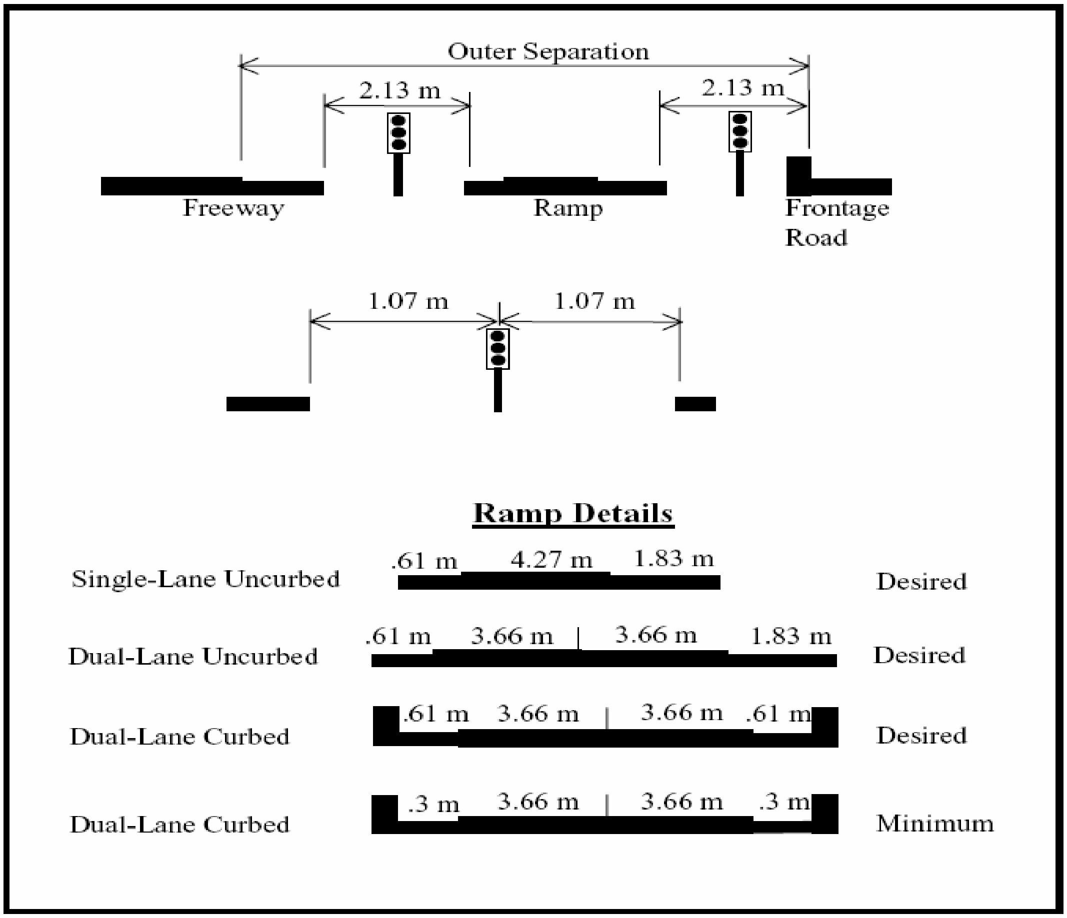

Figure 3-6: Cross section at a metered location (Chaudhary and Messer 2000b)

It should be noted that the gore-to gore length of a ramp depends on two geometric factors, outer separation and ramp angle. Outer separation is the distance from the outside edge of the right most freeway lane to the inside edge of the frontage road. In Figure 3-6, thick lines represent travel lines and thin lines represent shoulders. As shown, the offset to the signal head (setback) should be a minimum of 0.91 meters from the shoulder, or in case of a curb, from the edge of the travel lane. The bottom part of the figure illustrates the minimum and desired dimensions for ramps. Using these guidelines, one can determine the ranges of storage and acceleration distances for a given outer separation and ramp angle. The engineer can also use these results to determine if an acceptable ramp metering operation can be provided for given geometrics.

Research shows that an outer separation of less than 15.2 meters will not provide sufficient storage and acceleration distances on the straight ramp. Furthermore, the calculations suggest the need to design ramps with additional acceleration distance parallel to the freeway. Additional storage area may also be needed on the frontage road to provide an effective ramp- metering system.

3.4 Implementation Process

In the ramp meter design process, the designer must follow several steps to ensure successful implementation and proper orientation capabilities (O' Brien 2000). Many of the steps, such as highway lighting and communication requirements, must be addressed early in the design process and not after the design for the proposed location has been completed. The steps of a proper ramp metering design process are given below:

1. Collect initial data required for the proposed ramp meter design location.
2. Determine the ramp meter type required for the design location.
3. Evaluate geometric requirements and potential modifications for the location.
4. Determine the location of the ramp meter stop bar and signals, with potential iterations.
5. Based on the data collected, incorporate or modify highway lighting if not already present.
6. Determine the location of the ramp meter controller cabinet and electrical service.
7. Prepare the underground infrastructure, including detectors, conduit and pullboxes.
8. Perform cable routing to provide hardware interconnection.
9. Prepare signing and pavement markings as required for the ramp meter design.
10. Determine the communications medium used for the proposed location.
11. Revisit steps 5 through 9 until final design is complete.

Figure 3-7 provides a flow chart that describes the steps of the ramp metering design process.

Initial Data Collection

Prior to assessing the needs of a potential ramp meter location, various data need to be collected to properly evaluate the proposed ramp meter location. These include:

- AM and PM peak period volumes
- AM and PM peak hour volumes
- Future peak period/ hour volumes
- Site-specific issues or concerns based on an initial site visit
- Local trip generators nearby the ramp
- Ramp vertical grades
- Existing ramp width, flange to flange
- Existing ramp length to painted gore, and
- Current construction funding for project

Without this data collection, a proper ramp meter type and design cannot be guaranteed. The last item, namely current construction funding for the project, is a major concern with respect to whether the ramp is altered geometrically, and to what extent the ramp is altered.

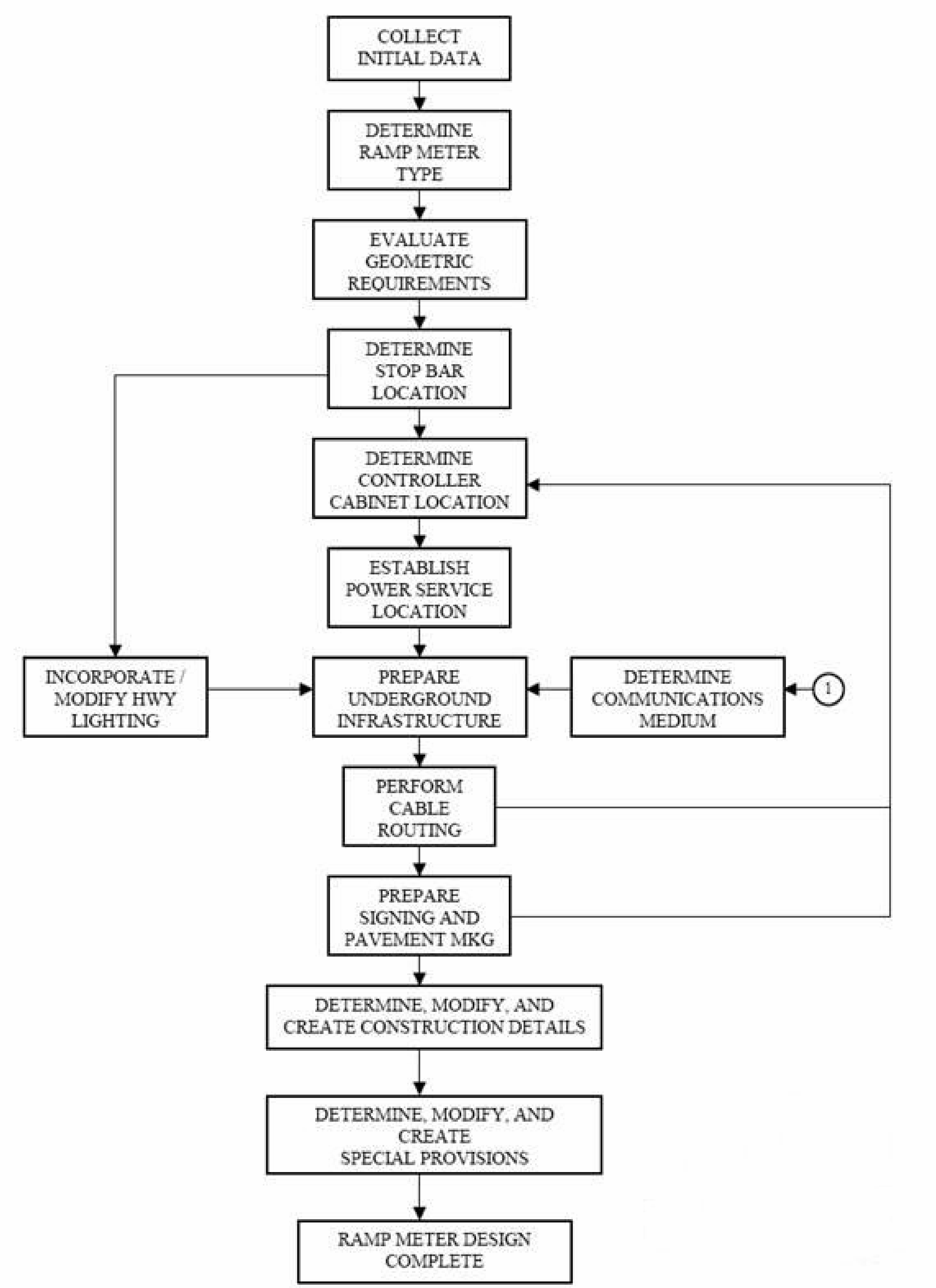

Figure 3-7: Flow chart for ramp meter design process (Wisconsin DOT 2000)

Determination of Ramp Meter Type

Based on the initial data collection, the designer can determine the type of ramp meter proposed. For the basis of this determination, an average vehicle length of 7.62 meters should be used, which factors not only average length of vehicles but also spacing between vehicles. Ramps with a known high truck volume may require a longer average vehicle length assumption. The following considerations are provided:

- **Peak Hour Volume –** The ramp must provide storage for a minimum of 10 percent of the current peak hour volume to ensure that the ramp meter queue does not back into the surface street. This factor is key in determining whether the ramp will contain one or two Single Occupancy Vehicle (SOV) lanes. For ramp meters designed in conjunction with ramp reconstruction, the ramp should accommodate a minimum of 10 percent of the design year (e.g. year 2020) projected peak hour volume. For ramp meters retrofitted to existing conditions, a storage minimum of five percent of the current peak hour volume may be used.

- **Ramp Length –** In addition to the peak hour volume calculation indicating the storage that is required, acceleration length per *AASHTO Policy of Geometric Design* must be factored in with the total ramp length (AASHTO 2001). These two in combination will begin to determine the stop bar location.

Geometric Considerations

Geometric considerations for metered ramps depend upon several factors, including:

- Peak hour volume which affects the storage length and width of the ramp.
- Percentage of high-occupancy vehicles (HOVs), if available, or local trip
- generators for the ramp which affects the acceleration distance after the stop bar
- Right-of-way availability, which will factor into the length and width of the ramp
- Enforceability of the ramp, which will determine whether an enforcement zone is desired for the ramp meter
- Construction funding, which may influence the extent to which the ramp can be modified, affecting ramp width, length, acceleration lanes and HOV treatment and enforcement.

These considerations will indicate whether a ramp meter is retrofitted to existing conditions, rehabilitated while maintaining the current alignment, or completely reconstructed. Table 3-3 provides recommended and minimum widths for ramp meters based on configuration type.

Table 3-3: Ramp meter configurations (Wisconsin DOT 2000)

Ramp Meter Configuration	Ramp with Shoulders				With Curb and Gutter	
	Traveled Way		Shoulder		Traveled Way	
	Recommended	Minimum	Inside	Outside	Recommended	Minimum
SOV	12ft	12ft	4ft	8ft	15ft	15ft
2 SOV	24ft	24ft	4ft	8ft	24ft	24ft
SOV/HOV	28ft	24ft	4ft	8ft	28ft	24ft
2 SOV/HOV	40ft	36ft	2ft	2ft	40ft	36ft
HOV Lane	16ft	12ft	n/a	n/a	16ft	15ft

In 1979, the Illinois DOT published a document dealing with the issue of freeway surveillance and control. This document discusses various issues related to single-lane one vehicle per green ramp-metering operation including (IDOT 1979)

- location and number of signal heads,
- signs,
- storage space,
- lane and shoulder widths,
- types and location of detectors, and
- control strategies (including metering rates)

In 1996, the Division of Traffic Operations at California DOT (Caltrans) put together specific design guidelines for single, dual and three lane (two regular lanes plus one high occupancy lane [HOV] lane) metering. Specifically, this document provides (California DOT 2000)

- Design criteria for lane and shoulder widths, storage space, acceleration lane and location of a stop bar, location of HOV lane and meter location.
- Hardware Criteria for signal heads, loop detectors and controller cabinet.

Moreover, it provides guidelines for signing, pavement markings, advance warning sign, HOV signing and pavement marking, vehicles per green, other pavement markings and enforcement issues.

The Washington DOT *Design Manual* dated August 1997 also provides some specific, but very basic, guidelines for ramp metering (Washington DOT 1997) including:

- types of signal heads
- storage space and alternates when adequate storage cannot be provided
- selection of ramp metering rates, including discussion of bulk metering
- location of ramp meter and
- driver compliance

Quality of Metering

Figure 3-8 shows the metering availability (percent of time the signal is metering) of various metering strategies for ramp demand volumes ranging from 800 to 1800 vph. For a ramp meter to produce the desired benefits, the engineer should select a metering strategy appropriate for the current or projected ramp demand. The ramp width will depend on this selection.

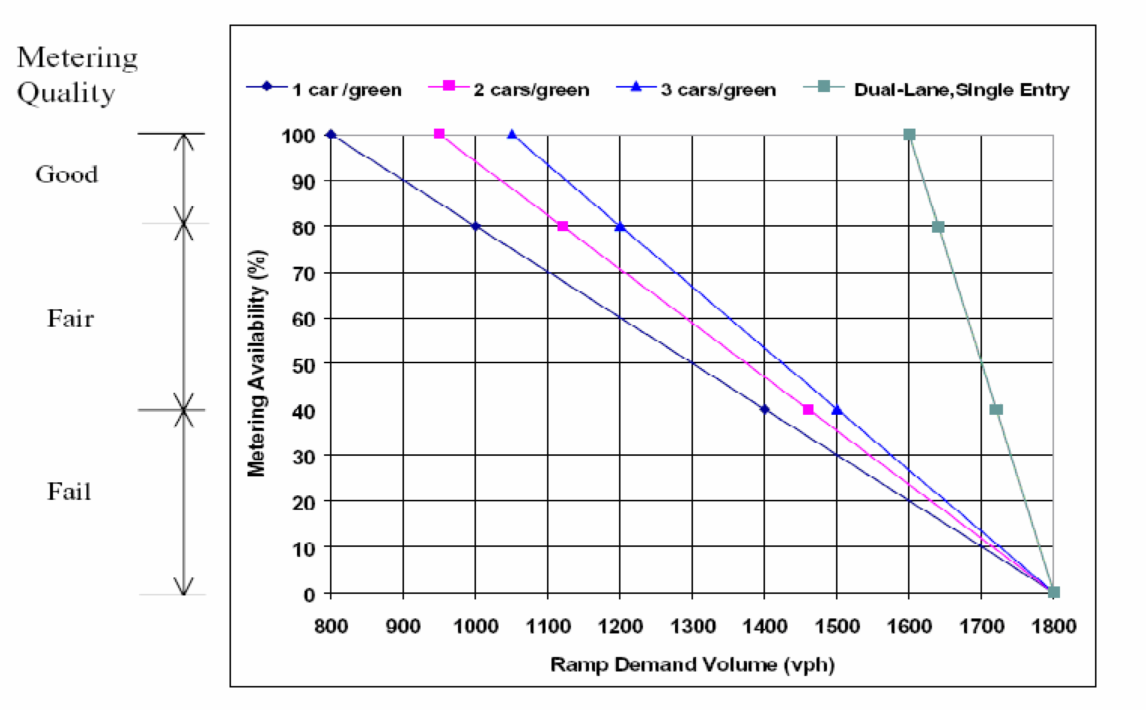

Figure 3-8: Quality of ramp metering (Chaudhary and Messer 2000b)

Figure 3-8 provides the following information about the quality of single and dual lane metering strategies:

- Single-lane ramps can be used to provide good quality metering (metering availability of 80 percent or higher) when the ramp demand is less than 1200 vph
- The quality of metering for single-lane ramps is fair for demand levels between 1200 and 1400 vph
- Single lane metering should not be used for demands higher than 1400 vph
- Dual lane metering provides good quality metering for demand up to 1650 vph

CHAPTER 4
METHODOLOGY

Assuming that the geometry allows a ramp meter to be properly placed, questions still remain of whether ramp metering is justified for local conditions and what is the most effective type of ramp metering for implementation.

To address those issues, a case study was performed with simulation modeling to determine the effects of ramp metering on Interstate corridors in the Birmingham region. The micro simulation tool CORSIM was chosen for this purpose. It is widely used in the U.S. that has been validated extensively and offers the capability to model a variety of ramp metering strategies. The study compared performance measures on the freeway mainline and ramps under non-metering as well as Clock Time, Demand/Capacity Control, Multiple Threshold Occupancy and ALINEA metering strategies. Details on simulation model selection and CORSIM features are available in Section 4.2, while additional information on the metering options analyzed are provided in Section 4.4.

The study test bed consisted of all major Interstates around the Birmingham region such as I-65, I-20, I-59 and I-459 and selected arterial streets in close proximity to Interstate on-ramps. These arterials were modeled to allow consideration of potential vehicle spillback when ramp metering is implemented. Geometric and control data as well as traffic volumes on the freeways and ramps were collected and entered into the CORSIM model.

A large number of simulation runs was performed to determine the impact of ramp metering options on traffic operations. Mainline freeway volumes were varied from 2000 vph to 5500 vph in 500 vph increments while ramp volumes ranging from 200 to 1500 vph were considered. The 5500 vph and 1500 vph thresholds were chosen to represent capacity conditions for freeway and ramp sections respectively. For each simulation run, 10 replications were performed to account for randomness in traffic behavior and the average results were taken.

Simulation outputs and animations were reviewed to determine the impact of the strategy on network operations. Tables and plots were developed to facilitate comparisons among MOEs obtained under the various ramp metering strategies. Particular attention was given to mainline upstream speed, mainline downstream speed and the ramp speed as well as mainline upstream, downstream, and ramp density. Other outputs considered include travel time, delays, and fuel consumption.

Based on the results from the analysis, warrants were developed for ramp metering implementation. Using the Birmingham test bed, simulated ramp metering was implemented to those ramps that met the criteria described by the warrants and comparisons were performed between MOEs obtained with and without ramp metering.

The following sections provide more details regarding the adoption of the simulation modeling approach, the simulation model selection process, the development of the study test bed and ramp metering options analyzed as part of this study.

4.1 The Role of Simulation in Traffic Modeling

Computer simulation is one of the most important tools of traffic engineering. It is possible to predict the effect of traffic control and the performance of transportation systems management (TSM) strategies if the transportation network can be simulated (Chu 2004). The prediction of the effect could be expressed in terms of measures of effectiveness (MOEs), which include average vehicle speeds, vehicle stops, delays, vehicle-hours of travel, vehicle-miles of travel, fuel consumption and pollutant emissions. While the MOEs provide insight into the effect of the applied strategy on the traffic stream, they can also provide the basis for optimizing that strategy.

Some MOEs needed in traffic studies cannot be measured in the field precisely or even adequately within reasonable time and cost constraints. Also, with computer simulation, the disruption of traffic operations caused by field experiments can be completely avoided when different traffic schemes are considered. Experimentation with various combinations of diverted traffic volumes, ramp metering rates, and origin and destination demand distributions are impractical in field study, especially for incident-based congestion; while they are easily accomplished through simulation studies (Scariza 2004).

The availability of traffic simulation models greatly expands the opportunity for the development of new and innovative concepts. Furthermore, because simulation models produce information that allows designers to identify the weakness in concepts and designs, they provide the basis to identify the optimal form of the candidate approaches. Thus, the eventual field implementation will have a high probability of success (Taylor 1998).

4.2 Simulation Model Selection

A variety of micro simulation models currently exist that perform traffic analysis. It is important to maintain a proper perspective when making modeling decisions. Simulation models cannot describe complex dynamic systems with perfect fidelity. This is particularly true for traffic systems. Traffic flow models implement general principles that are extracted from observations and measurements. Such principles (e.g. car following logic or rules for lane changing) are dependant not only on physical laws of traffic flow mechanics but also on driver behavior.

Driver behavior varies widely with geography, age, time of day, weather and a host of other variables and though it is important to capture this variability in the model, it is also important to recognize that the resulting model will always contain some degree of error. Consequently, modeling traffic systems with perfect fidelity is not and should not be the goal. Instead, the goal is to model the system with sufficient detail and to carefully design test scenarios to ascertain critical properties of the system's behavior. Figure 4-1 presents criteria that should be considered for the selection of a microscopic simulation model.

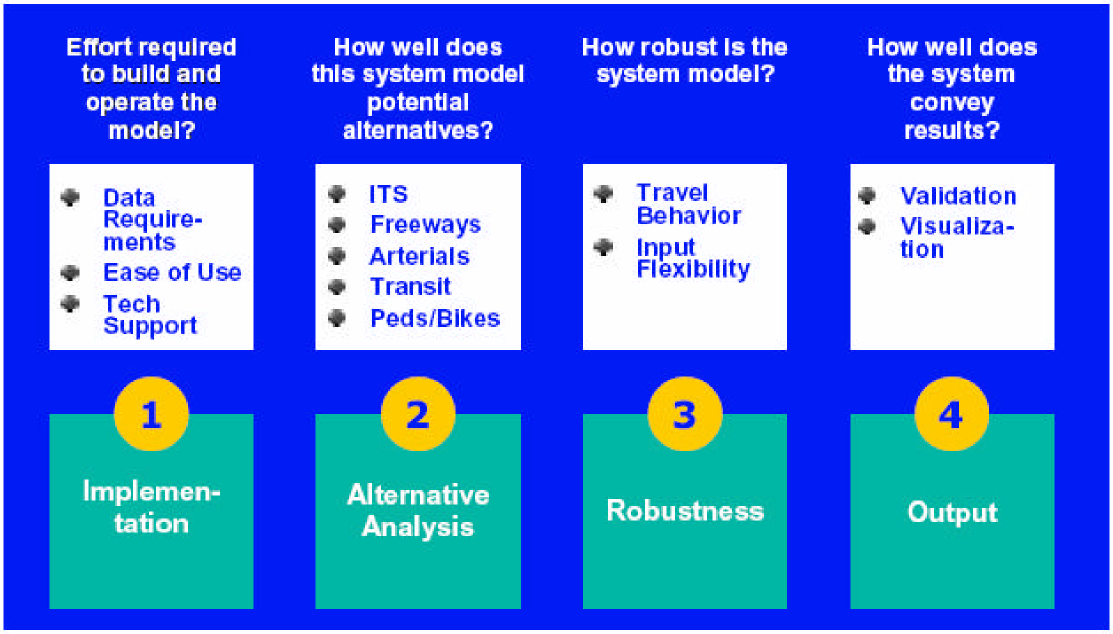

Figure 4-1: Criteria for selection of micro-simulation tool (Chien 2001)

This approach was adopted for the evaluation task at hand. A first step was to determine the extent to which the existing simulation models could be utilized to support the evaluation effort. It was decided that the CORSIM model was compatible with the requirements for evaluation of Ramp Metering Control (RMC). The CORSIM simulation model has been developed by the Federal Highway Administration and has been extensively used by transportation agencies and practitioners in the U.S for over three decades.

The simulation tool CORSIM has been selected for the simulation runs of ramp metering for a number of reasons. First of all, it can simulate stochastic individual traffic vehicle operations and control systems on integrated networks containing freeway and surface streets. Moreover, CORSIM can simulate fairly complex geometric conditions and realistic driver behavior after the model is appropriately calibrated and validated (The ITS Center 1999).

Table 4-1 shows the control, geometric and traffic data required by CORSIM. Control data provide information about traffic control such as number of the time periods, the duration of each time period, the time interval duration, desired output, etc. Geometric data indicate the number of lanes, the length of the lanes, grade of link, etc. Traffic data should express information about vehicle volumes, vehicle speed, traffic origins and destinations, vehicle types, traffic composition, etc.

Table 4-1: Data needed for CORSIM simulation model (Chien 2001)

Item	Control Data	Geometric Data	Traffic Data
1	number of the time periods	number of lanes	vehicle volume
2	duration of each time period	length of links	vehicle speed
3	time interval duration	grade of link	traffic O/D
4	Desired output	curve radius of link	vehicle type

4.3 Development of the Simulation Test Bed

4.3.1 Building the Network

The study network of the Birmingham region was built in CORSIM. The major freeways around the Birmingham region were coded, along with selected arterial streets. Major freeways in the test bed include I-65 from Washington Heights in the north to Oak Mountain State Park in the south; I-20 and I-459 from where they split in the east to where they join in the west; and I-59 from Trussville in the North East to its conjunction with I-459 in the southwest. All study freeways have three mainline lanes. Ramps along these freeway segments that have a volume of less than 900 vph have one lane (two lanes otherwise). Even though ramp metering was done on the ramps of the freeways, coding of the arterial streets which feed the ramps was also necessary. This is because the vehicles queue on the ramps during metering and it is important to check for spillback of vehicles from the ramps onto the arterial streets. A spillback of vehicles onto the arterials will hinder the performance of the arterial network and needs to be prevented, typically by appropriate control measures on the streets, or proper design of storage space on the ramp.

Figure 4-2 shows the network of the Birmingham region that was coded in CORSIM, including the freeways and the arterial streets connected to the freeways by ramps. Overall the network consisted of 9,247 nodes and 9,246 links.

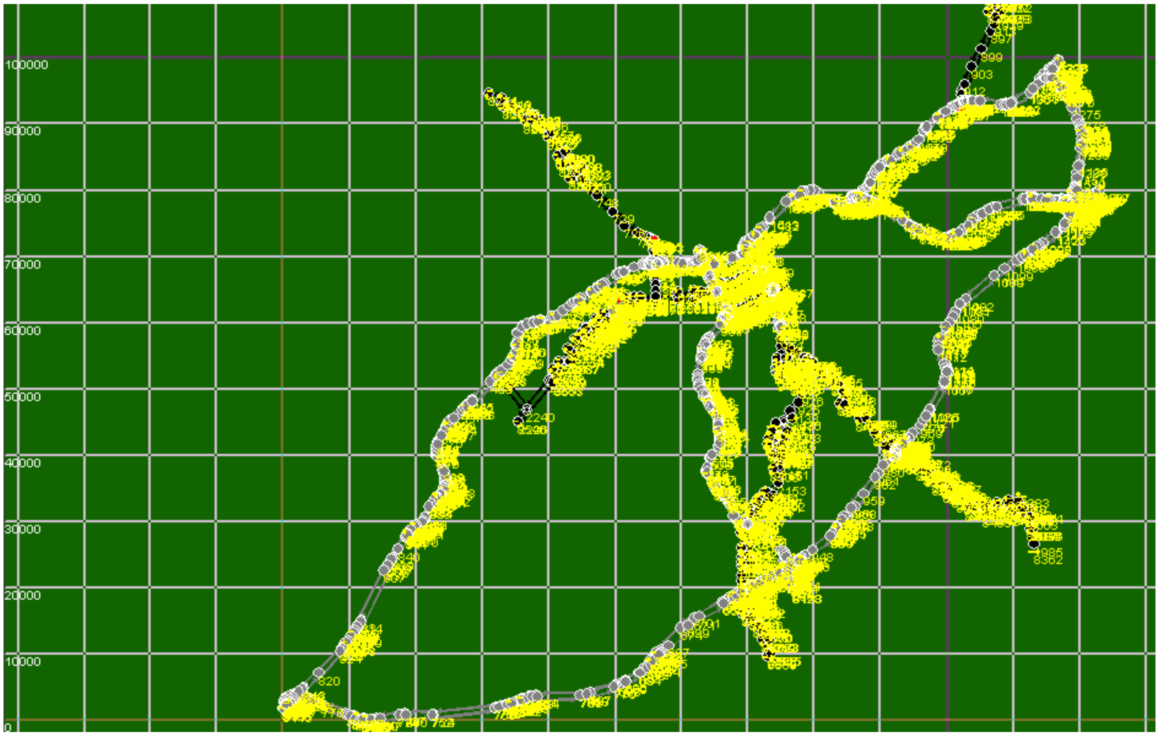

Figure 4-2: Study test bed: Birmingham area network

4.3.2 Data Collection

In order to properly code the network in CORSIM, geometric data and traffic volume data were required. Some of these data were collected through field studies while a large portion was available from other recent traffic studies in the Birmingham area.

Geometric data gathered for the study sections include:

- Lengths and number of lanes of freeway links
- Locations, lengths and number of lanes of ramps
- Lengths and number of auxiliary lanes
- Locations where geometry changes took place
- Grades, and
- Radii of curves

The speed on the freeways is limited to 70 mph and the speed on ramps ranges from 20 to 40 mph. All freeway segments modeled had three lanes per direction and all ramps had single lanes other than ramps, with volumes in excess of 900 vph, which had two lanes. These two lanes merged into one before they merged into the freeway.

Recent traffic counts (in vph) along the major Birmingham freeways such as I-65, I-20, I-59 and I-459 are coded in CORSIM. The traffic counts on the freeways range from 2,400 vph to 4,500 vph. The capacity of the study freeways was set at 5,500 vph and three lanes in each direction.

Traffic volumes on the different ramps are also collected and coded in CORSIM as inputs. Traffic volumes on the ramps range from 150 vph to 1,500 vph. Some traffic control information was also collected including signal timings along the study arterials.

4.4 Ramp Metering Options Analyzed

The evaluation of ramp metering control is conducted by performing extensive simulation with CORSIM for the following ramp metering options:

1. No Metering
2. Clock Time Control
3. Demand/ Capacity Control (DCC)
4. Multiple Threshold Occupancy (MT Occu), and
5. ALINEA

The no metering strategy was used as the base line and all the other types of ramp metering are compared against the non metering strategy. In order to generate unbiased estimates and results, ten simulation repetitions with different random number seeds were performed for each simulation run performed in this study. The results were then tabulated and plotted. Particular attention was given to upstream speed, downstream speed and ramp speed as well as upstream density, downstream density and ramp density. Different options of ramp metering are considered in this study.

4.4.1 No Metering

In this scenario, simulation results without ramp metering control are generated. These results are used as baseline results for comparative analysis with various metering control strategies. Under this situation, vehicles entering the mainline stream from ramps will not be regulated.

4.4.2 Clock Time Control

The Clock Time Strategy is applied on individual on-ramps, while the simulated network wide speeds and densities are analyzed. In the Clock Time Control strategy, the user can select if he wants to use one vehicle per green or two vehicles per green and select the time headway accordingly. Figure 4-3 below shows the parameters that the user can input in this type of ramp metering using CORSIM.

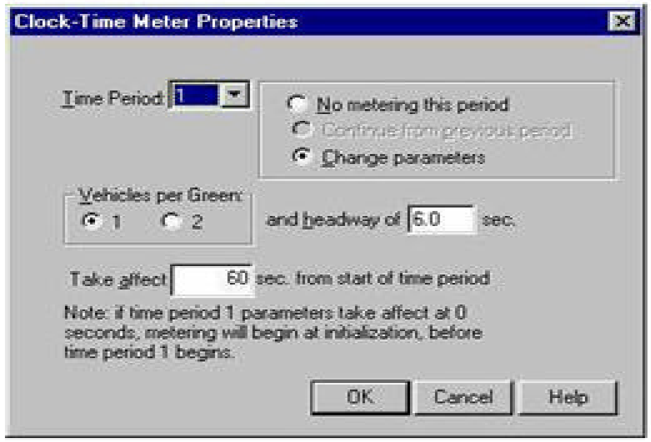

Figure 4-3: Clock- time meter properties (FHWA, 1996)

In this study, the headway in the clock time control ramp metering was initially selected at 5.0 seconds. Table 4-2 summarizes speed and density outputs for a 5-second clock time ramp metering strategy and for various traffic demand levels. As the volume of traffic on the freeway and the ramp increase, the speed on the freeway reduces drastically after the traffic volume reaches 5,500 vph on the freeway and 900 vph on the ramp. For volumes above these threshold values, the ramp meter headway is increased to 10 seconds. These results are an improvement in the speed on the freeway upstream and downstream compared to the 5.0 second headway. Table 4-3 reports the speed and density values for combination of headways (e.g. 5 sec. and 10 sec.).

Table 4-2: Clock time ramp metering with time headway of 5 seconds

CLOCK TIME WITH HEADWAY 5 SECONDS						
	SPEED(mph)			DENSITY(veh/ln/mi)		
Fr Vol/Ra Vol (vph)	Upstream	Downstream	Ramp	Upstream	Downstream	Ramp
2000/200	65.29	64.36	22.89	10.5	10.3	8.4
2500/300	65.14	63.37	22.45	13.1	12.7	8.2
3000/400	63.4	62.43	22.04	16.2	16.3	15.2
3500/500	64.12	63.73	22.77	18.7	17.8	15.8
4000/600	62.05	61.2	22.84	22.1	21.8	16.3
4500/700	57.89	51.23	22.98	23.5	23.3	25.3
5000/800	53.23	44.94	22.65	34.3	33.3	27.9
5500/900	20.09	29.35	22.43	40	36.7	28.2
6000/1000	19.75	21.73	22.99	86.5	88.8	28.7
6000/1100	19.41	20.36	21.76	87.2	89.1	29.3
6000/1200	18.53	19.71	21.43	87.7	89.6	29.9
6000/1300	18.05	18.32	20.37	88.1	90.2	30.3
6000/1400	17.94	17.75	20.12	88.3	90.4	30.7
6000/1500	17.22	17.41	19.98	88.9	90.7	31.3

Table 4-3: Clock time ramp metering with time headways of 5 and 10 seconds

CLOCK TIME WITH HEADWAY 5 secs AND 10 secs								
		SPEED(mph)			DENSITY(veh/ln/mi)		
Fr Vol/Ra Vol (vph)	Headway	Upstream	Downstream	Ramp	Upstream	Downstream	Ramp
2,000/200	5	65.29	64.36	22.89	10.5	10.3	8.4
2,500/300	5	65.14	63.37	22.45	13.1	12.7	8.2
3,000/400	5	63.4	62.43	22.04	16.2	16.3	15.2
3,500/500	5	64.12	63.73	22.77	18.7	17.8	15.8
4,000/600	5	62.05	61.2	22.84	22.1	21.8	16.3
4,500/700	10	65.72	65.71	22.98	24.7	21.1	25.3
5,000/800	10	65.23	65.76	23.26	26.2	23.5	28.3
5,500/900	10	65.31	63.78	24.04	28.9	26	30.2
6,000/1000	10	56.21	49.71	22.99	30.4	35	31.1
6,000/1100	10	56.12	46.68	22.69	30.5	37.3	31.9
6,000/1200	10	58.86	51.91	23.2	29.1	33.5	30.8
6,000/1300	10	58.15	50.01	23.93	29.4	34.9	30.6
6,000/1400	10	58.85	51.61	23.12	29	33.7	31.4
6,000/1500	10	53.32	47.46	20.86	33.6	42.5	34.9

Figures 4-4 through 4-6 demonstrate the impact of ramp metering headway selection on traffic operations by comparing the upstream speed, downstream speed and the ramp speed at a clock time headway of 5 seconds, and a clock time headway combination of 5 and 10 seconds. Based on this preliminary analysis, a 5-second headway clock time ramp metering strategy was selected for the test network for freeway volumes below 4,500 veh/mi and ramp volumes below 700 veh/mi, and the 10-second headway was chosen otherwise.

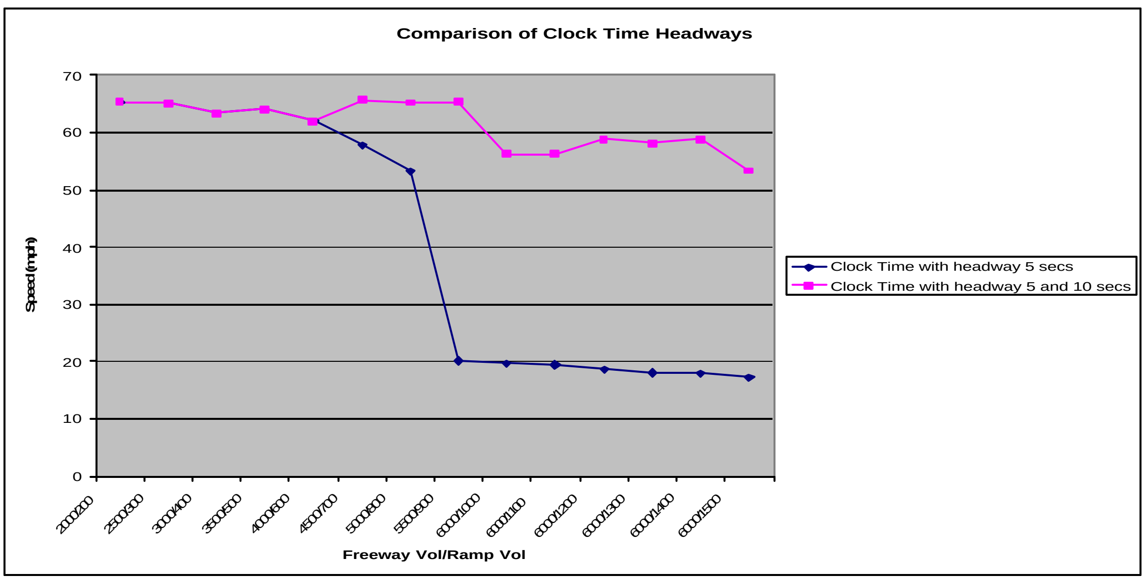

Figure 4-4: Speed comparison of clocktime headways on mainline, upstream

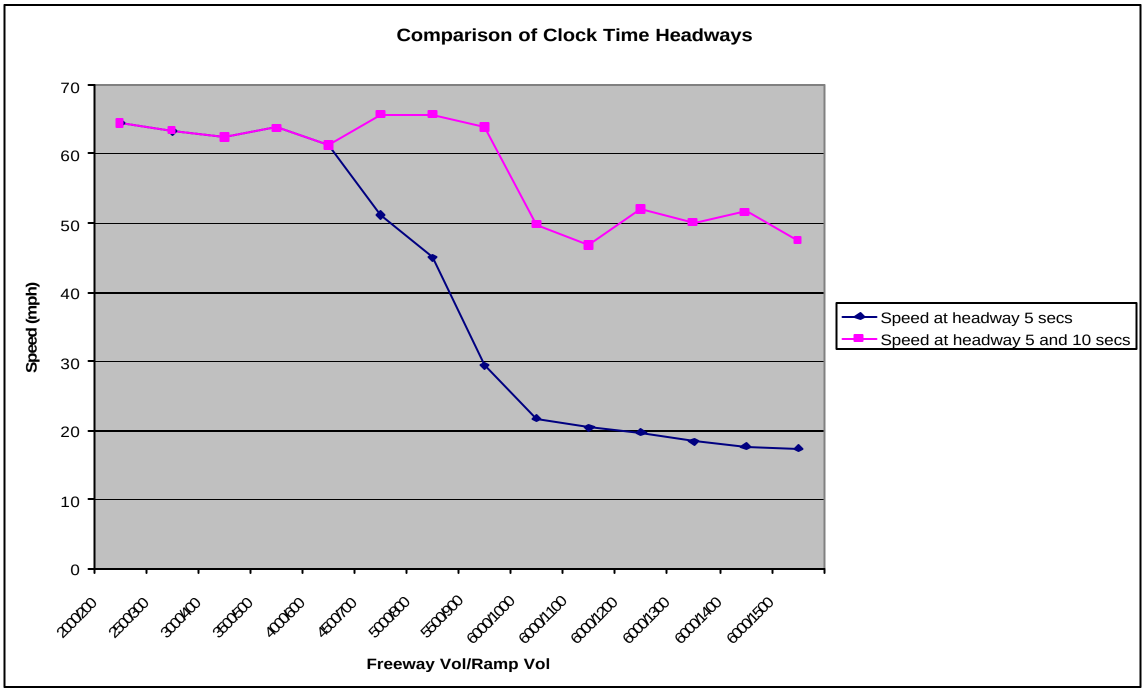

Figure 4-5: Speed comparison of clocktime headways on mainline, downstream

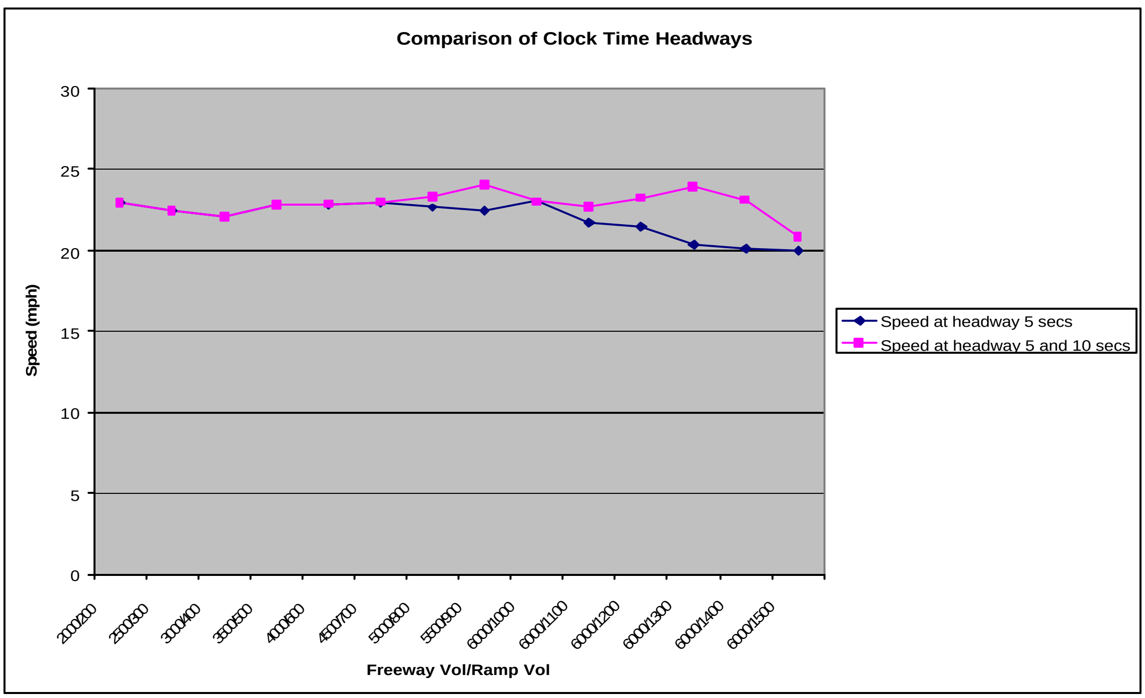

Figure 4-6: Speed comparison of clocktime headways on ramp

4.4.3 Demand/Capacity Meter

In the Demand/Capacity type of ramp meter, an evaluation of current excess capacity is performed at given intervals, immediately downstream of the metered on-ramp. This is based on counts from the surveillance detectors on the freeway mainline. A maximum metering rate is calculated such that the capacity of this freeway section is not violated. The calculated metering rate is applied in a fashion similar to clock-time metering. A minimum metering rate of three green signals per 60 seconds is applied to ensure that waiting vehicles are not trapped between the meter and the ramp connection to the freeway. The metering rate is also limited to headways that are greater than two seconds. Figure 4-7 shows the CORSIM table that is used by the user to input the parameters for the Demand/Capacity Ramp meter.

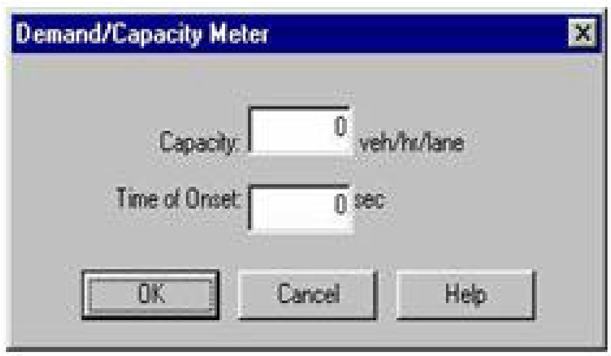

Figure 4-7: Demand/capacity ramp meter input table (CORSIM Manual)

When the Demand/Capacity type of ramp metering is coded in CORSIM, the capacity value has to be entered by the user. This entry specifies the capacity of the freeway (in vphpl) for demand/capacity metering. Another entry by the user is the “Time of Onset”. This entry specifies the time of onset of metering (in seconds) from the beginning of the simulation. If entered as zero, the metering will start at the beginning of initialization. It is recommended that the metering is not started immediately at the beginning of the initialization. This is because the network needs an initial time to fill up with vehicles. Once that takes place, then the results will be more realistic. This initial time is known as the “warm-up time” when the vehicles fill up the network. Hence, this time should be allowed to the network before metering is started. The time of onset depends on the size of network, as a larger network requires more time to fill up with vehicles. Usually, the “time of onset” is at least 10 seconds. This means that after the simulation starts, the metering starts after another 10 seconds. In this study, the “time of onset” chosen was 20 seconds. It was observed that this time was sufficient to fill the study network with vehicles.

4.4.4 Multiple Threshold Occupancy Meter

When the Multiple Threshold Occupancy type of ramp metering is coded in CORSIM, the user may input the metering rate in vph and the occupancy threshold. The latter is given in a percentage form. The user can choose to enter zero to six Rate/Threshold pairs and a minimum metering rate, or can choose to use the default table. Each rate indicates a ramp meter rate to use for mainline occupancies up to the corresponding threshold. Figure 4-8 gives the CORSIM Multiple Threshold Occupancy Meter user input table:

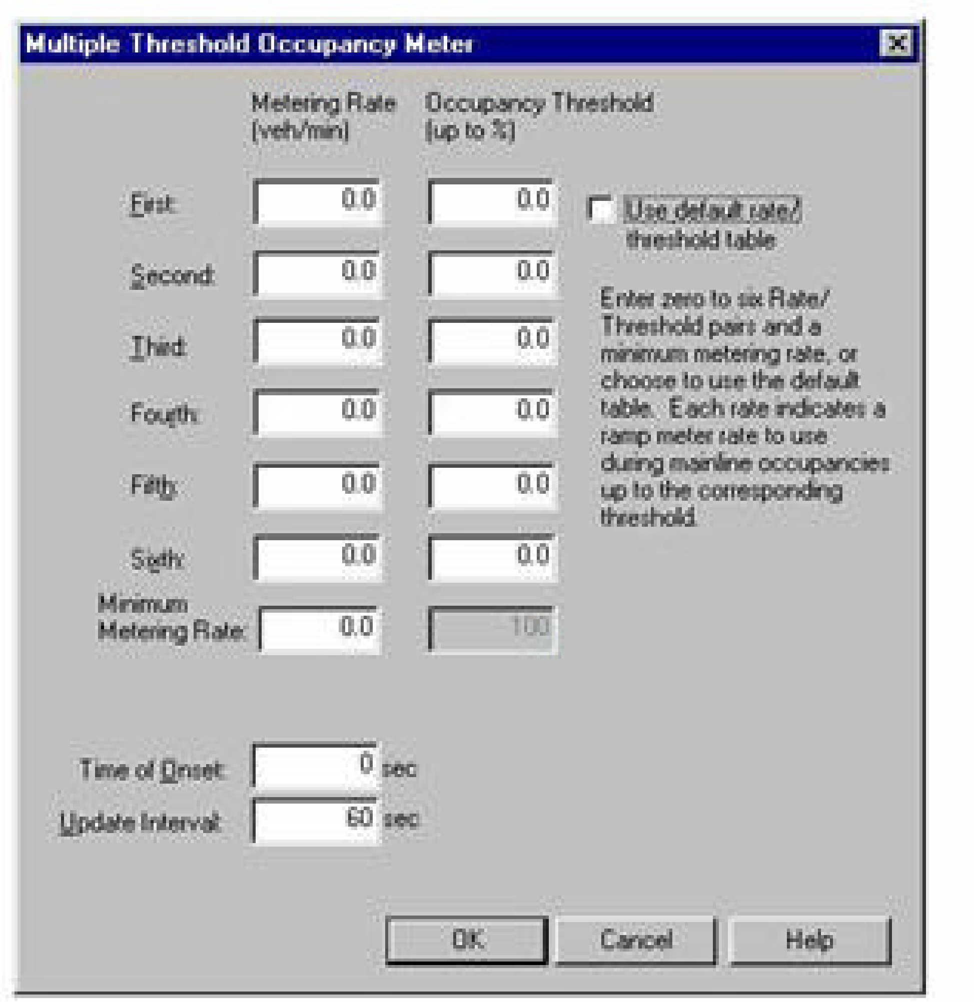

Figure 4-8: Multiple threshold occupancy meter input table (CORSIM Manual)

When the "Use default rate/threshold table" check box is selected, the user does not have to input any data and the default values are automatically used as shown in Figure 4-8. In this study, the default metering rate values were used. Should the user chooses not to use the default rate/threshold option, values in Figure 4-9 can input the preferred metering rates and occupancy thresholds.

Occupancy (%)	Metering Rate (vehicles/minute)
[0, 10]	12.0
(10, 13]	11.0
(13, 16]	10.0
(16, 19]	9.0
(19, 22]	8.0
(22, 25]	7.0
(25, 28]	6.0
(28, 31]	5.0
(31, 34]	4.0
(34, 100]	3.0

Figure 4-9: Default metering rate values in multiple threshold occupancy meter strategy (CORSIM Manual)

Occupancy thresholds should be entered in an increasing order. The "Time of Onset" entry specifies the time for the onset of metering from the beginning of the simulation (in seconds). If entered as a zero, the metering will start at the beginning of the initialization. In this study, the "time of onset" was taken as 20 seconds. The update interval entry specifies the time interval (in seconds) at which metering rate will be updated. It is assumed that the occupancy calculations will be updated at the same time. The update interval chosen for this simulation test was 60 seconds.

4.4.5 ALINEA Meter

The ALINEA ramp-metering control strategy has been a remarkably simple, highly efficient and easily implemented ramp metering application, based on the results of several field implementations in European countries. Because of the high performance of this algorithm, it is an excellent candidate for cost - effective ramp control, as well as for being embedded into a coordinated ramp control or integrated control system.

The ALINEA ramp metering control is based on feedback control theory, and applies to a local feedback ramp metering control policy. The algorithm attempts to maximize the mainline throughput by maintaining a desired occupancy on the downstream mainline freeway. The metering rate during the time interval (t, t+?t) is calculated based on the following formula:

$$r(t) = r(t - ?t) + K_r * (O^* - O(t))$$ Equation (2)

where,

?t = the update cycle of ramp metering implementation;

O* = the desired occupancy of the downstream detector station;

O(t) = the measured occupancy for time interval (t – ? t, t) at the downstream detector station;

r(t – ? t)= the measured metering rate of the time interval, and

K_r = the regulator parameter used for adjusting the constant disturbances of the feedback control.

The following is a summary of parameter settings used in the implementation of ramp metering:

1. The desired occupancy is set to be equal to slightly less than the desired occupancy, or the occupancy value at capacity.
2. Control results have been found to be insensitive for a wide range of values of the regulator K_r. In real-world experiments, the algorithm has been determined to perform well for $K_r = 70$.
3. The downstream detector should be placed at a location where the congestion caused by the excessive traffic flow originated from the ramp entrance can be detected.
4. A wide range of values for the update cycle of metering control has been used: ranging from 40 seconds to 5 minutes. In theory, if the value is small, the location of the downstream detector station should be close to the entrance ramp. Otherwise, there is a risk of congestion build-up in the interior of the stretch from the ramp nose to the detector.

The successful application of ALINEA depends upon the correct determination of four parameters: the update cycle of metering control, a constant regulator used for adjusting the constant disturbances of the feedback control, the location and the desired occupancy of the downstream detector station. Calibration of these operational parameters is required during the pre-implementation phase. Figure 4-10 shows the parameters which have to be input by the user in CORSIM to implement the ALINEA type ramp metering.

In this study, a 60 second update interval was used. The initial rate was selected at 10.0 veh/sec with a minimum rate of 3.0 veh/min. K_r was set at 32 and O* was selected as 20 percent with the onset time of 20 seconds.

Figure 4-10: ALINEA ramp meter input parameters (CORSIM Manual)

CHAPTER 5
SIMULATION STUDY RESULTS

The Birmingham simulation test bed was used to perform the analysis as described in the Methodology section (Chapter 3). In order to introduce randomness and thus, model traffic more realistically, ten simulation replications were performed for each simulation run using different random number seeds. The freeway volume is taken to a maximum of 5,500 vph as this is the capacity of the freeway. The ramp volume is taken up to a maximum of 1,500 vph as this is considered to be the capacity on the ramps.

The results from the analysis were carefully considered to determine the impact of the presence and the type of ramp metering on speed and density for various freeway and ramp volume levels. The metering impacts on speed and density were evaluated for both the freeway mainline (downstream and upstream of the ramp entrance) and the ramp itself. Tables 5-1 through 5-3 summarize ramp metering effects on speeds and can be used as guidelines to determine if ramp meters are justified under local conditions. To facilitate the comparisons, Figures 5-1 through 5-3 illustrate the values given in the tables in a plotted format.

Table 5-1: Mainline speed comparison-upstream of ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Upstream Speeds (mph)				
2000/200	63.75	65.29	65.42	67.41	67.16
2500/300	61.62	65.14	64.75	65.9	67.39
3000/400	60.5	63.4	64.99	67.2	67.07
3500/500	59.22	64.12	62.76	66.87	66.64
4000/600	56.7	62.05	63	65.64	66.15
4500/700	57.44	65.72	64.01	66.24	65.26
5000/800	39.98	65.23	62.79	65.74	65.79
5500/900	20.28	65.31	61.49	65.74	65.94
5500/1000	13.24	56.21	61.41	65.61	66.6
5500/1100	14.15	56.12	63.79	65.61	66.75
5500/1200	12.27	58.86	62.91	65.42	65.7
5500/1300	12.25	58.15	63.89	65.76	66.13
5500/1400	11.88	58.85	63.97	65.69	65.19
5500/1500	11.23	50.7	64.24	63.79	66.68

Table 5-2: Mainline speed comparison-downstream of ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Downstream Speeds (mph)				
2000/200	63.96	64.36	64.73	67.93	67.93
2500/300	62.14	64.37	63.92	66.89	68.63
3000/400	61.33	62.43	64.32	68.6	68.63
3500/500	60.18	63.73	62.38	67.89	67.83
4000/600	58.17	61.2	62.58	66.84	67.24
4500/700	54.53	65.71	63.61	67.11	65.42
5000/800	33.07	65.76	59.79	65.5	66.03
5500/900	28.64	63.78	55.48	65.19	65.2
5500/1000	25.38	49.71	56.86	65.35	66.5
5500/1100	25.88	46.68	60.99	64.21	67.03
5500/1200	25.23	51.91	59.38	63.89	66.04
5500/1300	24.23	50.01	59.67	65.1	65.74
5500/1400	23.76	51.61	60.31	64.9	65.41
5500/1500	22.95	40.65	58.16	55.34	66.86

Table 5-3: Speed comparison-on ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Ramp Speeds (mph)				
2000/200	34.06	22.89	21.44	19.62	20.46
2500/300	33.6	22.45	21.06	21.09	22.01
3000/400	33.4	24.04	22.62	22.09	21.7
3500/500	32.55	23.77	21.63	21.25	22.18
4000/600	32.9	22.84	22.33	21.14	19.23
4500/700	33.63	22.98	22.77	23.47	20.88
5000/800	32.43	23.26	22.95	20.15	21.47
5500/900	28.29	24.04	22.47	22.27	21.65
5500/1000	26.16	22.99	23.28	25.24	19.7
5500/1100	12.86	22.69	24.96	25.14	22.39
5500/1200	11.74	23.2	25.6	24.08	23.49
5500/1300	8.77	23.93	24.28	24.36	24.23
5500/1400	7.69	23.12	25.13	25.19	22.94
5500/1500	7.48	20.86	24.71	23.55	23.75

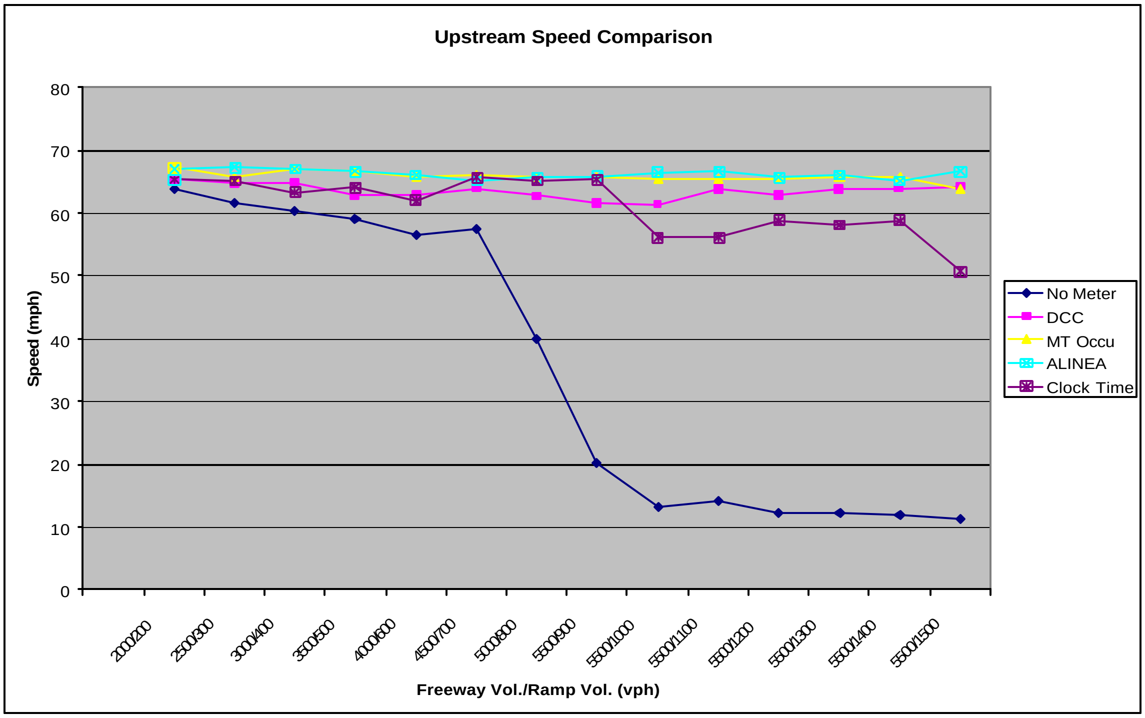

Figure 5-1: Mainline freeway speed comparison-upstream of ramp

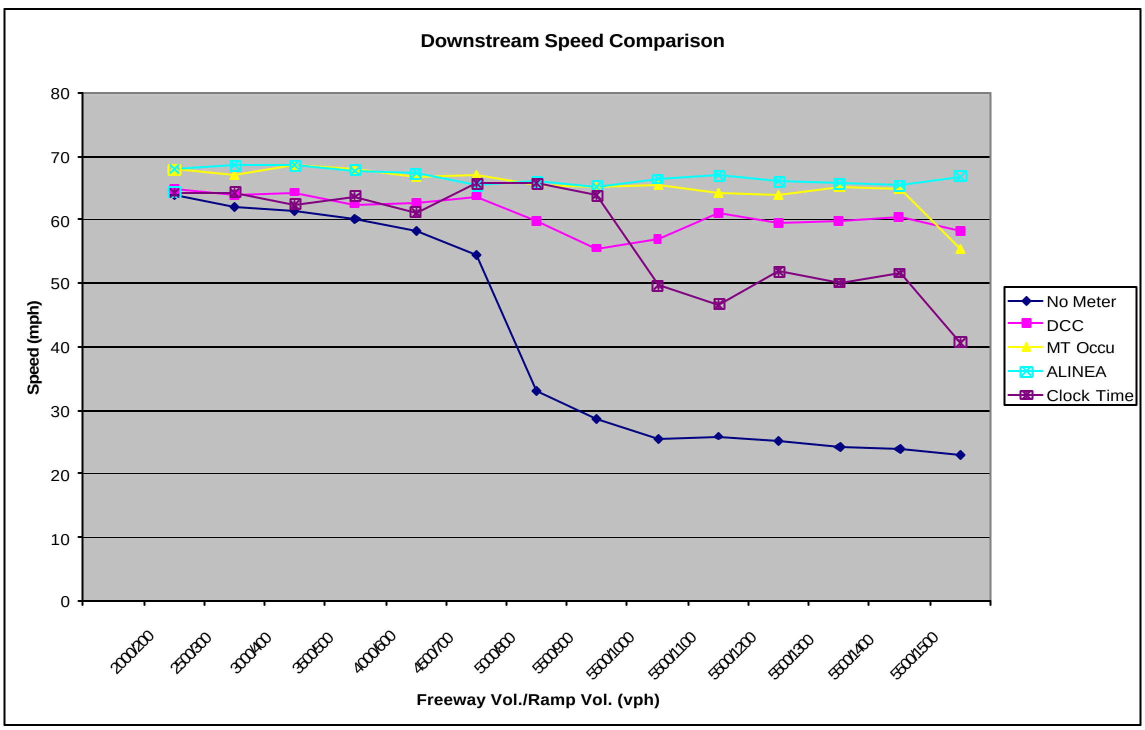

Figure 5-2: Mainline freeway speed comparison-downstream of ramp

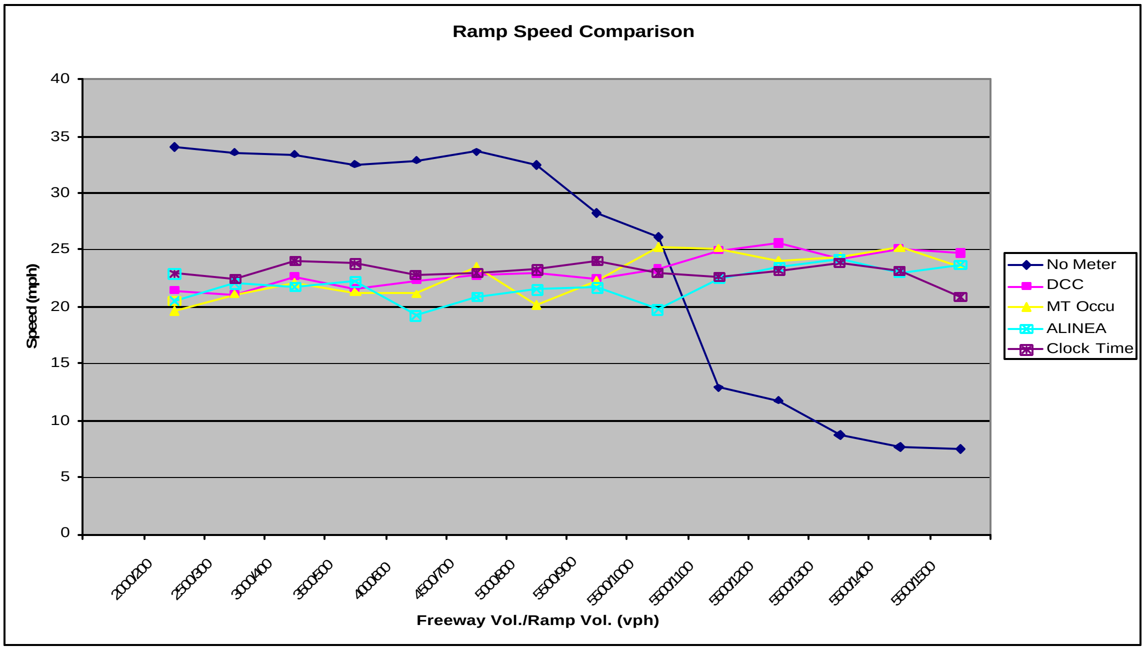

Figure 5-3: Speed comparison-on ramp

Figures 5-1 and 5-2 show that, for low mainline and ramp volumes, the presence of a ramp meter has negligible effect on speeds measured downstream and upstream of the subject ramp. However, as mainline volumes increase above 4,750 veh/hr and ramp volumes over 750 veh/hr, ramp metering options show a dramatic improvement of performance over the non-metered one. More specifically, in the presence of ramp metering the mainline speeds, both downstream and upstream of the ramp, remain almost constant as volume increases (as long as volume remains below the capacity). On the other hand, the absence of ramp metering is related to a quick deterioration of traffic conditions downstream resulting in a sudden drop of mainline speed from 60 mph to 20 mph as traffic increases from 4,500 veh/hr to 5,500 veh/hr on the mainline and 700 to 900 veh/hr on the ramp. Similar effects are observed for upstream traffic conditions too.

Figure 5-3 describes the impact of ramp metering on ramp speeds. As expected, the average ramp speeds are consistently lower when any ramp metering policy is implemented (20 to 25 mph), compared to the non-metered option (30 to 35 mph). Interestingly enough, this is true only for ramp volumes up to 1,000 vph. In the absence of ramp meters and when ramp volumes increase further (from 1,000 vph to 1,500 vph), ramp flow conditions rapidly deteriorate and a rapid drop in ramp speed can be observed. On the other hand, under similar ramp demand conditions (1,000 vph to 1,500 vph), ramp metering options are able to maintain ramp speeds at reasonable levels and allow for the smooth discharge of vehicles from the ramp entrance. Figure 5-3 also shows that all ramp metering options perform similarly, when it comes to maintaining speed on the ramps and the added benefit from using one over another for maintaining higher ramp speeds is practically negligible. Hence, should ramp metering be justified the type of ramp metering can be mainly decided by its performance in the upstream and downstream mainline flow. The impacts of various ramp metering options on density under various freeway and ramp volumes are also studied. Tables 5-4 to 5-6 give the numerical values of densities on the mainline upstream, downstream from the ramp and the ramp itself. Figures 5-4 to 5-6 graphically illustrate the results for easy reference.

Table 5-4: Mainline freeway density comparison-upstream of ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Upstream Density (veh/lane-mile)				
2000/200	10.7	10.5	10.5	10.1	10.2
2500/300	13.9	13.1	13.2	13	12.7
3000/400	17	16.2	15.8	15.3	15.3
3500/500	20.3	18.7	19.1	18	18
4000/600	24.1	22.1	21.8	20.9	20.7
4500/700	26.8	23.5	24	23.3	23.6
5000/800	42.7	26.2	27.2	26	26
5500/900	83.9	28.9	30.7	28.7	28.6
5500/1000	117.3	30.4	27.9	26.1	25.7
5500/1100	110.5	30.5	26.8	26.1	25.6
5500/1200	120.6	29.1	27.2	26.2	26
5500/1300	124.1	29.4	26.8	26	25.9
5500/1400	125.3	29	26.8	26.1	26.2
5500/1500	127.6	33.6	26.6	26.9	25.7

Table 5-5: Mainline freeway density comparison-downstream of ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Downstream Density (veh/lane-mile)				
2000/200	10.4	10.3	10.2	9.1	9.1
2500/300	13.7	12.7	12.7	11.7	11.2
3000/400	16.8	16.3	15.3	13.4	13.3
3500/500	20.2	17.8	18.7	15.8	15.8
4000/600	24	21.8	20.9	18.4	18.3
4500/700	29	21.1	22.7	20.6	21.1
5000/800	52.1	23.5	27.1	23.5	23.3
5500/900	61.3	26	32.2	25.9	25.9
5500/1000	65.5	35	28.3	21.8	23
5500/1100	65.6	37.3	26.5	22.3	22.8
5500/1200	67.2	33.5	28	22.4	23.3
5500/1300	69.3	34.9	26.7	21.9	23.4
5500/1400	71.7	33.7	27	22.1	21.6
5500/1500	73.8	42.5	27.9	25.9	21.1

Table 5-6: Density comparison-on ramp

	Metering Strategy				
Fr Vol./Ra Vol.	No Meter	Clock Time	DCC	MT Occu	ALINEA
(vph)	Ramp Density (veh/lane-mile)				
2000/200	10.4	10.3	10.2	9.1	9.1
2500/300	13.7	12.7	12.7	11.7	11.2
3000/400	16.8	16.3	15.3	13.4	13.3
3500/500	20.2	17.8	18.7	15.8	15.8
4000/600	24	21.8	20.9	18.4	18.3
4500/700	29	21.1	22.7	20.6	21.1
5000/800	52.1	23.5	27.1	23.5	23.3
5500/900	61.3	26	32.2	25.9	25.9
5500/1000	65.5	35	28.3	21.8	23
5500/1100	65.6	37.3	26.5	22.3	22.8
5500/1200	67.2	33.5	28	22.4	23.3
5500/1300	69.3	34.9	26.7	21.9	23.4

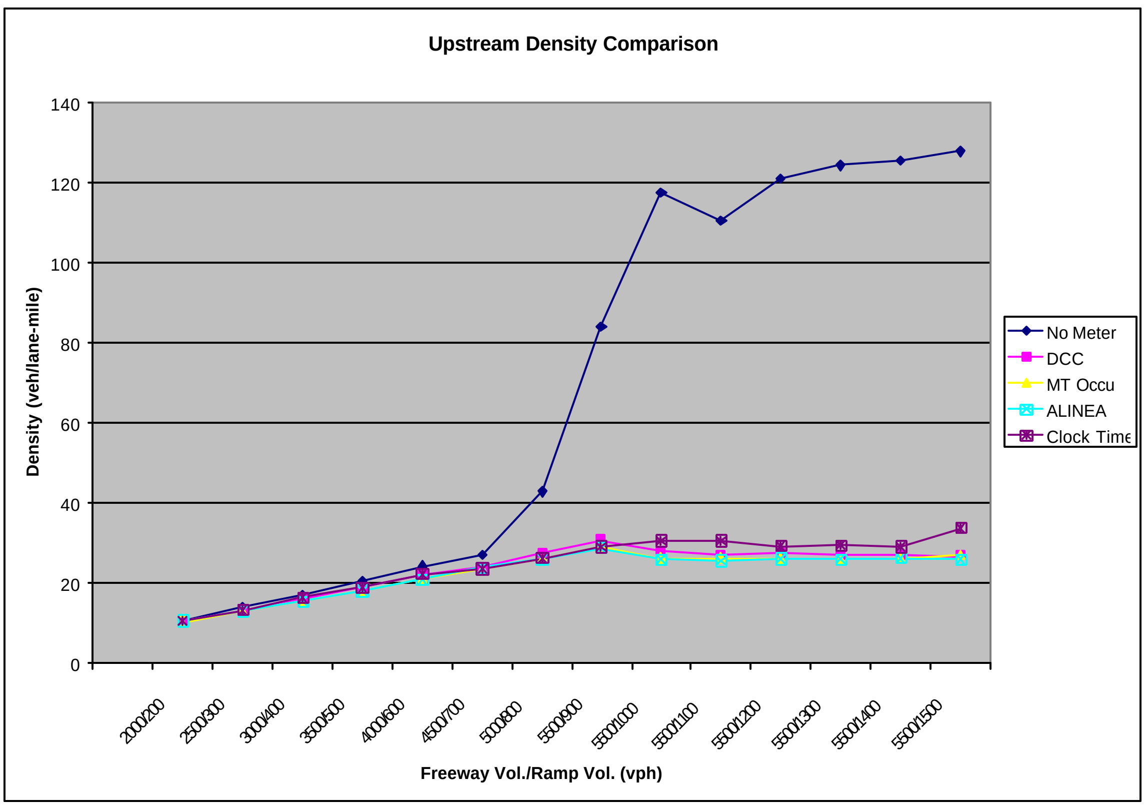

Figure 5-4: Mainline freeway density comparison-upstream of ramp

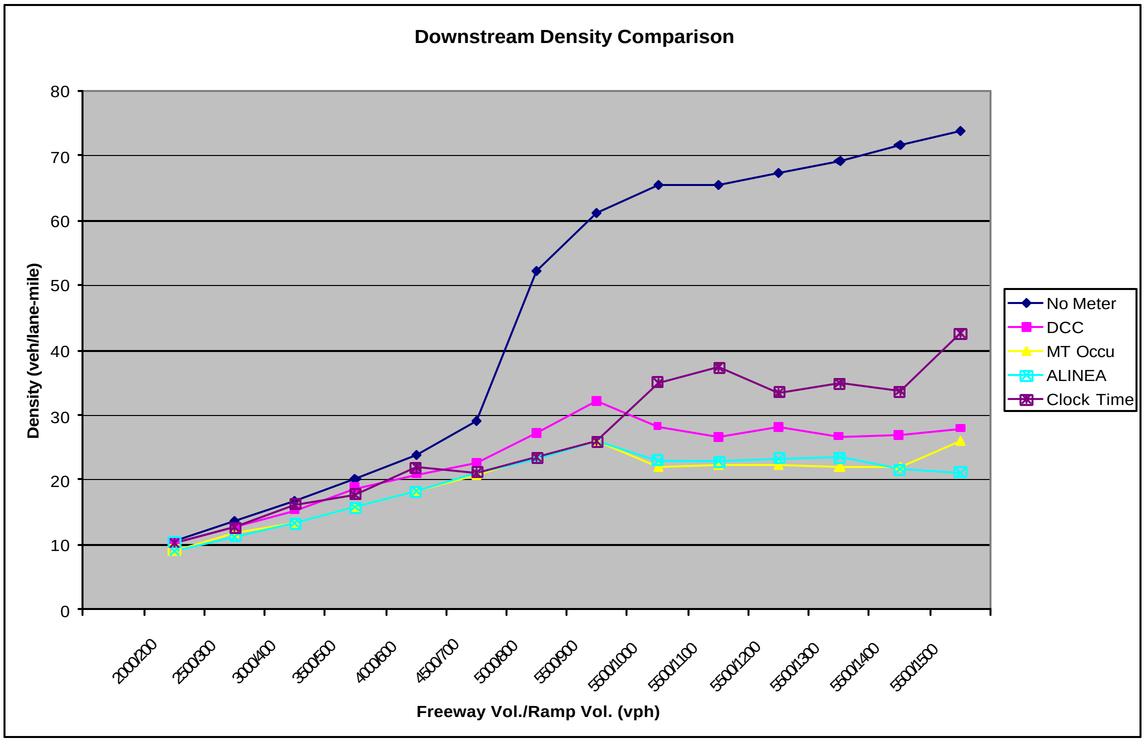

Figure 5-5: Mainline freeway density comparison-downstream of ramp

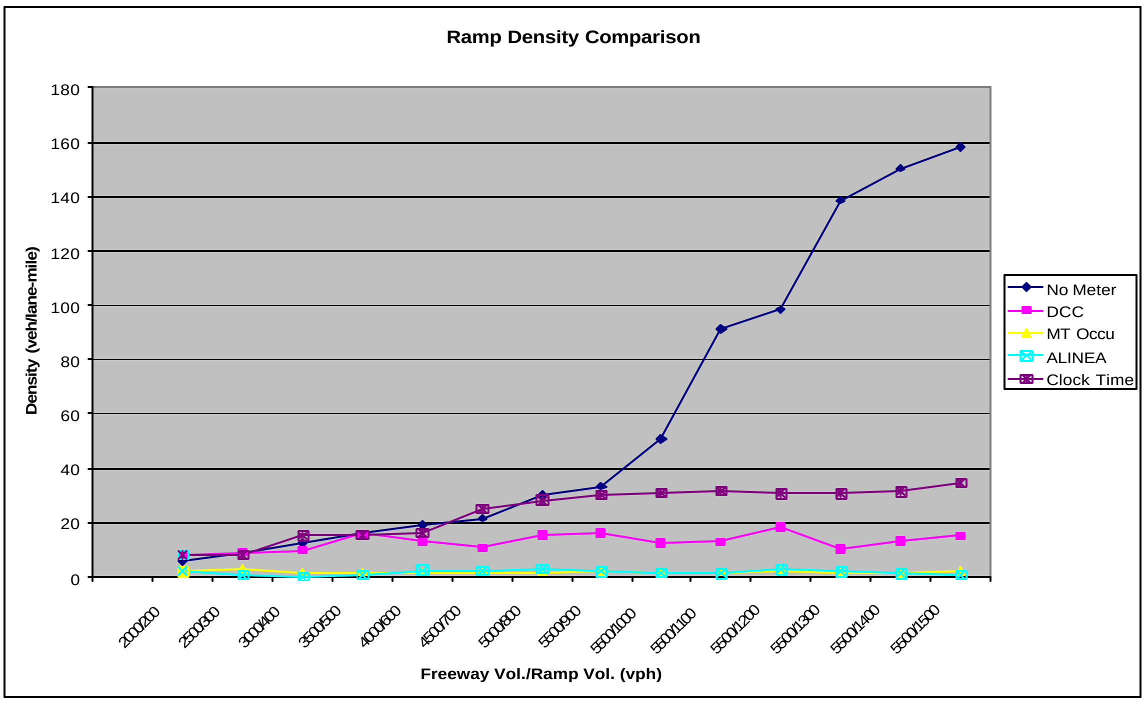

Figure 5-6: Density comparison-on ramp

Figures 5-4 and 5-5, demonstrate that there is not much difference in the density between no metering and all types of ramp metering considered when the freeway volumes and ramp volumes are low. But when the freeway volume increases above 5,000 vph and the ramp volume increases above 800 vph, a rapid increase in density under the non- ramp metering option is observed. On the other hand, only moderate increase in density is observed when ramp metering strategies are in place. Among all metering strategies tested, the ALINEA and Multiple Threshold Occupancy strategies show the best performance.

Figure 5-6 shows that the ramp density also increases drastically in the case of the no metering option when the freeway volume increases to 5,000 vph and the ramp volume increases over 800 vph. This implies that ramp metering is also justified based on ramp performance for ramp volumes in excess of 800 vph.

Assuming that a ramp metering strategy is selected for implementation, the ALINEA and the Multiple Threshold Occupancy strategies are the most desirable while the fixed time (clock time) strategy is the least effective. As the ramp volume increases from 900 vph to 1,500 vph, a mainline speed drop occurs under the clock time metering option, whereas none is evident under the ALINEA and Multiple Threshold Occupancy strategies.

CHAPTER 6
IMPLEMENTATION OF FINDINGS

6.1. Implementation of Simulation Findings to the Birmingham Region

From the simulation analysis, it became clear that ramp metering can be effective in places where the mainline volume is greater than 4,500 vph and the ramp volume exceeds 800 vph. Currently, none of the major Interstates around the Birmingham region have a mainline volume of more than 4,500 vph. From the study freeways, I-65 and I-20 have the most traffic on the mainline with volumes around 3500 vph to 4,000 vph in peak hours. With the anticipated rate of increase in traffic in Alabama, this volume will soon approach 4,500 vph, in which case ramp metering options can be considered.

However, there are twenty ramps in the study test bed which have a high volume of traffic, some of them in the range of 1,200 vph to 1,600 vph. These ramps were identified as potential implementation sites for ramp metering since they experience traffic volumes above 800 vph. Along I-65, four ramps were identified exceeding 800 vph volumes as well as four on I-59, nine along I-20 and three along I-459.

From the simulation analysis, it was further concluded that the Multiple Threshold and the ALINEA type of ramp metering are the most effective. Hence, additional simulation analysis was performed to determine the impact of ramp metering implementation on the twenty ramps that meet the warrant for metering implementation. Both the MT Occupancy and the ALINEA ramp metering strategies were considered. The results from the analysis were then compared with those obtained from base line conditions (i.e. without any ramp metering) as summarized in Table 6-1.

Table 6-1 confirms that the speed on the mainline is considerably lower in the case of no metering compared to when a ramp metering option is deployed. The analysis confirms that improved traffic operations result along the freeway network when the selected ramps are metered.

Table 6-2 gives the speeds on the different ramps. It is observed that for a high volume of vehicles on the ramps, the speeds on the ramps are higher when there is no ramp metering than when ramp metering is deployed. This is consistent with field observations because in the case of ramp metering, vehicles on the ramp are obliged to stop on the ramps before merging onto the freeway. When the average speed on the ramps is considered, it is observed that the reduction of average ramp speed due to metering is typically low. From the system optimization perspective, it can be argued that ramp metering is beneficial to traffic operations as it considerably improves freeway performance without significantly affecting the ramp operation.

Table 6-1: Mainline speed comparison

Freeway	Ramp No	Ramp Vol	Mainline Speed		
			No Meter	MT Occu	ALINEA
		(vph)	(mph)	(mph)	(mph)
I 65	1	1200	23.4	65.7	65.9
	2	900	28.3	66.2	66.4
	3	1000	26.5	65.8	66.1
	4	1100	24.7	65.1	65.8
I 59	5	1050	26.4	65.5	65.9
	6	1200	24.5	65.9	66.3
	7	900	30.3	67.2	67.9
	8	1150	25.1	66.3	66.7
I 20	9	1400	12.2	65.4	65.7
	10	1100	22.9	64.3	64.8
	11	1050	23.2	64.8	65.4
	12	800	30.7	67.1	67.7
	13	950	27.9	65.3	65.8
	14	1100	24.1	64.6	64.9
	15	1300	17.4	66.1	66.7
	16	1000	26.7	66.2	66.9
	17	1400	12.2	65.4	65.7
I 459	18	800	32.5	67.7	68.1
	19	1150	25.9	66.3	67
	20	1300	18.7	66.8	67.3

Spillback conditions were also tested on arterial streets which were close to the ramps. Seven out of the twenty ramps tested for ramp metering were so close to the arterial streets that they were checked for spillback through visual inspection of CORSIM animation files and queue related MOEs. No spillback conditions were observed on any of the ramps. This was further confirmed through the observation of the animation files produced by CORSIM. Figures 6-1 and 6-2 are examples that confirm the absence of spillback effects from the ramps onto adjacent arterial streets for the MT Occupancy and the ALINEA ramp metering strategies respectively.

Table 6-2: Ramp speed comparison

Freeway	Ramp No	Ramp Vol	Ramp Speed		
			No Meter	MT Occu	ALINEA
		(vph)	(mph)	(mph)	(mph)
I 65	1	1200	25.3	24.5	24.9
	2	900	28.3	26.2	26.4
	3	1000	27.7	25.8	26.1
	4	1100	27.2	24.9	25.3
I 59	5	1050	26.6	25.2	22.4
	6	1200	24.5	21.4	21.9
	7	900	28.9	22.2	22.7
	8	1150	24.7	21.6	22.1
I 20	9	1400	25.7	24.8	23.5
	10	1100	27.1	25.6	25.9
	11	1050	27.3	25.9	26.2
	12	800	30.7	28.6	29.2
	13	950	28.6	26.7	27.1
	14	1100	27.1	25.6	25.9
	15	1300	25.9	25.3	25.7
	16	1000	27.7	26.2	27.5
	17	1400	25.7	24.8	23.5
I 459	18	800	32.5	29.1	29.6
	19	1150	24.5	21.7	22.3
	20	1300	26.4	25.8	26.3

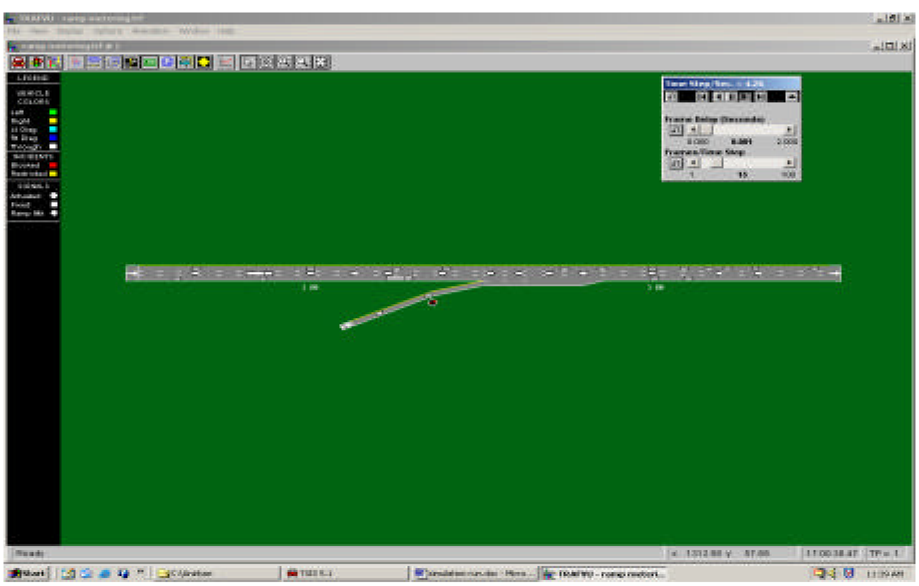

Figure 6-1: CORSIM simulation of MT occupancy ramp meter

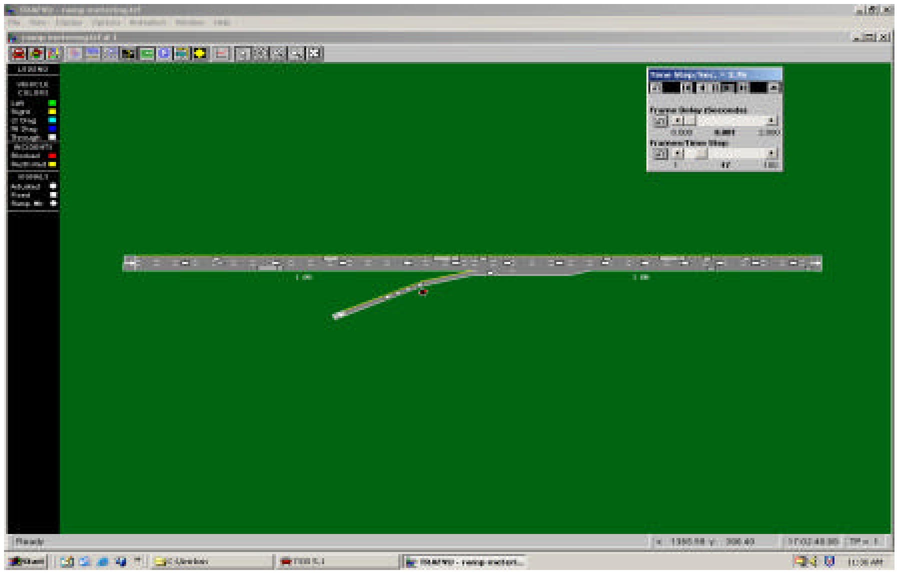

Figure 6-2: CORSIM simulation of ALINEA ramp meter

In addition to speeds and densities, other MOEs such as travel times and delay times were also calculated for upstream and downstream of the ramp and on the ramp itself. It was observed that on the freeway, upstream and downstream of the ramp, the travel time improved when there was ramp metering compared to the no ramp metering strategy. The Delay Times also decreased under metering conditions. As expected, ramp travel times and delays were higher when ramp metering was deployed. Table 6-3 summarizes these results of the average Travel Time and average Delay Time.

Table 6-3: Travel time and delay time comparison

Meter Type	Travel Time (min)			Delay Time (min)		
	Upstream	Downstream	Ramp	Upstream	Downstream	Ramp
No Meter	8.7	8.8	2.6	1.9	1.9	1.3
MT Occu	8.1	8.1	3.6	1.3	1.3	2.3
ALINEA	6.8	6.8	3.7	1.4	1.3	2.4

Network-wide travel time and delay time MOEs were obtained from the simulation runs of the entire Birmingham test bed. Under the no-metering scenario, travel time for the entire network was found to be 2.21 min/veh-mile and the delay time was found to be 0.78 min/veh-mile. When the Multiple Threshold Occupancy type of ramp metering was deployed at the selected potential ramp metering implementation sites, the network travel time was found to be 1.87 min/veh-mile and the Delay Time is found to be 0.65 min/veh-mile respectively. When the ALINEA type of ramp metering was implemented at those same sites, the travel time is found to be 1.46 min/veh-mile and the delay time is found to be 0.47 min/veh-mile respectively.

The ramps which have a volume of more than 900 vph have been designed to accommodate dual lanes in the CORSIM simulation network in accordance to ramp metering guidelines. Presently, two of the seven ramps which have a volume of more than 900 vph have dual lanes. Assuming that ramp metering is implemented, dual lanes are desirable for ramps that carry volumes over 900 vph. If the geometry allows, then these ramps should be constructed to dual lanes so that ramp metering can perform effectively on these ramps.

Hence, the implementation study shows that if ramp metering can be properly deployed at the proposed implementation sites, the travel time and the delay time for the entire Birmingham region are expected to reduce and thus traffic operation in the region are expected to improve as a result of ramp metering.

6.2. Analysis of Benefits and Costs

It is important that the benefit/cost ratio of the ramp metering system is estimated before it is actually implemented in the state of Alabama. The IDAS software is used to develop the estimates of benefits and costs that could be expected to result, should ramp metering is implemented at the selected ramps and corridors. The ITS Deployment Analysis System (IDAS) is a software developed by the Federal Highway Administration that it can be used in planning for Intelligent Transportation Systems (ITS) deployments (Parsons 1997). State, regional and local planners can use IDAS to estimate the benefits and costs of ITS investments-which are either alternatives to or traditional highway and transit infrastructure. IDAS can currently predict relative costs and benefits for more than 60 types of ITS investments. Practitioners will find a number of useful features that enhance ITS planning. For example, IDAS:

- Works with the output of existing transportation planning models
- Compares and screens ITS deployment alternatives
- Estimates the impacts and traveler responses to ITS
- Develops inventories of ITS equipment needed for proposed deployments and identifies cost sharing opportunities
- Estimates life-cycle costs including capital and O & M (operation and maintenance) costs for the public and private sectors
- Provides documentation for transition into design and implementation

For the proper working of the IDAS software, trip generation files were obtained from the TRANPLAN model. Coding of the TRANPLAN took place in an earlier study on behalf of the Regional Planning Commission of Greater Birmingham (RPCGB). The TRANPLAN files were used as an input in the IDAS software and assisted in establishing the study network in the IDAS software. The twenty ramps on the freeways which were identified as probable implementation sites for ramp metering are identified on IDAS model network and ramp metering was applied at these sites.

It was assumed that the ramp metering project starts in the year 2005 and the benefit/cost ratio is calculated for the next twenty years. Hence, the benefit/cost ratio is calculated till 2024. The value of money is taken in 2005 dollars and the inflation rate is assumed as 3 percent. The life of ramp meters is taken as 10 years.

First, the Cost Module Report is prepared. All the costs are taken to be public costs. For the Cost Module Report, the nine ramp meters on the Interstate 20 are considered. The initial cost values are entered along with the O & M (operation and maintenance) values. These are calculated over a period of 25 years with the life time of the ramp meters taken to be 20 years. Hence, after 10 years, the establishment cost for the ramp meters are again required. In this way, the Cost Module Report is prepared for the nine ramp meters on Interstate 20. The average cost of setting up and maintaining the ramp meters over a period of 25 years is calculated. From this value, the average cost of setting up and maintaining the twenty ramps on the interstates in the Birmingham region is also calculated. This value is found to be $208,000.

The Benefit Module report is then prepared. This module is prepared taking into account all twenty ramps on the interstates in the Birmingham region. This module takes into account trip assignments parameters such as Vol./Delay Curves, Market Sectors and Assignment Run Parameters. These values were inputted from the trip assignment files of the Birmingham region which were obtained from TRANPLAN. Also, the annual fuel savings and accident reduction savings were provided as input in the module report based on reports from previous tests of ramp metering in other states. In the IDAS Benefit Module report, there are other parameters like global warming and noise, but these factors are not considered and they are given a weight factor of 0.00. All these values are added and the annual average benefit is calculated over a period of 25 years. This value is found to be $3,065,000.

Using the findings above, the ratio of benefit to cost value is found to be 14.7:1. Hence, one can easily see that the benefit/cost ratio is very high and therefore ramp metering is a good option to implement in the probable implementation sites. Figure 6-3 gives the Benefit/Cost Summary as calculated by IDAS. Figures 6-4 and 6-5 are screenshots of the IDAS software.

Benefits/Cost Summary			
Project: Birmingham Ramp Metering			
Annual Benefits	**Weight**	**Ramp Meter[1]**	
Change in User Mobility	1.00	$	-
Change in User Travel Time	1.00	$	11,000
Travel Time Reliability	1.00	$	1,150,000
Fuel Costs	1.00	$	700,000
Accident Costs (Internal)	1.00	$	500,000
Accident Costs (External)	1.00	$	275,000
Emissions			
HC/ROG	1.00	$	9,000.00
Nox	1.00	$	35,000.00
CO	1.00	$	225,000.00
PM10	0.00	$	-
CO2	1.00	$	150,000.00
SO2	1.00	$	10,000.00
Global Warming	0.00	$	-
Noise	0.00	$	-
Other Mileage-Based External Costs	0.00	$	-
Other Trip-Based External Costs	0.00	$	-
Change in Public Agencies Costs	0.00	$	-
Other Calculated Benefits	0.00	$	-
User Defined Additional Benefits	0.00	$	-
Total Annual Benefits		**$**	**3,065,000.00**
Annual Costs			
Average Annual Private Sector Costs		$	-
Average Annual Public Sector Costs		$	208,000
Total Annual Costs		$	208,000
Benefit/Cost Comparison			
Net Benerit (Annual Benefit-Annual Cost)		**$**	**2,857,000**
B/C Ratio (Annual Beneft/Annual Cost)			**14.7:1**

[1] Benefits are reported in 2005 dollars

Figure 6-3: Benefit/cost summary in IDAS

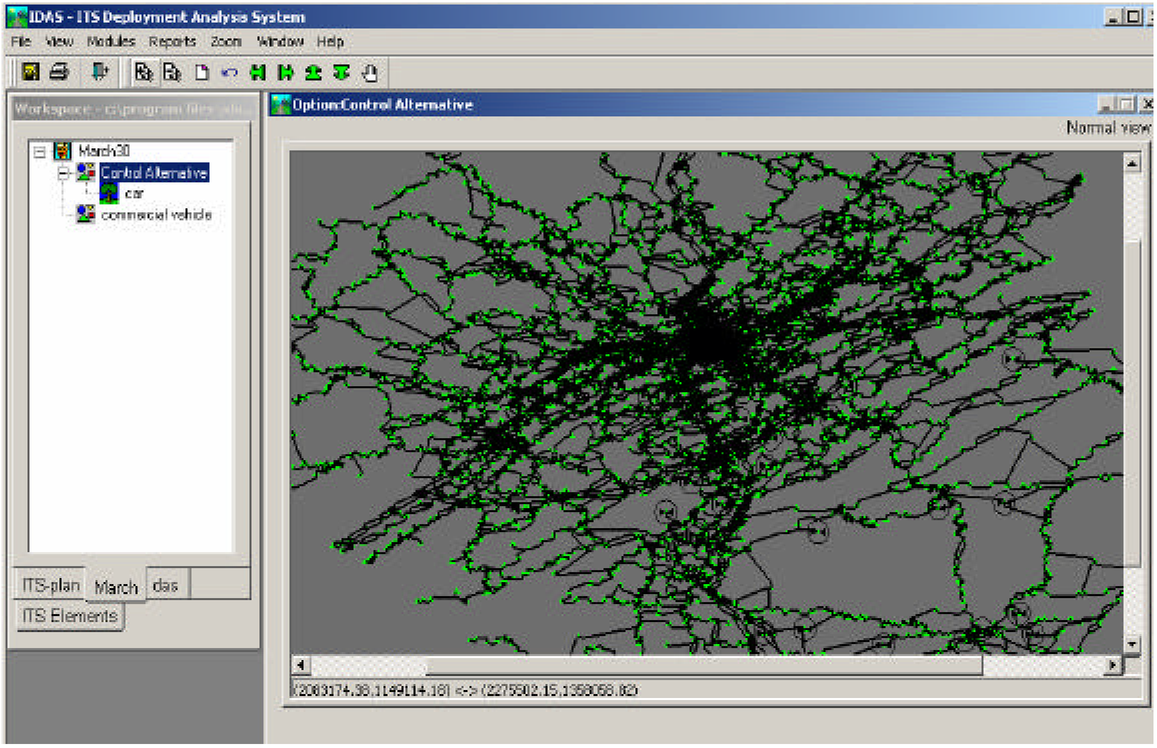

Figure 6-4: Birmingham region coded in IDAS

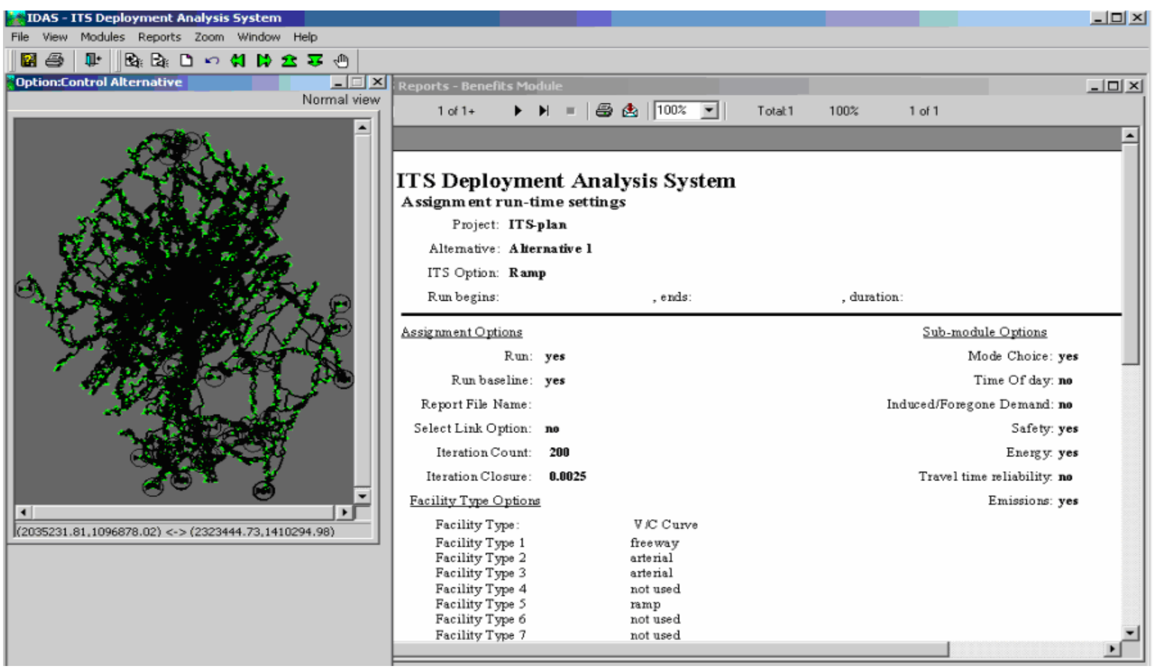

Figure 6-5: IDAS preparing the Benefits Module

CHAPTER 7
SUMMARY AND CONCLUSIONS

There is a consensus among traffic experts that ramp metering is a proven method to improve freeway traffic flow. Ramp metering studies have demonstrated that it reduces disturbance to freeway flow and freeway travel time and delay, and improves freeway travel speeds and motorist safety. Ramp metering has been also used to better utilize street capacity, disperse peak period traffic, redistribute traffic demand and assign proper traffic priority to high occupancy vehicle (HOV) lanes.

This study analyzed and compared the impact of various ramp metering strategies on freeway and ramp operations for various demand levels on the mainline and ramp. It determined conditions under which ramp metering is justified. The main findings follow.

1. Ramp metering strategies have a positive impact on freeway operations and assist in maintaining higher mainline speeds upstream and downstream from the ramp, compared to the non-metered option.
2. The benefit described above is significant for mainline volumes over 4,500 vph. Under such demand conditions the installation of ramp meters is justified with respect to freeway operations
3. For low ramp volumes, ramp speeds are higher under the non-metered option. However, as ramp demand exceeds 800 vph, ramp metering options result in higher speeds than the non-metered option. Therefore, for ramp volumes over 800 vph ramp meters are also justified with respect to ramp operations.
4. Despite its popularity, the fixed time (clock time) metering strategy proved to be the least effective strategy in maintaining high freeway speeds upstream and downstream of the ramp meter. From the metering strategies tested, the most effective proved to be ALINEA, closely followed by the Multiple Threshold Occupancy option.

Using these criteria for ramp metering implementation, the Birmingham study network currently has twenty ramps that qualify for ramp metering. Implementation of ramp metering strategies on those ramps was tested and proved to be beneficial for network operations. Moreover, a benefit/cost analysis performed in this project showed an expected benefit-to-cost ratio of 14.7-to-1, should ramp metering be implemented in the Birmingham region at the proposed 20 ramp locations. Thus ramp metering is recommended for further consideration as a strategy with an excellent potential to ease congestion in the Birmingham region which is further justified by the benefit-cost analysis. It is further recommended that public education campaigns are conducted to inform users of benefits associated with implementation of ramp metering options. Also, public meetings and user surveys should take place to receive feedback from stakeholders regarding their preferences and concerns, prior to implementation of ramp metering strategies in the state of Alabama.

Moreover, it is recommended that ramp metering should be viewed from a systems approach in future research. Some desired effects of ramp metering such as modal shift, time-scatter of roadway demand and use of alternative routes may not be attainable since they require significant organizational changes. Traffic control measures could create undue burden on users who are constrained, through no fault of their own, in their choice of transportation mode, commute routes and timing of their routes. Overall, the findings from this study support the notion that, although ramp metering alone may not solve the problem of congestion, when used effectively with a well planned and operated system, it has the potential to be a part of the solution.

CHAPTER 8
LIST OF REFERENCES

AASHTO, "A Policy on Geometric Design of Highways and Streets," January 2001.

Alkadri, Y. "Ramp Metering: A Systems Approach Pilot Survey of Acceptability by Freeway Users." January 2001.

Banks, J. Performance Measurement of a Metered Freeway System. TRB 1173. Washington D.C. U.S.A, 1988.

Bhat, C. and Guo, J. "Activity-Based Travel-Demand Analysis." Report No. FHWA/TX-03/4080-3. September 2001.

Bellemans, T. "Anticipative Ramp Metering Control for Freeway Traffic Networks." Available on-line from http://www.mtns2004.be/database/papersubmission/upload/320.pdf. Accessed August, 2004.

Bogenberger and May. "Ramp Meters on Trial." University of Minnesota. May 1999.

California Department of Transportation. "Ramp Meter Design Manual." Final Report prepared by the Traffic Operations Program in Cooperation with: Design and Local Programs and Department of California Highway Patrol, Sacramento, CA, January 2000.

California Department of Transportation and IBM, "TMS Ramp Metering Business Plan." Sacramento, CA, December 2002.

Cambridge Systematics Inc., Twin Cities Ramp Meter Evaluation – Final Report. Minnesota Department of Transportation, February 2001.

Chaudhary, A and J. Messer. Ramp Metering Technology and Practice. Report 2121-1. Texas Department of Transportation, May 2000.

Chaudhary, A and Messer, J. Design Criteria for Ramp Metering: Appendix to TxDOT Roadway Design Manual, November 2000.

Chien, S. "Evaluating Ramp Metering Control Systems Using Micro Simulation for U.S. Interstate Highway I – 80." October 2001.

Chu, L. "Development of a Simulation Laboratory for Evaluating Ramp Metering Algorithms" Available on-line from http://www.its.uci.edu/its/publications/papers/WP-01-13.pdf. Accessed on August. 2004.

Dudek, C. and Ullman, G. "Freeway Corridor Management." National Cooperative Highway Research Program Synthesis of Highway Practice. Report 177, Transportation Research Board, Washington, D.C. March 1992.

European Commission. "Ramp Metering Synthesis." Technical Report, December 2001.

Federal Highway Administration (FHWA). "CORSIM's User's Manual." Contract No. DTFH61-92-Z-00074. Washington D.C.,1996.

Hourdakis, J. and P. Michalopoulos. "Evaluation of Ramp Control Effectiveness in Two Twin Cities Freeways." Transportation Research Record 1811, Transportation Research Board, Washington, D.C., 2002.

Illinois Department of Transportation (IDOT). Freeway Surveillance and Control, 1979.

ITE Technical Committee. Displays for Metered Freeway Entrance Ramps. ITE Journal April, 1984.

Johnston, R. A., Lund, J. R., and Craig, P. P. "Capacity-Allocation Methods for Reducing Urban Traffic Congestion." Journal of Transportation Engineering, Vol. 121, No. 27, 1995.

MUTCD, Manual of Uniform Traffic Control Devices, AASHTO, November, 2003.

Pearsons, R. "Ramp Metering." ITS Decision Report, Partners for Advanced Transit and Highways, Berkeley, CA, 2001

Piotrowicz, G. and J. Robinson. Ramp Metering Status in North America 1995 Update. Report # DOT-T-95-17. Washington D.C., USA: U.S. Department of Transportation, 1995.

University of Minnesota, Center for Transportation Studies, "Ramp Metering." Available on-line from http://www.its.umn.edu/research/applications/rampmeter.html. Accessed on February, 2004.

Taiwan Area National Freeway Bureau,"Ramp Metering Systems." Available on-line from http://www.freeway.gov.tw/en_05_02.asp. Accessed on March, 2004.

Saito, M. and M. Hernandez. "Evaluation of the Effectiveness of Coordinated Ramp Meter Controls." Transportation Research Board Report 00962194, 2003.

Scariza, J. "Evaluation of Coordinated and Local Ramp Metering Algorithms using Microscopic Traffic Simulation." Available on-line from http://web.mit.edu/its/papers/scariza_thesis.pdf. Accessed June, 2004.

Stewart, P. "Ramp Metering Study." SIAS Limited Final Report TPRAMP2/55129, Dundee, UK, March 2003.

Taylor, C., Meldrum, D. and Jacobson, L. "Fuzzy Ramp Metering: Design Overview and Simulation Results." Transportation Research Record 1634, Transportation Research Board, Washington, D.C., 1998.

Tian, Z. Z., et al. "Integrated Control Strategies for Surface Street and Freeway Systems." Transportation Research Record 1811, Transportation Research Board, Washington, D.C., 2002.

U.S.DOT, Federal Highway Administration. "Coordinated Operation of Ramp Metering." Publication No. FHWA – RD – 95 – 130, 1996.

Wisconsin Department of Transportation (Wisconsin DOT). Design Manual, Chapter 3: Ramp Metering. December 2000.

Washington State Department of Transportation (Washington DOT). "Washington DOT Design Manual." Final Report. Washington State Department of Transportation, July 1997.

APPENDIX A

Summary of Agency Survey Responses

1. How many ramp meters does your agency operate?
   65 meters are in operation, all in the Phoenix area. They are considering deploying some in Tucson.

2. In what situations are they used? What types are used (fixed or adaptive)?
   Almost all meters are currently fixed time (1 vehicle per green), although there is a program underway to convert them to adaptive meters. Contact was not sure at what stage this project was. All new meters are adaptive. There are no set criteria for implementation. They look at volumes (peak 15 minute), speeds, lane configurations, requests from public, and how the segment fits into the overall freeway management system.

3. What were the criteria for implementation?
   As described above, the criteria are very broad. They try to avoid "orphan" meters, those which are isolated, because they tend to divert people to non-metered ramps and have only limited impacts.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
   Yes, very effective. Arizona DOT hired a consultant to assess their effectiveness. Copy of the report was obtained. Report found that ramp meters were effective in maintaining freeway speeds.

5. What has been public reaction to the ramp meters? Enforcement problems?
   Initial public reaction is almost always negative, but after ramp meters have been operational for a while public perception improves. In many areas that currently have meters they have received requests from the public for additional meters. No known enforcement problems. Proposition 400 was recently approved increasing the sales tax by ½¢ for the next 20 years, with most of that money going toward ITS and congestion management.

6. What have been your average installation costs? Annual maintenance costs?
   For isolated ramps installation costs have run about $90,000. If they are doing multiple ramps at a time they can get that cost down to $50 - $60k. Annual maintenance costs run "a few thousand" a year.

7. Have you removed any meters? Had major problems with them?
   No. Overall public support is good.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?
   Overall experience has been very positive. Arizona DOT is looking to expand ramp meter coverage in Phoenix and possibly begin installing meters in Tucson.

1. How many ramp meters does your agency operate?
   Operated throughout the State, primarily in major metro areas. CalTrans currently operates over 1000 meters statewide.

2. In what situations are they used? What types are used (fixed or adaptive)?
   Mostly on freeways. All newer meters are adaptive, although there are still a few older pre-timed meters left. Newest application is the use of meters in freeway-freeway interchanges. Requires advanced warning signs and uses red-yellow-green signals rather than traditional red-green. Use of freeway-freeway meters is expanding. In some cases HOV vehicles are allowed to bypass meters if ramp geometrics permit safe operation. In other areas where limited ramp design might create a conflict, HOV's must stop too, although only briefly. Signal serves more to slow them down.

3. What are the criteria for implementation?
   Used widely to reduce freeway congestion and increase freeway speeds. Criteria are based on volumes and geometrics. Design criteria are laid out in CalTrans design manual.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
   Yes. Several studies have been done in Sacramento, San Diego, and Los Angeles as well as other areas and have found that ramp meters are effective. Studies are old, however. Sacramento study was performed in the 1980's. Studies did find significant increases in freeway speeds and mainline capacities.

5. What has been public reaction to the ramp meters? Enforcement problems?
   Public reception has generally been good, but there are the typical complaints. Because they are so common in State they are generally well understood. No major enforcement problems out of the ordinary.

6. What have been your average installation costs? Annual maintenance costs?
   Installation costs depend on existing communications infrastructure. Cost can vary from $10k-$100k depending on changes needed. Caltrans designs ramps to accommodate meters, so it is not just hardware or meter costs to be considered. Maintenance in on the order of a few thousand dollars a year per meter.

7. Have you removed any meters? Had major problems with them?
   No major problems. Fairly well understood in the state.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?

Yes. CalTrans continues to add ramp meters as volumes warrant. Tries to conduct press campaigns before installing new meters. Lets meters run "green" for a few weeks while traffic volumes are sampled and drivers adjust to having meters present.

Ramp Metering Survey Questions Agency: Michigan DOT, MITS Center

1. How many ramp meters does your agency operate?
Michigan DOT operates 60 ramp meters, all in the Detroit area. The meters have been in operation for nearly 20 years, but the entire system is currently out of service and has been for more than 2 years. The communications and control for the old system were coaxial and the trunk cable was severed about 2 years ago in a construction project. The decision was made to leave the system off until it could be upgraded.

2. In what situations are they used? What types are used (fixed or adaptive)?
The meters are adaptive. The discharge rate on the ramps can be varied between 5 and 15 cars/min. The mainline detectors are placed at the gore point and can trigger the ramp meter into operation, although in the past they were usually triggered (on/off) from the control center. Deployed along all of I-94 and M10 in Detroit.

   The Michigan DOT metering strategy has been to release all the vehicles on the ramps before the next platoon of vehicles arrive. In this way it differs from some other cities where vehicles are often held on ramps for significant time periods. The Michigan strategy is simply to disperse the platoons arriving from signals and smooth the merging onto the freeway, so the discharge rate is adjusted at each ramp accordingly. Because they do not generally create excessive delays on the ramps they are not terribly controversial and compliance has generally been good.

3. What were the criteria for implementation?
No set criteria, but they were installed along entire corridors, not just selected ramps.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
No study has been done. They have done a few spot trials where they've turned ramp meters off for a few days to compare operation. They have found that the ramps tested functioned better with the ramp meters than without, although it is based on anecdotal observations rather than rigorous analysis. He stressed that it is important to show users that all people benefit from ramp meters, not just people on the freeway, and that these trials did that.

5. What has been public reaction to the ramp meters? Enforcement problems?
Okay. Observance was generally good on the old ramps. No major enforcement problems that he was aware of. They tried some meters on a new freeway facility and found that compliance was not so good. People who had not been exposed to them before did not understand procedures very well and there were compliance problems. Specifically, people did not understand the "one car per green" rule. They also saw an increase in rear-end accidents because some motorists were not expecting to stop on the ramps. MDOT had not performed any public education and the person thought that would have been very helpful.

6. What have been your average installation costs? Annual maintenance costs?
   No firm figures. Communications and knocked down signal heads were the most common maintenance costs. The old coaxial system required a fair amount of maintenance. Installation cost depends on availability of communications in area. Recommended installing conduit for fiber optics on all major road projects.

7. Have you removed any meters? Had major problems with them?
   They have not removed and meters, although they have disabled some meters temporarily due to complaints. In general they operated well and were well received by the public.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?
   Overall they feel they have been effective, but they have run into resistance trying to deploy them in suburban corridors. Because some feel there would be intense opposition to them in suburban corridors the MDOT has not pursued it, even though it was felt there are some facilities that could use it. It has raised an interesting criticism, that because all the meters are in Detroit (mostly black) and none are in the suburbs (mostly white) some feel the meters favor suburban (white) commuters at the expense of urban (black) commuters.

   Ramp meter system should be back up in 2-4 years. They are trying to move away from proprietary hardware and are using Internet Protocol rather than the RS232 communication protocols.

Ramp Metering Survey Questions Agency: Minnesota DOT

1. How many ramp meters does your agency operate?
There are 419 ramp meters in the Twin Cities metro area, of which 213 have the potential to operate during the AM peak and 266 during the PM peak. This number has been stable over the past few years.

2. In what situations are they used? What types are used (fixed or adaptive)?
Stratified Ramp Metering is the traffic responsive algorithm that operates the meters and updates every 30 seconds. After a system wide study of ramp meter effectiveness conducted in 2001, the ramp metering algorithms were changed to reduce waiting times on ramps. Under the new algorithms, no motorist should have to wait more than 4 minutes on a ramp. There were considerably longer delays under the old system.

3. What are the criteria for implementation?

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
The Minnesota DOT feels that the ramp meters are very effective. The 2001 study performed by Cambridge Systematics confirmed that ramp meters do in fact increase freeway speeds, reduce overall delays, and reduce the number of accidents at freeway merges. The results of the study are available online at:

   http://www.dot.state.mn.us/rampmeterstudy/background.html.

5. What has been public reaction to the ramp meters? Enforcement problems?
Public reception has been good overall, and even better since the study, which clearly demonstrated that they are effective. MnDOT cited the helpfulness of local media in publicizing the results of the study and getting the word out that ramp meters are effective. Motorist compliance has generally been good, although the number of law enforcement devoted to it is small. When asked if compliance improved with the shorter ramp wait times MnDOT said that they did not feel there was really much of a problem before. They have no studies that have looked directly at compliance. MnDOT noted that much of the opposition prior to the 2001 study was political rather than popular.

6. What have been your average installation costs? Annual maintenance costs?
Average installation costs for hardware have averaged about $8k-$10k, but that figure does not include communications or software or any ramp modifications. Annual maintenance costs have been on the order of a few thousand dollars per meter.

7. Have you removed any meters? Had major problems with them?
Have not physically removed any meters, but several meters were turned off as a result of the 2001 study and are not likely to be turned on again anytime soon. Main reason is that it was not felt they provided enough benefits to justify motorist delay.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?
Overall experience has been good. No immediate plans to implement outside of the Twin Cities metro area or on additional facilities within the area, although they pretty much have most of the existing freeway network covered. Future freeway facilities will likely have meters when they are built.

1. How many ramp meters does your agency operate?
The New York DOT operates 99 ramp meters, exclusively in Long Island as part of the INFORM Program.

2. In what situations are they used? What types are used (fixed or adaptive)?
Adaptive. They use essentially three different metering algorithms: restrictive when sufficient storage exists, partially restrictive when limited storage exists and queues should not exceed a certain length, and non-restrictive when inadequate storage exists.

3. What were the criteria for implementation?
There are minimum volume criteria before the NYDOT will consider ramp metering, namely ramp volumes of at least 240 vph (400vph for two lanes) but less than 900 vph (1800vph for two ramp lanes).

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
Yes, evaluation was done in 1990 with system on/off observations. The evaluation found that freeway speeds were 10%-20% higher with the meters on, and overall vehicle miles were constant.

5. What has been public reaction to the ramp meters? Enforcement problems?
Compliance has generally been very good. One study found motorist compliance to be around 95%. No major enforcement problems. Overall public reaction is somewhere in the middle, but most people seem to recognize that it does some good, particularly in terms of reducing accidents (which one study put at 15%).

6. What have been your average installation costs? Annual maintenance costs?
Price is hard to determine, it depends on what is included in total. Average between $60k-$80k per installation including communications. Since these are installed as part of the overall INFORM program in the corridor and communications are already in place for sensors, cameras, and VMS the actual price could be much less. Maintenance costs average about $150 a month per meter, or $2000 per year. They recommended using off-the-shelf hardware whenever possible to keep costs down.

7. Have you removed any meters? Had major problems with them?
No. Overall public support is good, or at least there is an attitude of acceptance.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?

Overall experience has been good. No plans to expand outside of current corridor, and NYDOT does not seem to have any interest at present in deploying meters in other parts of the state.

Ramp Metering Survey Questions Agency: Virginia DOT, Smart Traffic Center

1. How many ramp meters does your agency operate?
   The Northern Virginia Smart Traffic Center currently operates 26 ramp meters, all inside the Washington Beltway on I-66 and I-395. The meters have been in place for some time.

2. In what situations are they used? What types are used (fixed or adaptive)?
   Used in areas where both mainline and ramp volumes are high. Ramps are used exclusively during rush hours. Ramps are all traffic responsive with mainline sensing loops.

3. What were the criteria for implementation?
   Did not used to have specific criteria for implementation and that caused problems in a few places, mainly due to insufficient storage causing significant delays on side streets. Now have criteria in place based on mainline volumes, ramp volumes, and available storage. This has worked better and there have been fewer problems since.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
   Yes. A study was performed many years ago that showed some improvement in freeway speeds with ramp meters. Copy was not available, but he said most current ramp meter use is based on anecdotal observations. They have observed operations with meters turned on and off and found that meters do improve conditions significantly.

5. What has been public reaction to the ramp meters? Enforcement problems?
   "All negative" He said people don't typically like them but will accept them as long as the operating agency is judicious in their use. No enforcement problems to speak of, but he felt that is because they try to limit their use to only the very peak times. When they do receive complaints they look at whether or not they can change the times of use to address them.

6. What have been your average installation costs? Annual maintenance costs?
   Field hardware alone may only be $10-$15k, but that does not include communications and associated control hardware or software. Hard to put a number on average installation cost because it depends what portion of the communication infrastructure is already out there. Annual maintenance costs can run anywhere from $2000 - $6000 per year per ramp meter.

7. Have you removed any meters? Had major problems with them?
   No, have not removed any but have restricted times of use in response to complaints.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?

Overall experience has been good, but there are no plans to expand coverage of ramp meters. Ramp volumes in other parts of the corridors are generally very high and there is insufficient storage space to stack vehicles on the arterials. They are afraid that if they tried to put in any new meters they would be forced to turn them off soon after because of excessive delays/congestion on arterials.

1. How many ramp meters does your agency operate?
All ramp meters are in Seattle area, although they are soon to expand into the Tacoma area. First pre-timed meters were installed in the late 60's. First adaptive meters installed in the early 80's. More than 100 now in operation, all adaptive control.

2. In what situations are they used? What types are used (fixed or adaptive)?
All meters are adaptive now, although early meters were pre-timed. They have recently switched to fuzzy logic control, which takes into account speed, delays, and queues when setting metering rates. Fuzzy logic has smoothed metering rates, which had a tendency to jump around abruptly.

3. What were the criteria for implementation?
No specific criteria, although they meter entire corridors rather than specific sites since meters tend to drive motorists to un-metered ramps. They activate meters based on traffic volumes and speeds and shut them down as soon as they are no longer needed. On/off decision is from a central control center. They have found the practice of using them only when needed is good for public acceptance.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
Yes, very effective. Studies are available at:
http://www.wsdot.wa.gov/regions/northwest/traffic/tsmc/RampMeters/

5. What has been public reaction to the ramp meters? Enforcement problems?
Public acceptance is good. Public has even requested ramp meters at some locations. Overall compliance is good, although most violations occur at HOV bypass lanes. Seattle uses HOV lanes at all meters, partly to ensure emergency vehicle access.

6. What have been your average installation costs? Annual maintenance costs?
DOT policy is to install ITS surveillance systems first and then upgrade to ramp meters, so the incremental cost is not large, on the order of a few thousand dollars. To install a complete meter at a new location would range between $30,000 and $50,000. Annual maintenance costs average between $2,000 and $3,000 per year, with knocked over poles being the biggest expense.

7. Have you removed any meters? Had major problems with them?
No. They respond to public complaints by trying to be more careful about when the meters are turned on and off. Very often, adjusting or restricting the times of meter use will satisfy public complaints. Agency tries to be flexible with meter use and recognize needs at each site.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?
   Very good experience and the agency intends to expand coverage. Next area for use will be the Tacoma region. Additional corridors in Seattle will be added as needed.

   They stressed the importance of teaching the public the benefits of ramp metering. The public will see delays but need to understand that overall delays are less. Also need to explain that congestion will continue to increase with or without ramp meters, but congestion and delays will be less than they would be without meters.

Ramp Metering Survey Questions Agency: Wisconsin DOT

1. How many ramp meters does your agency operate?
Approximately 110 ramp meters, all in the Milwaukee or Madison metro areas, part of the MONITOR program that also includes cameras and VMS.

2. In what situations are they used? What types are used (fixed or adaptive)?

3. What were the criteria for implementation?
Currently deployed primarily in Milwaukee area. Criteria include volumes and current congestion and whether ramp geometry permits effective use of ramps. Some meters are added only after ramps have been modified as part of larger freeway projects.

4. In your agency's view, have they been effective? Has your agency performed any impact studies and are copies available?
Study of ramp meter effectiveness nearing completion, performed by University of Wisconsin at Milwaukee. Study is focusing on crash reduction, congestion reduction, and effects of ramp meters on driver behavior (i.e., diversion to other facilities).

5. What has been public reaction to the ramp meters? Enforcement problems?
Public reaction has generally been favorable. No enforcement problems that they are aware of.

6. What have been your average installation costs? Annual maintenance costs?

7. Have you removed any meters? Had major problems with them?
No major problems. No meters have been removed. Have adjusted times of operation or limited operations for a few in response to complaints.

8. How would you characterize your overall experience with ramp meters? Does your agency plan to implement more in the future?
Good. System will be expanded as part of larger highway projects.