EVALUATION OF RAMP METERING ON MADISON BELTLINE

FINAL REPORT

Prepared for

Wisconsin Department of Transportation

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By

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Executive Summary

The Wisconsin Department of Transportation (WisDOT) implemented ramp metering along the Beltline Highway in Dane County, Wisconsin in July 2001. This report summarized several research activities that evaluated the impact of ramp metering on the Madison Beltline.

Ramp meters are traffic signals located at the entrance ramps of freeways, which regulate the number of vehicles entering US 12/14/18/151 (commonly known as the Madison Beltline) from entrance ramps during periods of heavy traffic volume in order to maintain a non-congested, safer flow of freeway mainline traffic. There are five ramp meter locations along the Madison Beltline:

- Park Street WB (S-W)
- Park Street WB (N-W)
- Fish Hatchery Road WB (S-W)
- Fish Hatchery Road WB (N-W)
- Whitney Way EB

The ramp meters operate during the morning (6:30AM – 8AM) and afternoon (3PM – 6PM) peak periods. The ramp metering pilot program map is illustrated in Figure E.1.

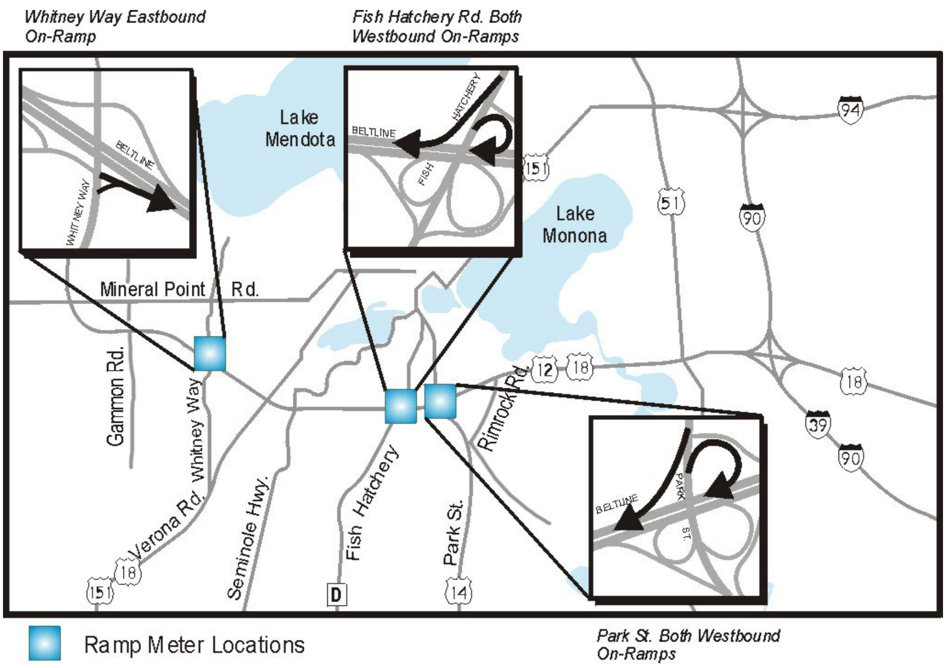


FIGURE E.1 RAMP METERING PILOT PROJECT ON MADISON BELTLINE

This report measures the qualitative and quantitative impact of ramp metering according to a number of pre-defined goals and objectives, including travel time, traffic flow, safety, public perception and air quality. The Measures of Effectiveness (MOEs) are defined based on incident management, motorist travel times, and user acceptance. The MOEs are assessed through the use of volume and travel time data, CORSIM simulation, agency surveys, and motorist surveys. The data was collected before and after ramp metering was implemented on the Madison Beltline. A computer-based traffic model, CORSIM, simulated traffic and traffic control systems using commonly accepted vehicle and driver behavior models. A summary of the ramp meter evaluation findings are shown in Table E.1:

Table E.1: Summary of Evaluation Findings

Evaluation Objective	Measures of Effectiveness
Reduce the number of crashes.	▪ While the entire Beltline from Stoughton Road to Old Sauk experienced a 57% reduction in crashes, the area identified as the eastbound ramp meter influence zone near Whitney Way experienced a significant reduction in crashes during metered and non-metered periods (86% for both periods). ▪ The westbound ramp meter influence zone in the vicinity of Park and Fish Hatchery showed a reduction in 50% of crashes during metered time periods, and an overall reduction of 27%.
Improve the ability to mitigate effects of traffic incidents.	▪ Results from the agency survey of law enforcement and transit personnel indicate that ramp metering contributes to a quick response to and clearing of incidents. ▪ About 96% of agency users found the time to clear accidents has improved because of the introduction of ramp meters along the Beltline. ▪ Approximately 64% of the agency respondents found that the time to respond to accidents has improved with ramp metering. ▪ Simulation shows that ramp meters can reduce delay by as much as 15% during a traffic incident.
Reduce average travel delay and improve the reliability and predictability of travel.	▪ Despite significant growth in traffic volumes, travel times increased slightly during three of the four metering periods, with a slight reduction in the westbound AM metering period. ▪ With the exception of the PM westbound metering period, ramp meters have generally been able to assist in maintaining consistent localized travel times (i.e., in the vicinity of the ramp meter location). ▪ Simulation indicates that ramp meters can reduce travel time delay by over 20% (over a 2-hour simulation period).
Maintain existing balance between freeway and arterial traffic loading.	▪ The Beltline has experienced significant growth in traffic. ▪ Results from the ramp counts indicate that motorists at some locations are seeking alternative routes to avoid using the metered ramps. ▪ Travel times on arterial roadways were not adversely impacted, with some showing a slight increase and others a slight decrease.
Reduce travel time variance and reliability across time and space.	▪ Three out of the four travel periods experienced a lower variability in travel speeds. ▪ The most significant finding is in the Westbound AM period where the variation of travel speeds was reduced from +/-10.9 seconds down to +/-3.8 seconds after ramp metering. ▪ The largest variations before and after ramp metering continue to be observed in the vicinity of Seminole and Verona.
Reduce vehicle emissions and improve air quality.	▪ Simulation shows a slight reduction in emissions after ramp meter installation ranging from 1-4%.
Reduce fuel consumption.	▪ Simulation shows a slight increase in overall fuel consumption (8%) and a slight increase in fuel efficiency (6%).
Improve motorist perception of the program.	▪ Most motorists feel they are waiting in the ramp meter queue longer than they actually experience. On average, motorists felt they waited approximately 30 seconds longer than actually measured in the field. ▪ Feedback from the driver survey indicates that the overall perception of ramp metering is mixed. Respondents noticed an improvement during rush hour traffic, since it is easier to get on the Beltline and entering traffic has a more controlled, paced flow. ▪ Only one in five respondents indicated they not understand, or where not aware of the HOV lanes.
Encourage driver compliance and reduce the violation rate.	▪ SOV lanes violations ranged from 0-10% while HOV lanes experienced a much higher violation rate of 5-35%. ▪ Approximately 61% of officers indicated that more than half of motorists complied with the ramp meters.
Reduce delay costs.	▪ Using the delay calculated savings from simulation; ramp meters have contributed to an overall delay savings of over $4,300 per hour (during peak travel hours).

The reason evaluation findings are somewhat mixed may be due to the limited installation of ramp meters along the Madison Beltline. As observed in other parts of the country, the maximum benefits of ramp meters can be realized when installed as a system, where vehicles do not divert to an un-metered ramp immediately downstream to gain access to the facility. If WisDOT considers ramp meters as a future strategy to enhance safety and mobility in the Madison area, a minimum of 3-4 consecutive on-ramps should be metered to maximize the use available freeway capacity.

1. INTRODUCTION

1.1 Background

In the past decade, urban growth and development patterns have placed a tremendous burden on freeways in most metropolitan areas of the country. In many cases, it is not uncommon for traffic to reach a stop-and-go state, especially during peak periods. These conditions may persist for hours and can compromise motorist safety in addition to imposing a tremendous cost to society in terms of lost time, increased fuel consumption and emissions.

Transportation agencies around the country have implemented a variety of measures to mitigate freeway traffic congestion, including ramp metering. Various forms of ramp control were implemented during the late 1950s and 1960s in Chicago, Detroit and Los Angeles. By early 1990s, ramp metering existed in about 30 metropolitan areas within the United States, along with other cities around the world.

In Wisconsin, ramp meters were first installed on a limited basis on the Milwaukee metropolitan freeway system in 1969, and installed on a system-wide basis in 1994 under the initial build-out of the MONITOR Freeway Traffic Management System. Currently, there are approximately 120 ramp meters in operation on Milwaukee metropolitan freeways.

The Madison Beltline

Serving as the main arterial linking Southwest Wisconsin to the national and state transportation system, the Beltline (US 12/14/18/151) is essential to Madison's quality of life and economic vitality. The west Beltline serves as not only the dominant west-side route for travel in the Madison area, but also as the gateway used by most outlying motorists to travel to central Madison.

Traffic on the west Beltline has been growing at an explosive rate of two to six times the state average. The importance of the route on a local, state and national level has led to "growing pains" for both motorized and non-motorized travel, and created an urgent need for safety and congestion improvements.

Based on a previously completed Wisconsin Department of Transportation (WisDOT) Study it was observed that:

- From 27,000 vehicles per day in 1967, Madison area growth has raised Beltline traffic volumes to 120,000 vehicles per day in 2000. During that period, the Madison area has enjoyed an efficient transportation corridor that moves people, goods and services from one side of town to another without serious delays.
- Most of the Beltline reaches its capacity during the morning and evening rush hours, and Beltline traffic volumes are projected to grow up to 136,000 by 2020. This will cause increased congestion and an extension of the morning and evening rush hours.
- The westbound Beltline from Todd Drive to Whitney Way regularly experiences congestion during the morning and evening rush hours. This contributes to a higher than normal crash rate for the area.

To improve safety and traffic flow on the Beltline, the WisDOT installed five ramp meters on the Madison Beltline in July 2001. These meters operate only during the morning and afternoon rush hours. Figure 1.1 illustrates the ramp metering pilot program locations along the Beltline.

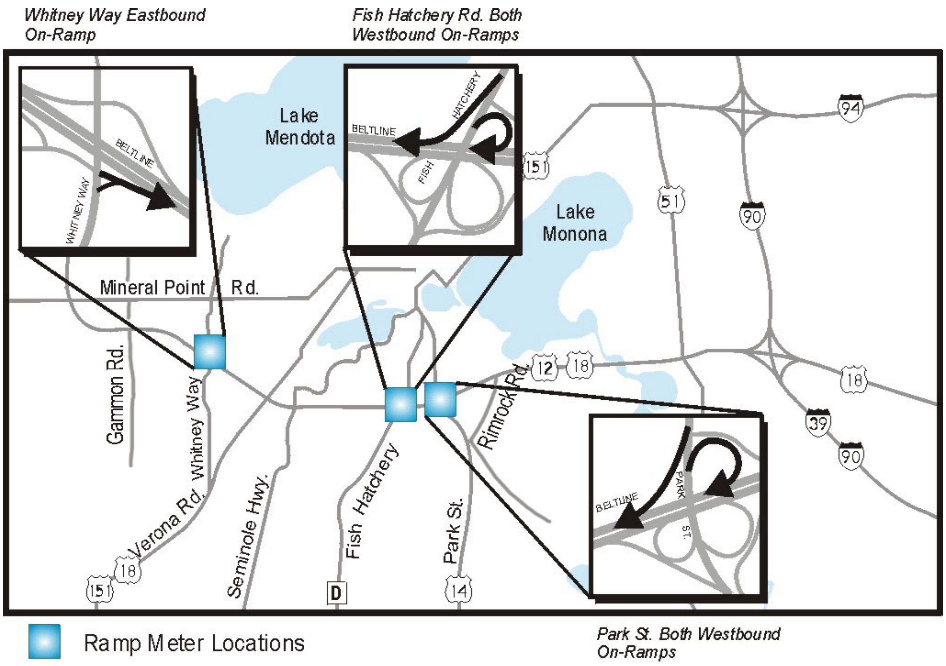


Figure 1-1 Ramp Metering Pilot Project on Madison Beltline

1.2 Evaluation Objectives and Performance Measures

The objectives of the Beltline Ramp Metering Pilot Project and related performance measures of the evaluation include:

1. Improve transportation safety.
    a. Reduce the number of crashes.
    b. Improve the ability to reduce effects of traffic incidents.
2. Enhance transportation productivity.
    a. Reduce travel delay and improve the reliability and predictability of moving people and goods for all transportation users.
    b. Maintain existing balance between freeway and arterial traffic loading.
3. Enhance the quality and efficiency of travel.
    a. Improve traffic speed uniformity across space and time.
    b. Reduce vehicle emissions.
    c. Reduce fuel consumption.
4. Determine user acceptance.
    a. Develop a positive user perception of effectiveness and benefits of program.
    b. Encourage driver compliance and reduce the violation rate.
5. Develop a transportation management system that most effectively supports the optimal deployment of appropriate technologies.
    a. Reduce delay costs.

1.3 Organization of Report

The report is organized into several sections:

1. **Section 1. Introduction -** Provides background information on the rationale for the Madison Ramp Metering Project including objectives and supporting evaluation performance measures.
2. **Section 2. Field Data Collection -** Includes discussion on the data collected to support analysis of the performance measures.
3. **Section 3. Traffic Data Analysis -** Described results of the analysis of before and after data collected in the field and attached in Appendices A and B.
4. **Section 4. Traffic Simulation Analysis -** Included discussion related to the analysis performed using the CORSIM microsimulation model.
5. **Section 5. User Perception And Agency Survey Analysis –** Provides insight into the ramp meter portion of the Dane County Driver Survey.
6. **Section 6. Conclusions and Recommendations -** Provides a summary of the evaluation findings and offers suggestions for future evaluation and research activities related to ramp meters.
7. **Appendices –** Includes before and after data collection reports and CORSIM set-up information.

2. Field Data Collection

Researchers and transportation engineering students at the University of Wisconsin-Madison collected data to properly evaluate ramp metering using various performance measures. Numerous city, county and state agencies cooperated in the data collection including input from the general public through representative surveys of Dane County drivers. The CORSIM simulation model was also used to determine changes before and after ramp metering implementation.

2.1 Traffic Volumes

Mainline traffic volume data was collected using 10 video cameras in April 2000 and Traffic Condition Cameras provided by WisDOT District 1 positioned at five locations along the Beltline in April 2002. These video tapes were analyzed by UW-Madison transportation engineering students who compiled peak hour traffic volumes. The locations are indicated below:

1. EB Beltline, West of Rimrock Road Exit
2. WB Beltline, West of Rimrock Road Exit
3. EB Beltline, East of Park Street Exit
4. WB Beltline, East of Park Street Exit
5. EB Beltline, West of Park Street Exit
6. WB Beltline, West of Park Street Exit
7. EB Beltline, East of Fish Hatchery Road Exit
8. EB Beltline, West of Seminole Highway Exit
9. WB Beltline, West of Seminole Highway Exit
10. EB Beltline, West of Verona Road Exit

The traffic volumes were collected for 8 days during the morning peak hours of 7 AM – 9 AM and the afternoon peak hours of 4 PM – 6 PM. The before and after traffic volume data is located in Appendices A and B.

2.2 Travel Times

Travel times were collected by UW-Madison transportation engineering students along the Beltline between Mineral Point Road and Rimrock Road in April 2000 and April 2002, respectively. Travel time runs were recorded for both eastbound and westbound directions using the floating car method. Data was collected for 10 days between the morning peak hours of 7 AM – 9 AM and the afternoon peak hours of 4 PM – 6 PM.

Additional travel time data was collected on eight key side-street facilities listed below in April 2000 and April 2002, respectively:

1. McKee Road: Verona Road to Fish Hatchery Road
2. Hammersley Road: Whitney Way to Verona Road
3. Fish Hatchery Road: Park Street to McKee Road
4. South Service Road: Fish Hatchery Road to Verona Road
5. Damon Road (North Service Road): Fish Hatchery Road to Todd Drive
6. Odana Road: Whitney Way to Nakoma Road

7. Whitney Way: Mineral Point Road to Raymond Road
8. Verona / Nakoma Road: Odana Road to McKee Road

The travel time runs were performed for both eastbound and westbound directions along the roadway. Travel time data was collected during the morning peak hours of 7 AM – 9 AM and the afternoon peak hours of 4 PM – 6 PM for each side-street facility using the floating car method. Before and after travel time data is located in Appendices A and B.

2.3 Crash Data

The safety component of the evaluation analyzes the relationship between WisDOT DMV crash database records and the ramp meters installed at the five locations on the West Beltline Highway in Dane County.

There are two sets of data that have been compared in this study. Crash information collected between January 1999 and the end of December 2000 is considered the before data. The after data set includes crash information collected between January 2002 and the end of December 2003.

Ramp Meter Influence Zone and Locations
The ramp meters in this study were located at Park Street, Fish Hatchery Road, and Whitney Way. Table 2-1 shows the influence zone length assumed for locations upstream and downstream of the ramp meter merge locations. The influence zone was established using similar techniques used in other ramp meter studies from around the country. Table 2-2 identifies the reference points and associated cumulative mile identifiers extracted from the State Trunk Highway Log, which catalogs most roadway features along state highways in Wisconsin.

Table 2-1 Ramp Meter Influence Zone

Influence Zone Length	feet	mile
upstream	2000	0.379
downstream	1200	0.227

Table 2-2 Ramp Meter Influence Zone

Ramp	Merge Location		Upstream		Downstream	
	RP*	CM**	RP	CM	RP	CM
Park Street WB (S-W)	347+00	12.79	348+0.54	12.41	347+0.23	13.02
Park Street WB (N-W)	347+31	13.10	347G+09	12.72	347+0.54	13.33
Fish Hatchery Road WB (S-W)	347+0.58	13.37	347+0.20	12.99	346+0.20	13.60
Fish Hatchery Road WB (N-W)	346+0.10	13.50	347+0.33	13.12	346+0.33	13.73
Whitney Way EB	340+0.30	43.31	338+1.54	42.93	340+0.53	43.54

* RP = Reference Point from State Trunk Highway Log
** CM = Cumulative Mile Reference from State Trunk Highway Log
Note: Due to the close proximity of the westbound ramp meter locations, a single influence zone has been defined including the location upstream of the S-W ramp at Park and the location downstream from the N-W ramp at Fish Hatchery (i.e., CM 12.41 to CM1 3.70).

Information from the WisDOT Division of Motor Vehicles crash database have been used to assess before and after safety impacts of the ramp meters. A complete listing of crash data is located in Appendix C.

2.4 Ramp Delay and Compliance

As part of the overall evaluation, studies were conducted to determine both ramp delay times and the percentage of drivers that violate ramp metering.

Ramp travel times were collected using both the “floating car” technique and video cameras. The ramp travel time refers to the duration of travel time from the beginning of the ramp to the end of the ramp metering signal point. This definition is used to measure the impact of the ramp meters on ramp travel time and delay.

On-ramp traffic volumes and ramp signal violations were collected for morning and afternoon peak hour periods using manual counts of 15-minute intervals. Ramp meter locations with both SOV and HOV lanes were treated separately for each lane type. Vehicles that did not stop for a metered red light in an SOV lane constituted an SOV lane violation. Similarly, a vehicle that did not stop at a metered red light in an HOV lane constituted an HOV lane violation. An HOV violation also included the presence of any passenger vehicle or truck containing less than two people. For statistical analysis purposes, data for each ramp was collected for three consecutive weekdays (Tuesday-Thursday) during October 2001.

2.5 Traffic Control Data

Within the project limits a variety of traffic control data was collected including locations of traffic signals, ramp meters, stop/yield signs, and posted speed limits.

2.6 Geometric Data

To assist with the coding of the CORSIM simulation model a variety of as-built information was collected for a section of the Beltline Highway from Park Street to Gammon Road. The basic information required for coding the geometrics within the CORSIM model include number of lanes, taper types, and horizontal/vertical curves.

2.7 Dane County Driver and Agency Survey Data

A before and after survey containing a subset of questions related to ramp meters was analyzed to assess motorist perceptions. The overall purpose of the survey was to: 1) assess drivers’ opinions on travel conditions in Dane County, 2) investigate the extent of drivers’ knowledge regarding general freeway issues, and 3) determine user awareness and perception of the Dane County Incident Management Program. The Before and After Dane County Driver Survey is located in Appendix F.

To assess agency perception of the effectiveness of ramp metering, a survey was administered to the following transportation and law enforcement agencies: the Wisconsin State Patrol-District 1 (based in DeForest), Madison Police Department, Dane County 911 and Madison Metro Transit.

3. TRAFFIC DATA ANALYSIS

3.1 Analysis MOEs

Table 3-1 indicates the evaluation objectives, the corresponding measure of effectiveness (MOE), the evaluation approach, and associated report section that discussed the evaluation findings.

Table 3-1 Measures of Effectiveness

Evaluation Objectives	MOE	Evaluation Approach	Report Section
1.a. Reduce the number of crashes.	Number of Crashes	The incident clearance reports from 911 were used to compare the number of crashes at merging points and other locations on the Beltline before and after ramp meter implementation.	3.2
1.b. Improve the ability to mitigate effects of traffic incidents.	Delay Due to Incidents	The CORSIM simulation model was used to evaluate the change of incident-related delay before and after ramp meter implementation.	4.4
2.a Reduce average travel delay and improve the reliability and predictability of travel.	Average Travel Time	Volume and travel time data were recorded on ramps, mainline and side streets in order to determine travel time and delay changes before and after ramp meter implementation.	3.3, 3.4, and 3.5
2.b. Maintain existing balance between freeway and arterial traffic loading.	Traffic Volume on Freeway and Arterials	Traffic volume on freeway and arterials were recorded to determine the change before and after ramp meter implementation.	3.3 and 3.4
3.a. Reduce travel time variance and reliability across time and space.	Variance in Travel Time	The mean and variance change of travel times were analyzed before and after ramp meter implementation.	3.3
3.b. Reduce vehicle emissions and improve air quality.	Emissions Rate	The CORSIM simulation model was used to evaluate vehicle emission and air quality before and after ramp meter implementation.	4.5
3.c. Reduce fuel consumption.	Fuel Consumption	The CORSIM simulation model was used to evaluate vehicle fuel consumption ramp meter implementation.	4.6
4.a. Improve motorist perception of the program.	User Acceptance	A user survey was sent to motorists in the Beltline Corridor in order to determine perception of ramp metering.	5.1 and 5.2
4.b. Encourage driver compliance and reduce the violation rate.	Violation and Enforcement Rates	The number of violations of ramp meters were studied for several sample time periods to determine the violation rate. Using the records of local law enforcement agencies, the rate of enforcement was also determined.	3.4
5.a. Reduce delay costs.	Delay Cost	The CORSIM model was used to evaluate delay cost for the Beltline Corridor before and after ramp meter implementation.	4.7

3.2 Traffic Crashes

One of the principal objectives of ramp metering is to improve traffic safety, and the most relevant measure of this objective is the number of traffic incidents reported on the Beltline. The safety component of the evaluation analyzes the relationship between WisDOT DMV crash database records and the ramp meters installed at the five on-ramp locations (i.e., the influence zones) on the west Beltline Highway in Dane County.

There are two sets of data that have been compared in this study. Crash information collected between January 1999 and the end of December 2000 is considered the before data. The after data set includes crash information collected between January 2002 and the end of December 2003. Table 3-2 shows a summary of the crash data along the Madison Beltline and the influence areas in the vicinity of the ramp meters.

Table 3-2 Before and After Crash Analysis

Total Crashes on Madison Beltline (Stoughton Road to Old Sauk Road)
1999-2002

	Property Damage	Injury	Total
1999	133	77	210
2000	142	98	240
TOTAL Before	275	175	450
2002	56	43	99
2003	33	61	94
TOTAL After	89	104	193
Change	-186	-71	-257
% Change	-67.6%	-40.6%	-57.1%

Total Crashes in Ramp Meter Influence Zone
Eastbound at Whitney Way
1999-2002

	Property Damage	Injury	Total
1999	14	9	23
2000	13	14	27
TOTAL Before	27	23	50
2002	0	1	1
2003	3	3	6
TOTAL After	3	4	7
Change	-24	-19	-43
% Change	-88.9%	-82.6%	-86.0%

Total Crashes in Ramp Meter Influence Zone during Metering Periods
Eastbound at Whitney Way
1999-2002

	Property Damage	Injury	Total
1999	8	4	12
2000	6	4	10
TOTAL Before	14	8	22
2002	0	1	1
2003	2	0	2
TOTAL After	2	1	3
Change	-12	-7	-19
% Change	-85.7%	-87.5%	-86.4%

Total Crashes in Ramp Meter Influence Zone
Westbound at Park / Fish Hatchery
1999-2002

	Property Damage	Injury	Total
1999	6	4	10
2000	7	5	12
TOTAL Before	13	9	22
2002	3	3	6
2003	8	2	10
TOTAL After	11	5	16
Change	-2	-4	-6
% Change	-15.4%	-44.4%	-27.3%

Total Crashes in Ramp Meter Influence Zone during Metering Periods
Westbound at Park / Fish Hatchery
1999-2002

	Property Damage	Injury	Total
1999	2	2	4
2000	2	2	4
TOTAL Before	4	4	8
2002	0	2	2
2003	2	0	2
TOTAL After	2	2	4
Change	-2	-2	-2
% Change	-50%	-50%	-50%

Findings

The analysis of crash data two years before and two years after installation of ramp meters and associated roadway geometric enhancements (i.e., lengthened tapers) have contributed to positive safety impacts along the Madison Beltline. While the entire Beltline from Stoughton Road to Old Sauk experienced a 57% reduction in crashes, the area identified as the eastbound ramp meter influence zone near Whitney Way experienced a significant reduction in crashes during metered and non-metered periods (86% for both periods). The westbound ramp meter influence zone in the vicinity of Park and Fish Hatchery showed a slight reduction in crashes during non-metered (27%) and metered periods (50%).

A complete listing of crash data used for the evaluation is located in Appendix C.

3.3 Travel Time and Traffic Volumes

Overall Travel Time Comparison
For the roadway section from Rimrock Road to Gammon Road, the average total travel time and percent change before and after installation of ramp meters are provided in Table 3-3.

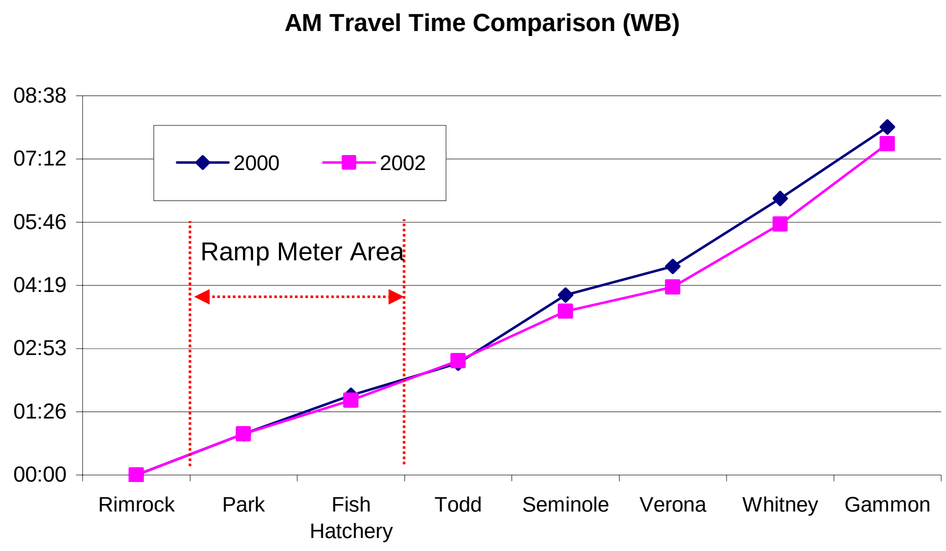
Table 3-3 Average Beltline Travel Time Changes Before and After Ramp Metering (min:sec)

Direction	Before AM	After AM	Change	% Change	Before PM	After PM	Change	% Change
Eastbound (Gammon to Rimrock)	6:44	7:15	+ 0:31	+7.8%	7:01	7:51	+0:50	+12.1%
Westbound (Rimrock to Gammon)	7:56	7:33	- 0:23	-4.7%	6:59	7:55	+0:56	+13.4%

*For Average Ramp Wait Times, See Section 4.4

Overall Travel Time Findings
The travel time fluctuations from 2000 to 2002 show a slight increase in the eastbound AM and PM peak periods. The westbound AM peak experienced a slight decrease in travel time, while the westbound PM period experienced a similar increase observed for eastbound travel. The increase in travel time can be attributable to the larger growth of traffic volumes along the Beltline. The ramp meters seem to have contributed slightly to the decrease in travel times during the Westbound AM metering period.

Travel Time Comparison – by Segment
To support a more refined analysis of the potential causes of travel time fluctuations, interim travel times were collected at the major interchanges along the Beltline. Segment oriented travel time information from 2000 and 2002 is compared in the graphs associated with Figures 3-1 and 3-2 and also corresponding data in Table 3-4.



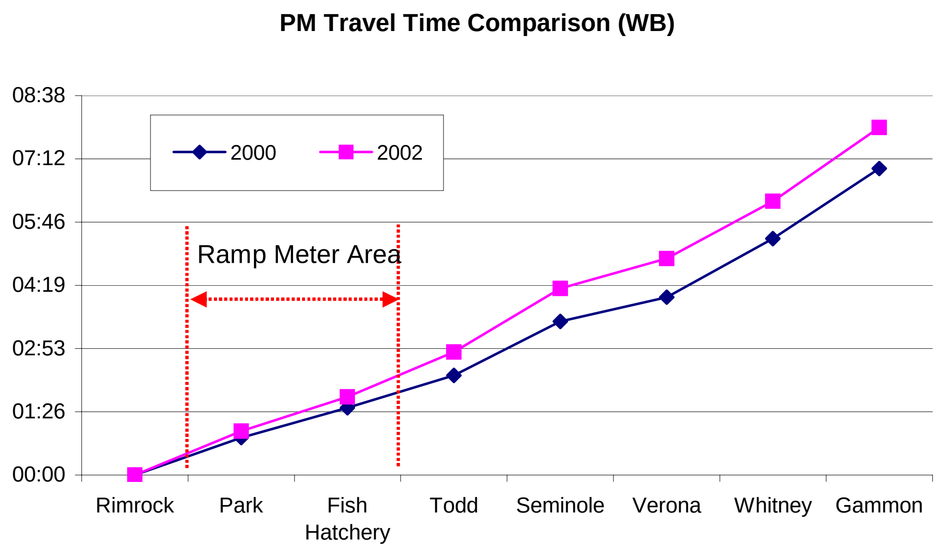


Figure 3-1 Travel Time Comparison for Before and After Ramp Meters (WB)

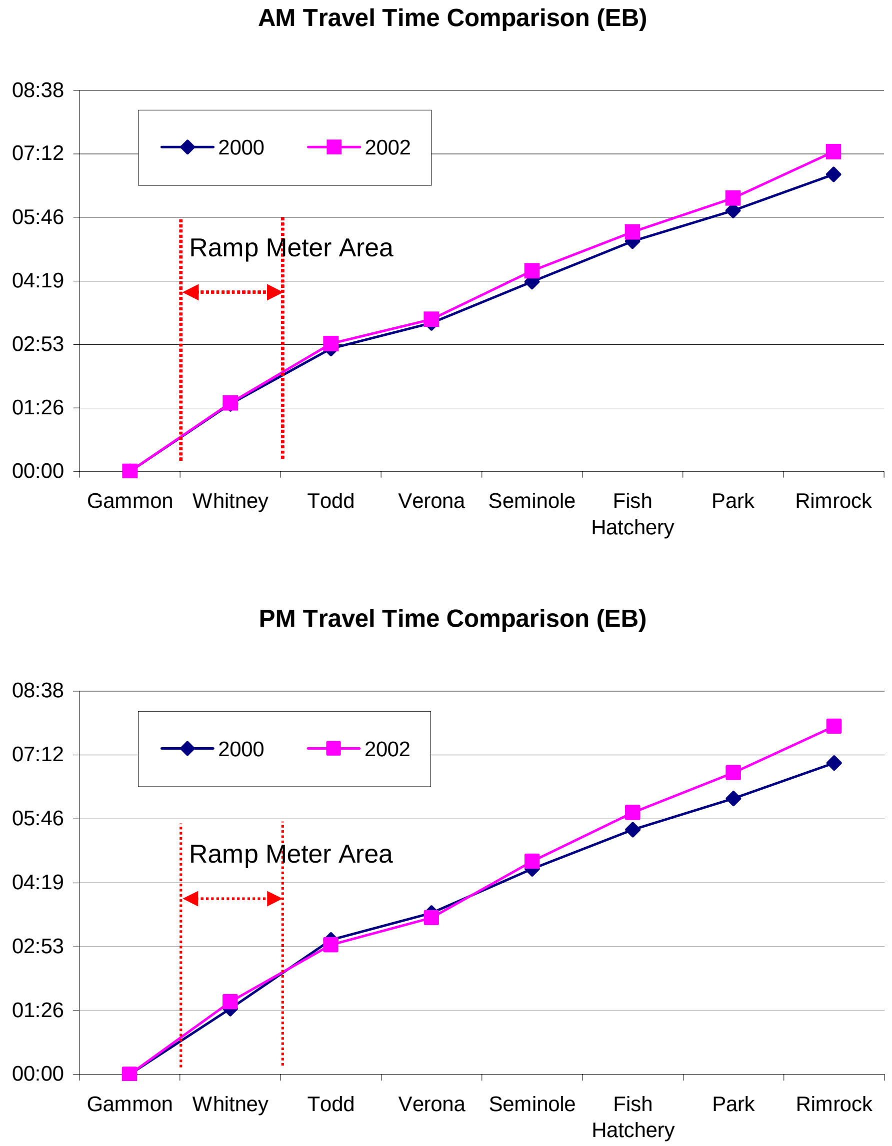


Figure 3-2 Travel Time Comparison for Before and After Ramp Meters (EB)

Table 3-4 Travel Time Changes on Each Section Before and After Ramp Metering (min:sec)

Westbound AM	Before	After	Change
Rimrock	00:00	00:00	-
Park	00:56	00:56	00:00
Fish Hatchery	01:49	01:42	-00:07
Todd	02:33	02:36	+00:03
Seminole	04:06	03:44	-00:22
Verona	04:45	04:17	-00:28
Whitney	06:18	05:43	-00:35
Gammon	07:56	07:33	-00:23

Westbound PM	Before	After	Change
Rimrock	00:00	00:00	
Park	00:51	01:00	+00:09
Fish Hatchery	01:32	01:47	+00:12
Todd	02:16	02:48	+00:32
Seminole	03:30	04:15	+00:45
Verona	04:03	04:56	+00:53
Whitney	05:23	06:14	+00:51
Gammon	06:59	07:55	+00:56

Eastbound AM	Before	After	Change
Gammon	00:00	00:00	-
Whitney	01:32	01:33	+00:01
Todd	02:47	02:54	+00:07
Verona	03:22	03:27	+00:05
Seminole	04:18	04:33	+00:15
Fish Hatchery	05:13	05:26	+00:13
Park	05:55	06:12	+00:17
Rimrock	06:44	07:15	+00:31

Eastbound PM	Before	After	Change
Gammon	00:00	00:00	-
Whitney	01:29	01:38	+00:09
Todd	03:02	02:55	-00:07
Verona	03:38	03:32	-00:06
Seminole	04:38	04:48	+00:12
Fish Hatchery	05:31	05:54	+00:10
Park	06:13	06:48	+00:35
Rimrock	07:01	07:51	+00:50

Travel Time-by Segment Findings

Three of the four metering periods experienced slightly higher travel times, with a slight reduction in the westbound AM metering period. The change in before and after travel times seem to build most greatly in the area around Seminole Highway and Verona Road, where the large increase in traffic volumes and the geometric lane drops have pushed the roadway segment closer to its physical capacity. With the exception of the PM Westbound metering period, ramp meters have generally been able to assist in maintaining consistent localized travel times (i.e., in the vicinity of the ramp meter location).

One of the measures that have been investigated in the study includes whether or not the travel times along the Beltline have become more consistent or stable with the introduction of ramp meters. In other words, do the ramp meters contribute to minimize travel time fluctuations or variations from day to day? The method for determining the variability of trips along the Beltline included calculating the standard deviation of the sample travel time runs. The standard deviation, reported in plus or minus seconds, is reported in Table 3-5.

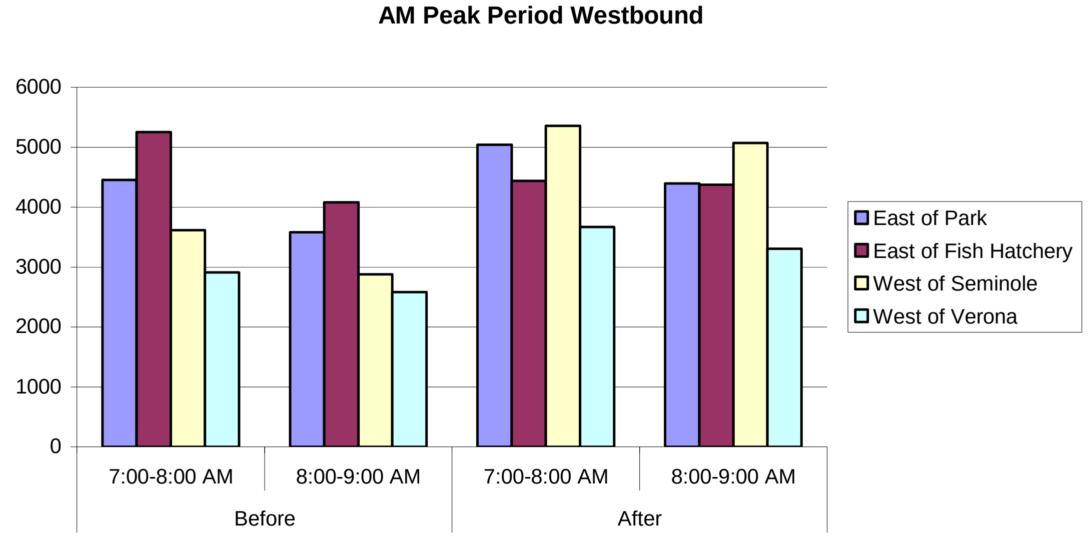
Table 3-5 Travel Time Consistency (+/- seconds)

Direction	Before	After	Change
Westbound AM	10.9	3.8	-7.1
Eastbound AM	13.1	6.8	-6.3
Westbound PM	11.8	6.0	-5.8
Eastbound PM	11.1	15.2	4.1

Three out of the four travel periods experienced a lower variability in travel speeds. The eastbound PM peak period experienced a slight increase of +/- 4.1 seconds. The most significant finding is in Westbound AM period where the variation of travel speeds was reduced from +/- 10.9 seconds down to +/- 3.8 seconds. When the travel time was further examined by segment, the largest variation observations were in the vicinity of Seminole Highway and Verona Road where there are currently no ramp meters.

Traffic Volume Comparison

The mainline traffic volumes on the Madison Beltline are shown in Figure 3-3, Figure 3-4, Table 3-6 and Table 3-7. Table 3.8 shows a variety of average daily traffic (ADT) within the Beltline corridor.



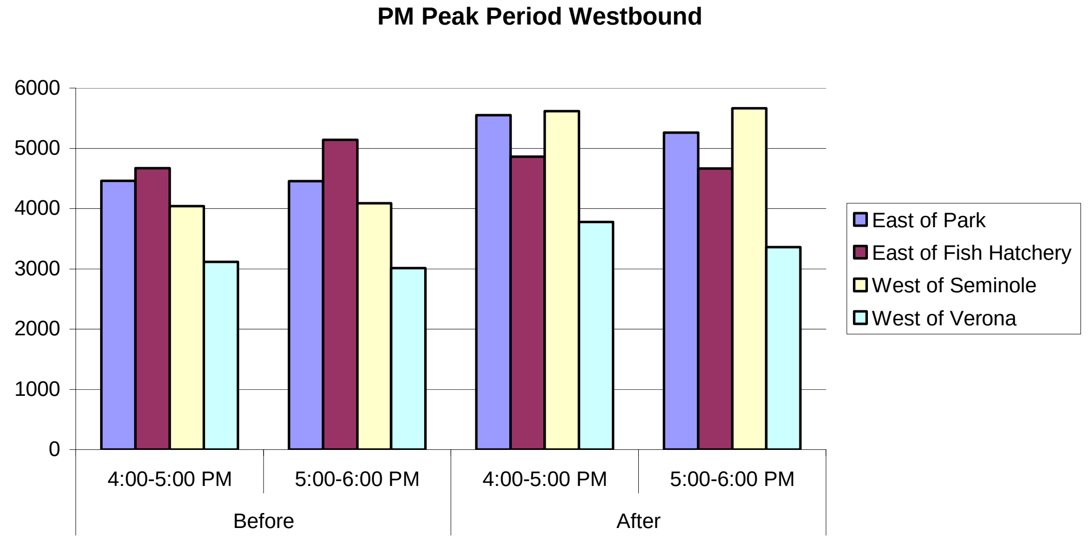
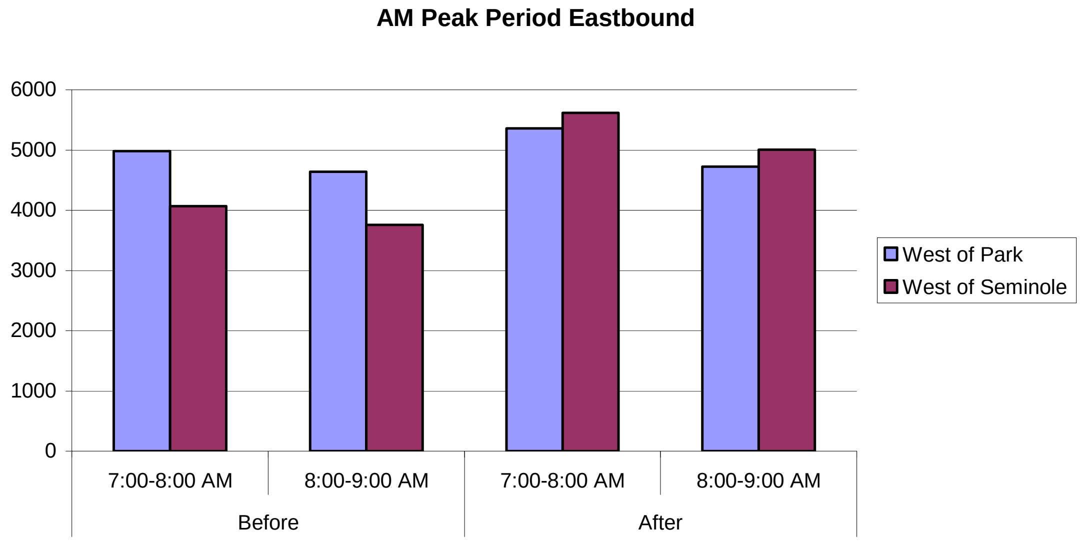


Figure 3-3 Traffic Volume Comparison for Before/After Ramp Meters (Westbound)



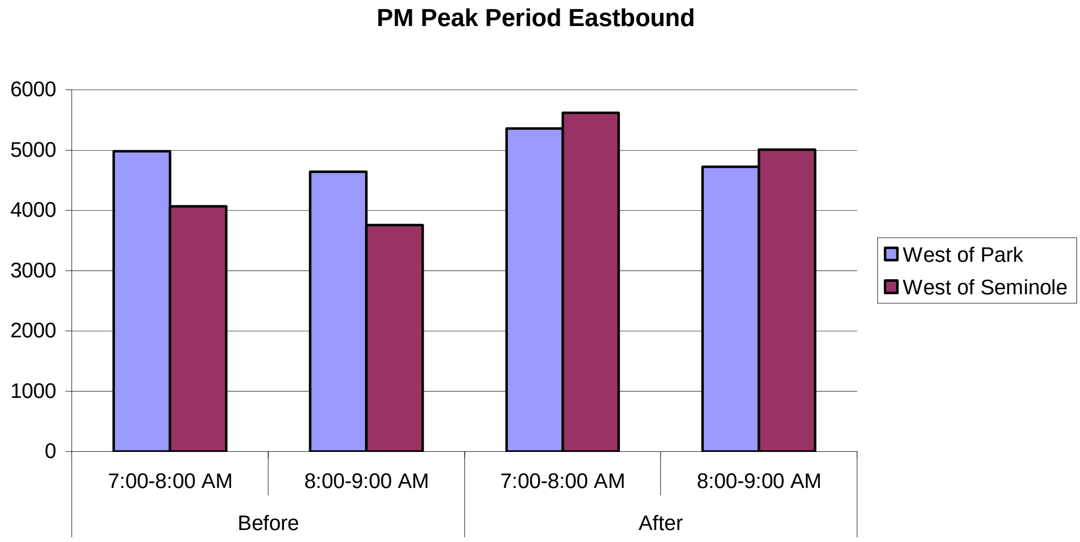


Figure 3-4 Traffic Volume Comparison for Before/After Ramp Meters (Eastbound)

Table 3-6 AM Traffic Volume (vph) Changes Before and After Ramp Metering

Direction	Location	Time	Before	After	Change	Comparison
EB	East of Park	7:00-8:00 AM	4450	5037	+587	13%
	East of Fish Hatchery		5250	4438	-812	-15%
	West of Seminole		3614	5356	+1742	48%
	West of Verona		2910	3669	+759	26%
WB	West of Park		4980	5361	+381	8%
	West of Seminole		4068	5616	+1548	38%

Direction	Location	Time	Before	After	Change	Comparison
EB	East of Park	8:00-9:00 AM	3578	4394	+816	23%
	East of Fish Hatchery		4080	4374	+294	7%
	West of Seminole		2878	5070	+2192	76%
	West of Verona		2580	3306	+726	28%
WB	West of Park		4641	4721	+80	2%
	West of Seminole		3756	5009	+1253	33%

Table 3-7 PM Traffic Volume (vph) Changes Before and After Ramp Metering

Direction	Location	Time	Before	After	Change	Comparison
EB	East of Park	4:00-5:00 PM	4461	5550	+1089	24%
	East of Fish Hatchery		4673	4862	+189	4%
	West of Seminole		4039	5619	+1580	39%
	West of Verona		3116	3778	+662	21%
WB	West of Park		5062	4828	-234	-5%
	West of Seminole		3929	5540	+1611	41%

Direction	Location	Time	Before	After	Change	Comparison
EB	East of Park	5:00-6:00 PM	4457	5259	+802	18%
	East of Fish Hatchery		5144	4667	-477	-9%
	West of Seminole		4089	5664	+1575	39%
	West of Verona		3014	3358	+344	11%
WB	West of Park		4451	4781	+330	7%
	West of Seminole		3841	5794	+1953	51%

Table 3-8 ADT around Hwy 12/18 in Madison

LOCATION	Year	ROAD AADT	EB	WB
USH 12-14 N OF CTH S - MINERAL POINT RD	1999	37094	-	-
USH 12-14 N OF CTH S - MINERAL POINT RD	2000	34633	-	-
USH 12-14 N OF CTH S - MINERAL POINT RD	2001	38029	-	-
USH 12-14 N OF CTH S - MINERAL POINT RD	2002	40675	20422	20253
USH 12-14 N OF CTH S - MINERAL POINT RD	2003	41520	20885	20635
USH 12-18 E OF USH 151 & USH 14 INTERCHANGE	1996	91497	-	-
USH 12-18 E OF USH 151 & USH 14 INTERCHANGE	1999	110760	-	-
USH 12-18 E OF USH 151 & USH 14 INTERCHANGE	2002	117353	58333	59020
USH 12-18 E OF RIMROCK RD	1996	78028	-	-
USH 12-18 E OF RIMROCK RD	1999	97383	-	-
USH 12-18 E OF RIMROCK RD	2002	110637	53777	56860
USH 12-18 BTWN CTH BB & USH 51	1996	75671	-	-
USH 12-18 BTWN CTH BB & USH 51	1999	102989	-	-
USH 12-18 BTWN CTH BB & USH 51	2002	101793	49209	52584

Traffic Volume Findings
Traffic volumes along the Madison Beltline are growing at very rapid rates, especially in the vicinity of Seminole and Verona by nearly 40% and as high as 76% over a two year period. Very few locations observed a decrease in volumes. Observations of large traffic volume increases and the ability for ramp meters to maintain localized travel times suggests the need for a systematic installation along the Beltline corridor to manage travel times.

3.4 Impact of Ramp Metering on Diversion

The introduction of ramp meters along the Madison Beltline suggested that there could be traffic diversion from motorists attempting to avoid waiting to enter the freeway. To that end, a variety of analyses were performed to better understand the impact of ramp meters on surface streets including ramp volume counts, ramp delay measurements, and travel times on possible alternate routes.

Ramp Volume Analysis
Table 3-9 lists the comparison of ramp traffic volumes before and after ramp meter installation.

Table 3-9 Ramp Volume Changes Before and After Ramp Metering

Ramp	AM				PM			
	Before	After	Change	Comparison	Before	After	Change	Comparison
Park Street WB (S-W)	464	854	+390	+84.0%	336	406	+70	+20.8%
Park Street WB (N-W)	406	388	-18	-4.4%	1419	920	-499	-35.2%
Fish Hatchery Road WB (S-W)	1230	603	-627	-51.0%	1547	756	-791	-51.1%
Fish Hatchery Road WB (N-W)	615	694	+79	+12.8%	1429	1476	+47	+3.3%
Whitney Way EB	1800	1812	+12	+0.1%	2731	2710	-21	-0.1%

Ramp Volume Analysis Findings

According to the analysis, ramp traffic volumes decreased after ramp meter installation on the following ramps:

1. SB Park Street to westbound Beltline (N-W ramp),
2. NB Fish Hatchery Road to westbound Beltline (S-W ramp)

Ramp traffic volumes remained similar after ramp meter installation on the following ramps:

1. SB Fish Hatchery Road to westbound Beltline (N-W ramp); and
2. Whitney Way to eastbound Beltline.

Ramp traffic volumes on northbound Park St. to westbound Beltline (S-W ramp) increased. The increase may be due to the fact drivers from South Park St. do not have a reasonable alternate route to gain access to travel westbound on the Beltline.

Ramp Delay

The average ramp travel times are shown in Table 3-10.

Table 3-10 Average Ramp Travel Times (in seconds)

Ramp	AM	PM
Park Street WB (S-W)	80	25
Park Street WB (N-W)	25	20
Fish Hatchery Road WB (S-W)	16	20
Fish Hatchery Road WB (N-W)	20	60
Whitney Way EB	60	50

Ramp Delay Findings

Based on data collected in November 2001, the study concludes that ramp meters do have a significant impact on ramp travel times. For the five ramp meters installed, the average ramp travel times increased and ranged between 16 seconds and 80 seconds during AM and PM peak periods.

Alternate Route Travel Time Analysis

Three logical alternate routes were targeted for investigation. Each case is described below.

Case 1:

Origin: South of Madison
Destination: West Town
Route: Fish Hatchery RD → Beltline →Gammon Rd

Alternate Route 1:
Fish Hatchery RD → Service RD → Todd Dr → Beltline → Gammon RD
Alternate Route 2:
Fish Hatchery RD → Service RD → Verona RD → Beltline → Gammon RD

Alternate Route 3:
Fish Hatchery RD → Service RD → Hammersley RD → Whitney Way → Beltline → Gammon RD
Alternate Route 4:
Fish Hatchery RD → Service RD → Hammersley RD → Gammon RD

Case 2:

Origin: South of Madison
Destination: East Town
Route: Whitney Way → Beltline → East Town

Alternate Route 1:
Whitney Way → Hammersley RD → Verona RD → Beltline → East Town

Case 3:

Original: North of Madison
Destination: West Town
Route: Park Street → Beltline → Gammon RD

Alternate Route 1:
University Ave → Midvale Blvd → Mineral Point RD → Gammon RD
Alternate Route 2:
Park Street → Fish Hatchery RD → Emil St. → Damon RD → Beltline → Gammon RD

Figures 3.4-3.6 illustrate the alternate routes for each case.

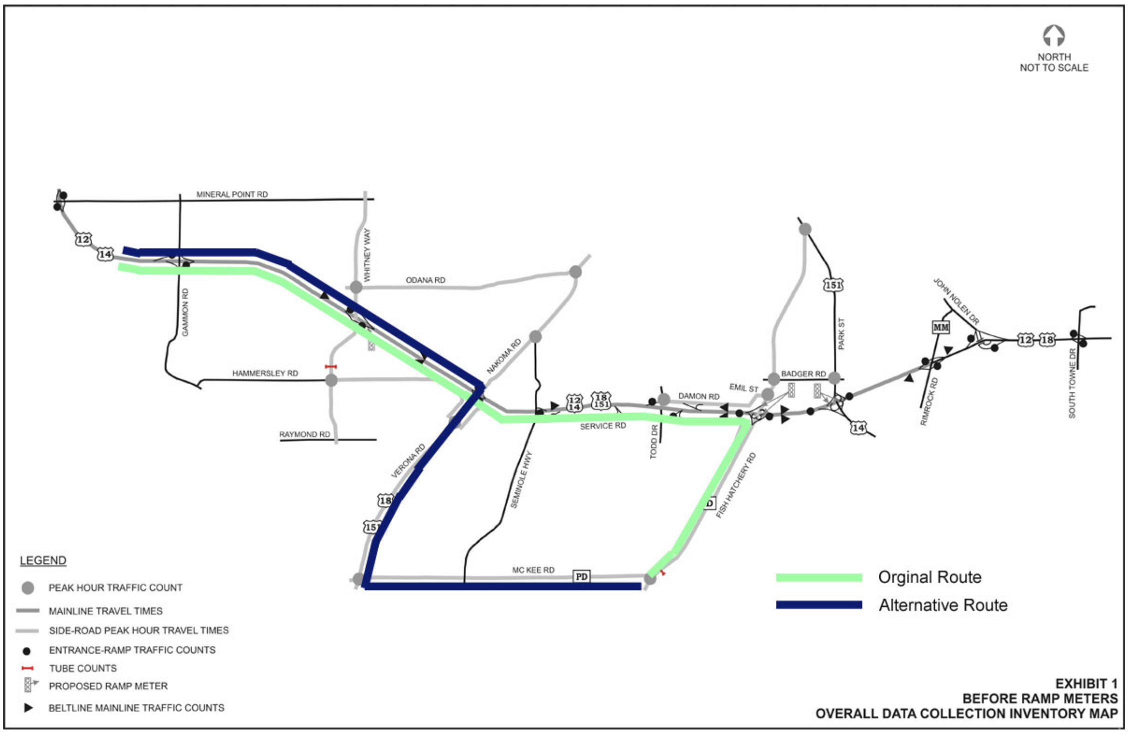


Figure 3-5 Diversion Route Case 1

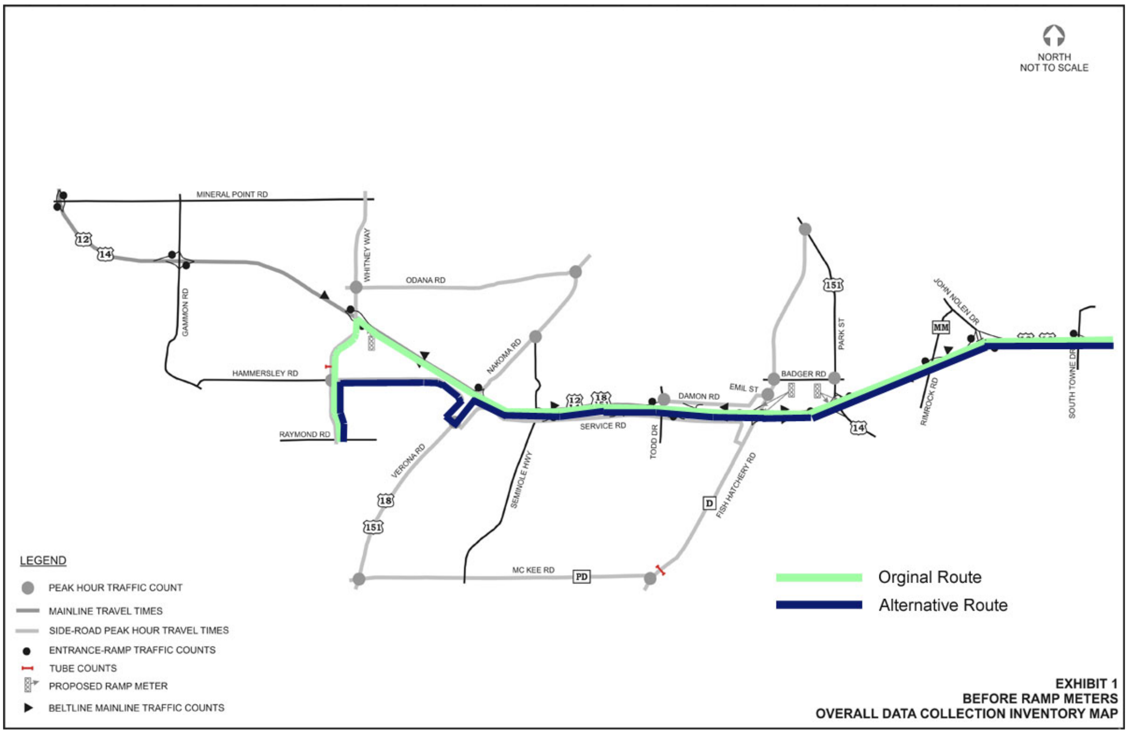


Figure 3-6 Diversion Route Case 2

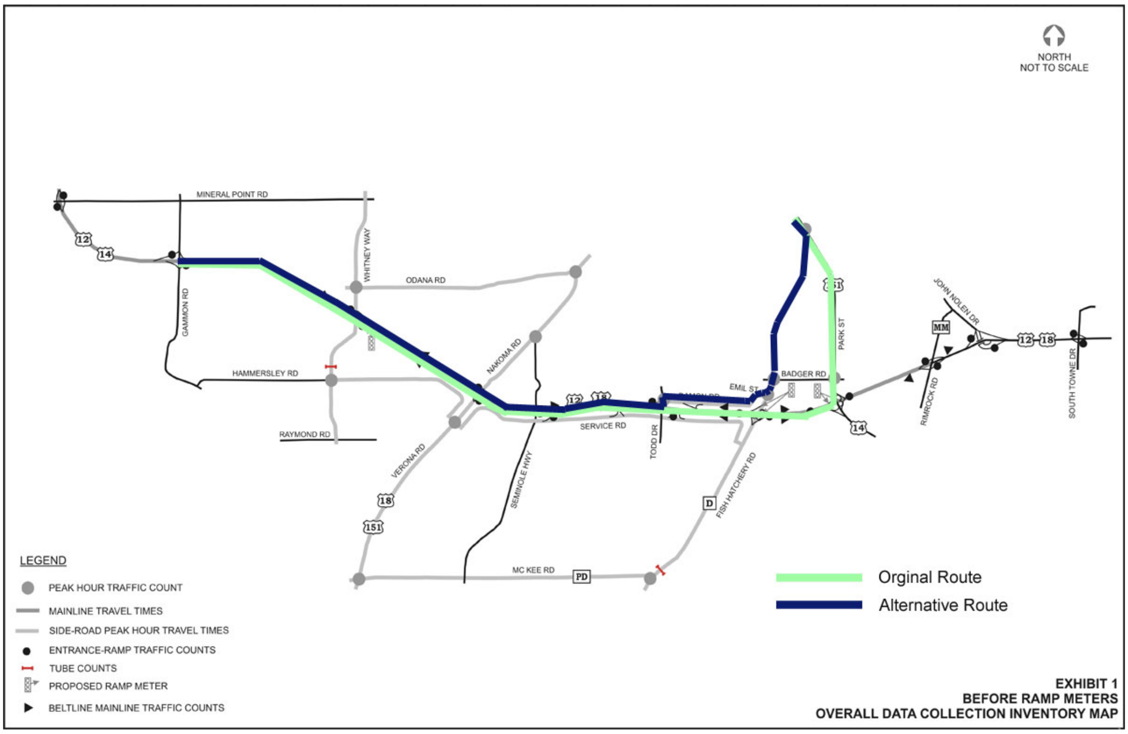


Figure 3-7 Diversion Route Case 3

Case 1 Findings

Table 3-11 Average Travel Time Before and After Ramp Metering - Case 1

Route	AM			PM		
	Before	After	Change	Before	After	Change
McKee between Fish Hatchery and Verona (WB)	04:48	04:18	-00:30	05:03	05:21	+00:18
Verona between McKee and Odana (NB)	12:03	11:56	-00:07	10:37	11:02	+00:25
Fish Hatchery between McKee and Park (NB)	19:20	19:11	-00:09	18:20	17:55	-00:25
Service Rd between Fish Hatchery and Verona (WB)	27:22	25:01	-02:21	25:29	24:05	-01:24

For Case 1, the travel times on the alternate route decreased during the AM and PM Peak Periods. Even with a reduction of traffic volumes at the Fish Hatchery S-W Ramp, the Case 1 alternate route maintained consistent travel times before and after ramp meters.

Case 2 Findings

Table 3-12 Average Travel Time Before and After Ramp Metering - Case 2

Route	AM			PM		
	Before	After	Change	Before	After	Change
Whitney between Raymond and Mineral Point (NB)	03:19	04:02	+00:43	03:02	03:41	+00:39
Hammersley between Whitney and Verona(EB)	08:48	08:47	-00:01	06:00	08:46	+02:46

For Case 2, little change was observed in the AM peak period, while there was almost a 3 minute increase during the PM Peak Period. The volumes remained fairly constant at the EB Whitney Way on-ramp. The increase in travel time may be partially attributable to construction of some large scale trip generators that where installed around the same time as the ramp meters (i.e., Home Depot and others in SW Quadrant of Verona Road Interchange.

Case 3 Findings

Table 3-13 Average Travel Time Before and After Ramp Metering - Case 3

Route	AM			PM		
	Before	After	Change	Before	After	Change
Fish Hatchery between Park and McKee (SB)	04:53	06:21	+01:28	05:09	04:58	-00:11
Damon between Fish Hatchery and Todd (WB)	07:10	08:39	+01:29	07:42	08:14	+00:32

For Case 3, most travel times increased in year 2002. The volumes at the Park Street N-W entrance ramp stayed consistent in the AM Peak. However, there was a noticeable drop in volumes during the PM Peak. This decrease may imply drivers adjusted their routes in order to avoid using the metered ramps at Park Street interchange, thereby moderately increasing travel times along the Case 3 alternate route.

Ramp Meter Compliance

Violations for SOV lanes were identified as vehicles not properly obeying the ramp meter signal. Violations for HOV lanes were identified as a vehicle not properly obeying the ramp meter signal and/or less than two occupants per vehicle. Tables 3-14 and 3-15 provide a summary of the ramp meter violations. For SOV lanes, violations ranged from 0.9% - 9.0%, while violations for HOV lanes ranged between 8.3% - 34.3%. Based on data collected during AM and PM peak traffic periods, the study determined that a large portion of ramp meter violations occurred during PM periods. In addition, the results indicate that as ramp delay increases, fewer vehicles comply with the ramp signal. Data was also compiled to show the relation of compliance and non-compliance to the ramp signals on each ramp, as well as the relation of compliance to ramp signals with travel time on each ramp.

Table 3-14 AM Period Ramp Meter Violations (7:00 – 9:00 AM)

	Ramp Volumes (Veh)		Ramp Violations			
	SOV	HOV	SOV	SOV(%)	HOV	HOV(%)
Park Street WB (N-W)	394	32	14	3.6%	3	8.3%
Park Street WB (S-W)	1485	N/A	13	0.9%	N/A	N/A
Fish Hatchery Road WB (N-W)	635	38	8	1.3%	6	15.9%
Fish Hatchery Road WB (S-W)	544	N/A	15	2.7%	N/A	N/A
Whitney Way EB	1733	125	27	1.6%	11	9.1%

Table 3-15 PM Period Ramp Meter Violations (4:00 – 6:00 PM)

	Ramp Volumes (Veh)		Ramp Violations			
	SOV	HOV	SOV	SOV(%)	HOV	HOV(%)
Park Street WB (N-W)	831	81	52	6.3%	28	34.3%
Park Street WB (S-W)	612	N/A	55	9.0%	N/A	N/A
Fish Hatchery Road WB (N-W)	1162	138	21	1.8%	29	21.2%
Fish Hatchery Road WB (S-W)	853	N/A	35	4.1%	N/A	N/A
Whitney Way EB	2452	190	23	1.0%	24	12.8%

A complete listing of ramp meter compliance data used for the evaluation is located in Appendix E.

4. TRAFFIC SIMULATION ANALYSIS

4.1 CORSIM Simulation Scenarios – with and without Ramp Metering

The CORSIM model was used to evaluate several performance measures of ramp metering on the Madison Beltline. CORSIM is a comprehensive microscopic traffic simulation, applicable to freeways, surface streets, and integrated networks with a complete selection of control devices (i.e., stop/yield sign, traffic signals, and ramp metering). CORSIM simulates traffic and traffic control systems using commonly accepted vehicle and driver behavior models. A section of the Beltline highway from Park Street to Gammon Road was selected and the network was simulated under "with" and "without" ramp metering conditions. The five locations equipped with ramp meters (i.e., Park, Fish Hatchery, and Whitney Way) were coded into the model. Ramp meters were not simulated at any other locations along the Beltline. The sequence of steps used in the study includes:

1. Gather Beltline network geometric and traffic data;
2. Set up network with ramp metering on the basis of ramp meter signal and ramp geometry;
3. Run CORSIM model with and without ramp metering; and
4. Compare speeds and other MOEs on mainline and ramp to analyze the effectiveness of ramp metering.

The model development process is illustrated in Figure 4-1.

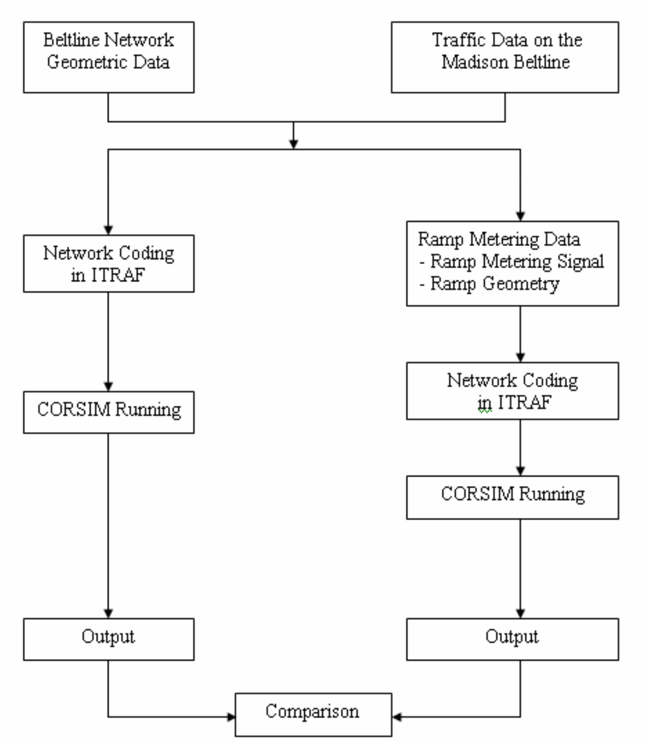


Figure 4-1 CORSIM Microsimulation Model Development

<u>Test Area Selection and Description</u>

1. Model Description and Location
   - CORSIM Model for Ramp Metering in Madison Beltline

2. Traffic Flow and Speed Characteristics
3. Field Data Description and Analysis
   - Pavement conditions
   - Traffic volumes (SOV / HOV)
   - Violation rates (SOV / HOV)

Scenarios

There were four scenarios with ramp metering along arterial.

- Baseline existing (without incidents)
- Baseline existing (with incidents)
- With ramp metering system (without incidents)
- With ramp metering system (with incidents)

Assumptions

One of the most crucial steps for modeling and simulation in this study was to identify all relevant assumptions.

- Type of incident = disabled automobile
- Time of incident = weekday, 4:30 pm
- PHV = 5000 vph

4.2 CORSIM Analysis MOEs

The Measures of Effectiveness for the CORSIM study were:

- Travel speed (miles per hour)
- Total Vehicle- Miles
- Vehicle-Hours of: Move Time
- Vehicle-Hours of: Delay Time
- Minutes/Mile of: Delay Time
- Minutes/Mile of: Total Time
- Fuel consumption = gal and miles per gallon
- Emission rate (grams per mile

4.3 Travel Speed Analysis

Comparison of Travel Speeds - Westbound

Figures 4-2 and 4-3 show the simulated westbound travel speeds along the Beltline during both AM and PM periods. As shown in the graphs, the travel speeds on both “with ramp meter” and “without ramp meter” scenarios have similar profiles. The most significant speed increases occurred between Fish Hatchery Road and Verona Road after ramp meters were installed. The travel speed at the Seminole Highway exit ramp is lower than at other sections of the Beltline. Similar to the trends observed in analyzing the raw data, the speed fluctuation is attributable to off-ramp back-ups. As a result, travel speed increases to some degree with ramp metering compared to without ramp metering.

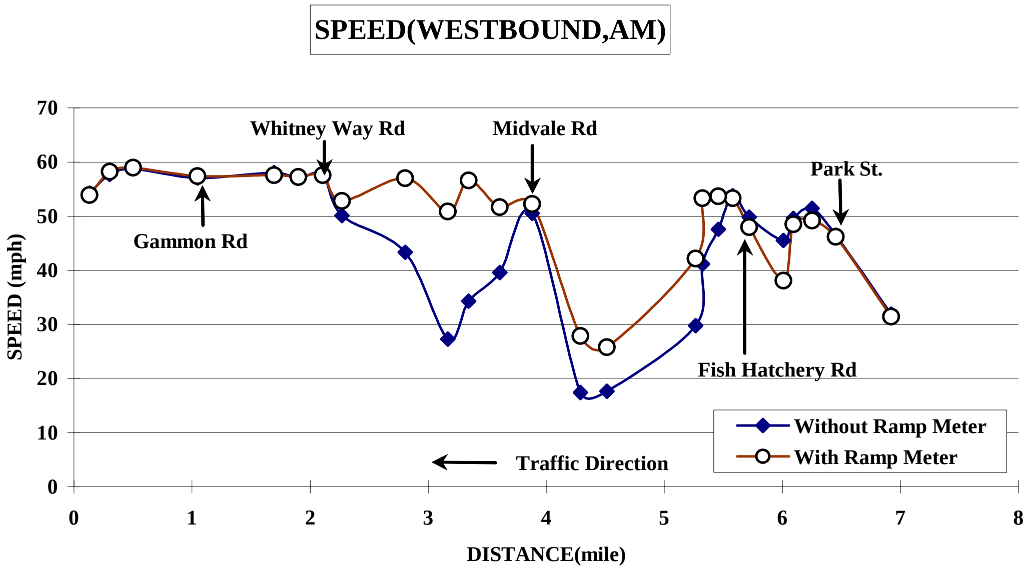


Figure 4-2 Simulated travel speeds along the westbound Beltline (AM)

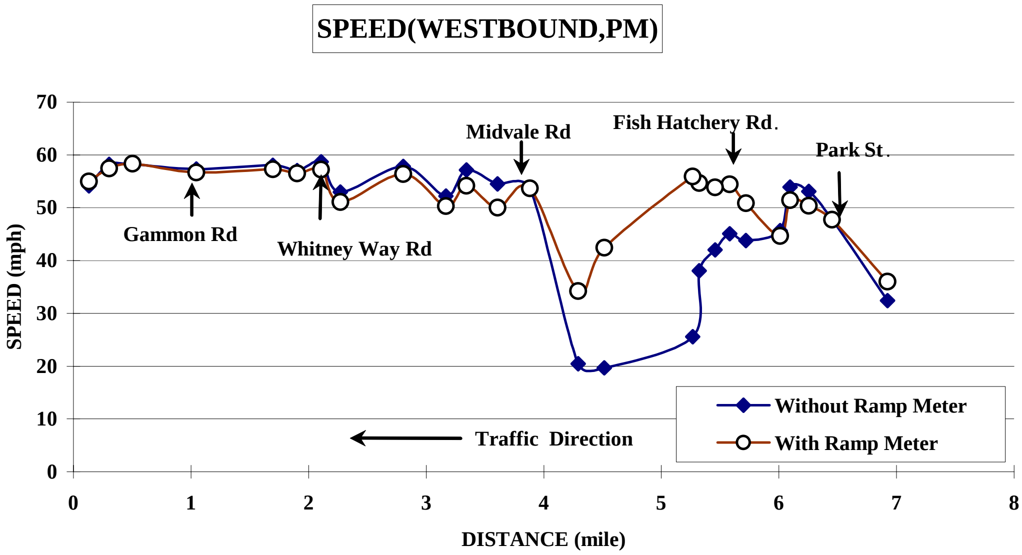


Figure 4-3 Simulated travel speeds along the westbound Beltline (PM)

Table 4-1 indicates the average westbound speeds for both the mainline and ramps along on the Beltline. Average speed is calculated by using vehicle speed of all links and ramps along the westbound Beltline between Park Street ramp and Gammon Road ramp.

Table 4-1 Simulated Average Mainline and Ramp Speeds - Westbound

	Mainline (mph)				Ramp (mph)			
	Without RM	With RM	Change	Comparison	Without RM	With RM	Change	Comparison
AM	45.1	49.6	+4.5	9.8%	37.1	31.2	-5.9	-18.9%
PM	47.9	51.6	+3.7	7.7%	38.8	32.1	-6.7	-20.9%

Comparison of Travel Speeds - Eastbound

Figures 4-4 and 4-5 show the simulated eastbound travel speeds along the Beltline during both AM and PM periods. As shown in the graphs, the travel speeds on both "with ramp meter" and "without ramp meter" scenarios have similar profiles. The lowest speed occurs near Midvale Road due to a lane reduction in which three lanes are merged into two lanes near the Midvale Road ramp. The travel speed at that location (Midvale Rd.) is around 28mph.

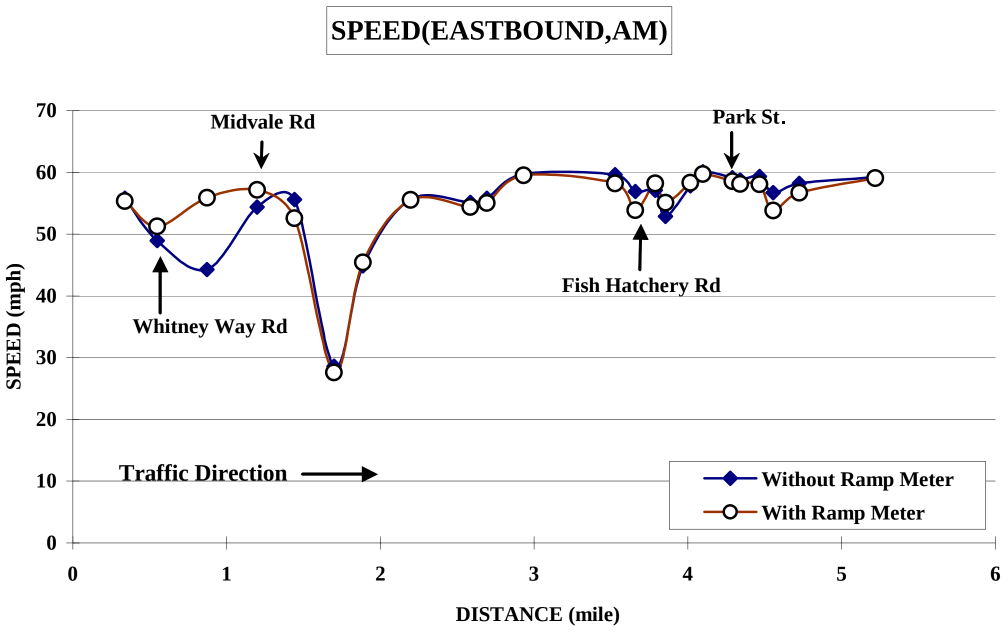


Figure 4-4 Simulated travel speeds along the eastbound Beltline (AM)

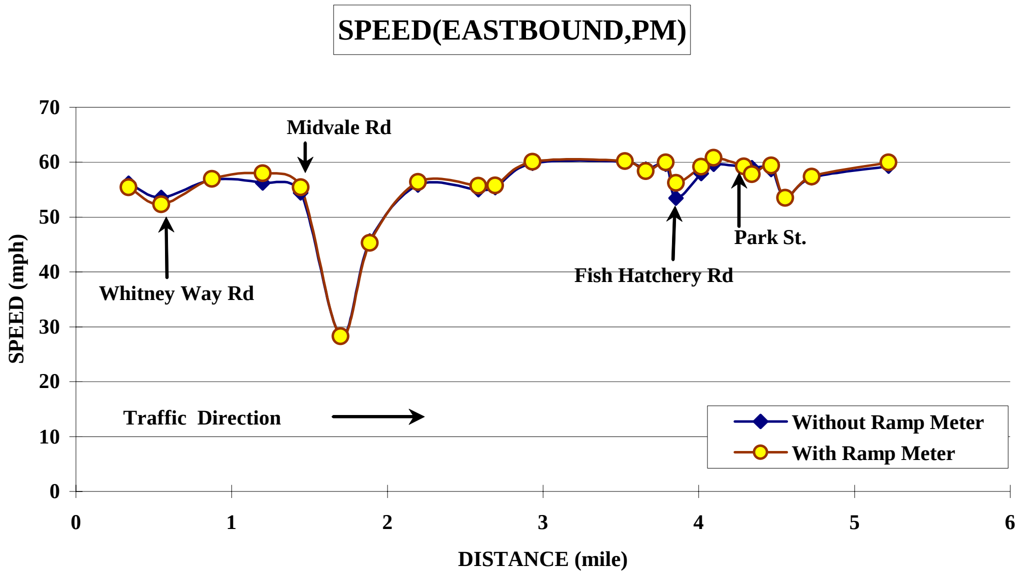


Figure 4-5 Simulated travel speeds along the eastbound Beltline (PM)

Table 4-2 indicates the average eastbound speeds for both the mainline and ramps along on the Beltline.

Table 4-2 Simulated Average Mainline and Ramp Speeds - Eastbound

	Mainline (mph)				Ramp (mph)			
	Without RM	With RM	Change	Comparison	Without RM	With RM	Change	Comparison
AM	54.6	54.7	+0.1	+0.2%	38.9	36.2	-2.7	-7.5%
PM	55.4	55.7	+0.3	+0.5%	38.4	37.0	-1.4	-3.8%

Simulation Travel Speed Findings

Simulation of ramp meters on the Beltline indicate an overall travel speed increase by almost 10% (AM) and 8% (PM) in the westbound direction. Most notably, the travel speed between Fish Hatchery Road and Verona Road is increased by 16% (AM) and 39% (PM).

The increase of less than one percent in the eastbound direction for both AM and PM peak periods suggest minimal travel savings because of the installation of a single ramp meter at Whitney Way. Additional travel speed increases would have likely been observed if additional ramp meters were simulated.

4.4 Incident Related Delay

Stalled vehicles, traffic stops, highway debris, spilled loads, and crashes are examples of traffic incidents that account for about one-third of all delay due to traffic congestion on our nation's highways. Along with weather, construction, and special events, these non-recurring incidents are responsible for nearly 60 percent of delay caused by traffic congestion. Therefore, it is critical to evaluate the proper operations strategy under a traffic incident to understand how ramp meters can assist with traffic management during an incident. In this study, to understand the impact of a traffic incident with and without ramp metering, a typical accident was simulated.

Table 4-3 shows 911 data that has been collected from the Dane County 911 Communications Center during five months (September 2001 ~ January 2002). The average traffic accident duration (responsive time + clearance time) is estimated at 30 minutes.

Table 4-3 Summary of Accident Duration on the Beltline Based on 911 Data (Sep. 2001. ~ Jan. 2002)

Month / Year	Frequent Accident Location	Average Accident Duration (Min.)
September 2001	Whitney Way	21
October 2001	Fish Hatchery Road	26
November 2001	Whitney Way Road	40
December 2001	Park Street	30
January 2002	Fish Hatchery Road	36
	Average	30

The CORSIM model allows users to "insert" a traffic incident, which could be a crash, or a disabled vehicle. In this study, an incident was positioned approximately 500 feet downstream from the Fish Hatchery Road westbound on-ramp. One of the three lanes was blocked for 30 minutes (4:30 – 5:00 p.m.). The result of the CORSIM traffic incident simulation has been summarized in Table 4-4.

Table 4-4 Simulated Traffic Incident Results

	Without Ramp Meters	With Ramp Meters	Difference	Comparison
Total Vehicle- Miles	34332	35992	1660	4.8%
Vehicle-Hours of: Move Time	673.49	720.94	47.45	7.0%
Vehicle-Hours of: Delay Time	742.77	635.11	-107.66	-14.5%
Move/Total	0.48	0.53	0.05	10.4%
Minutes/Mile of: Delay Time	1.3	1.06	-0.24	-18.5%
Minutes/Mile of: Total Time	2.48	2.26	-0.22	-8.9%

Incident Delay Findings

Simulation indicates total delay has decreased after ramp metering installation by almost 15%. Also delay time per driving mile has been reduced from 1.3 minutes to 1.06 minutes. The slight increase in total vehicle miles and vehicle-hours of move time indicate that vehicles are able to enter and exit the model more quickly when ramp meters are operational. These results indicate ramp meters serve as an effective tool in managing the flow of traffic flow in the vicinity of a traffic incident.

4.5 Vehicle Emissions

One of the CORSIM output files includes vehicle emissions such as carbon monoxide (CO), hydrocarbons (HC), and nitric oxide (NO). Previous research (Rouphail, et al. (2000)) found the highest emissions rate is produced during acceleration. Emission rates can be twice as high during "stop and go" travel when compared to normal conditions. Thus a reduction of delay, which can reduce the chance of deceleration and acceleration, essentially contributes to a decrease in vehicle emissions.

Table 4-5 shows the results of the PM period emission output file categorized by vehicle type with and without ramp metering.

Table 4-5 Simulated Vehicle Emission Results (grams/mile)

Hydrocarbons (HC)								
Vehicle Type	1	2	3	4	5	6	7	Total
Without Ramp Meters	0.26	0.27	15.23	10.34	8.93	7.17	0	42.2
With Ramp Meters	0.27	0.29	14.76	10.24	8.34	6.5	0	40.4
Difference	0.01	0.02	-0.47	-0.1	-0.59	-0.67	0	-1.8
Comparison	3.8%	7.4%	-3.1%	-1.0%	-6.6%	-9.3%	-	-4.3%
Carbon Monoxide (CO)								
Without Ramp Meters	18.61	20.35	285.76	172.19	141.32	106.45	0	744.68
With Ramp Meters	19.7	21.64	279.24	175.89	135	97.61	0	729.08
Difference	1.09	1.29	-6.52	3.7	-6.32	-8.84	0	-15.6
Comparison	5.9%	6.3%	-2.3%	2.1%	-4.5%	-8.3%	-	-2.1%
Nitric Oxide (NO)								
Without Ramp Meters	1.1	1.02	35.67	26.51	23.57	17.63	0	105.5
With Ramp Meters	1.13	1.03	34.89	27.11	23.14	16.95	0	104.25
Difference	0.03	0.01	-0.78	0.6	-0.43	-0.68	0	-1.25
Comparison	2.7%	1.0%	-2.2%	2.3%	-1.8%	-3.9%	-	-1.2%

VEHICLE TYPES 1,2 = AUTO 3,4,5,6 = TRUCK 7 = TRANSIT BUS

Vehicle Emission Findings
Results of the CORSIM simulation show a slight reduction in emissions after ramp meter installation. The highest percent of reduction in HC emissions and the largest amount of reduction in CO emissions have been observed.

4.6 Fuel Consumption

CORSIM simulation generates a fuel consumption output file that is reported in total consumption (in gallons) and fuel efficiency (miles per gallon). In previous research [Rakha and Ding (2003)], the fuel consumption rate per unit distance is described as a convex function with respect to cruise speed. The highest fuel consumption rate was observed at 6 mph and the lowest was measured when vehicle cruising speed was around 55 mph. The rate continues to rise with an increase in the cruise speed above 55 mph.

Considering the relationship, the fuel consumption increase and fuel use rate is logically related with the result of CORSIM simulation, which shows an increase of average speed to around 50 mph.

Table 4-6 Simulated Fuel Consumption Results

Gallons								
Vehicle Type	1	2	3	4	5	6	7	Total
Before Ramp Meter	604.34	1166.42	309.44	83.97	52.27	19.5	0	2236
After Ramp Meter	637.8	1220.24	355.21	101.27	66.65	24.03	0	2405
Difference	33.46	53.82	45.77	17.3	14.38	4.53	0	169.3
Comparison	5.50%	4.60%	14.80%	20.60%	27.50%	23.20%	-	7.6%
M.P.G.								
Before Ramp Meter	11.05	17.65	2.34	3.82	2.99	3.26	0	6.85
After Ramp Meter	11.47	18.61	2.45	4.12	3.38	3.41	0	7.24
Difference	0.42	0.96	0.11	0.3	0.39	0.15	0	0.39
Comparison	3.80%	5.40%	4.70%	7.90%	13.00%	4.60%	-	5.7%

VEHICLE TYPES 1,2 = AUTO 3,4,5,6 = TRUCK 7 = TRANSIT BUS

Fuel Consumption Findings

The observed increase in total fuel consumption (7.6%) and an overall improvement in fuel efficiency (5.7%) is representative of the complex relationship between the two measurements. The counterintuitive finding is because of the increase in fuel consumption by a relatively small percentage of truck traffic in the model and the larger population of passenger cars. The stop and go conditions created by ramp meters has the largest impact on fuel consumption on the truck vehicle category as illustrated by an increase of 15-28% in fuel consumption.

4.7 Delay Costs

Calculating costs related to travel time delays is a factor that can be used to better understand the financial benefits associated with different travel options. According to the mobility study completed by Texas Transportation Institute (TTI) in 2004, congestion cost consists of the value of travel delay (estimated at $13.45 per hour of person travel and $71.05 per hour of truck time) and excess fuel consumption. Table 4-7 indicates a 21 percent reduction of delay based on CORSIM model simulation.

Table 4-7 Simulation Results (Normal Condition: 2 Hours Simulation)

	Without Ramp Meters	With Ramp Meters	Difference	Comparison
Total Vehicle- Miles	118023.2	128419.4	10396.2	8.8%
Vehicle-Hours of: Move Time	2341.444	2534.394	192.95	8.2%
Vehicle-Hours of: Delay Time	2489.242	1962.412	-526.83	-21.2%
Move/Total	0.48	0.56	0.08	16.7%
Minutes/Mile of: Delay Time	1.27	0.92	-0.35	-27.6%
Minutes/Mile Of: Total Time	2.46	2.1	-0.36	-14.6%

Considering the five percent truck population setting, the economic benefit of delay reduction can is calculated as follows.

Passenger Car Delay Cost (523.83/2)*$13.45*0.95	$3,366 / hour
Truck Delay Cost (523.83/2)*$71.05*0.05	$936 / hour
Total Delay Cost	$4,302 / hour

Delay Cost Findings

With a simulated 21% reduction in vehicle hours of delay and a calculated delay cost savings of over $4,300 per hour (during peak hour travel), ramp meters and other cost effective methods should be considered to aggressively manage traffic on the Beltline.

5. User Perception and Agency Survey Analysis

5.1 2000 Dane County Driver Survey (Before Data)

The University of Wisconsin-Madison ITS Program developed a 41 question Dane County Driver Survey for the year 2000. The purpose of the survey was to: 1) assess drivers' opinions on travel conditions in Dane County, 2) investigate the extent of drivers' knowledge regarding general freeway issues, and 3) determine user awareness and perception of the Dane County Incident Management Program.

The following general areas of research were included in the survey:

- General Perceptions about Driving in Dane County
- Knowledge and Perceptions of General Freeway Issues
- Driving Habits and Preferences
- Knowledge and Perceptions of the DCIM Program
- Driving Experiences
- Demographic Characteristics of Sample

During the month of August, 2000 a total of 1,000 survey questionnaires were sent out to completely random drivers residing in Dane County. 263 completed surveys were returned and used for analysis. 374 surveys were mailed back to the Graduate Department ITS Program "Return To Sender," indicating a change of address. The "unopened" surveys were subtracted from the original total. As a result, a response rate of approximately 42 % was calculated.

In order to encourage Dane County residents to complete and mail in their surveys, two 33 cent stamps were enclosed within the envelopes containing the questionnaires along with a letter explaining the intent of the survey and its importance to Dane County drivers. In addition, a book of 10 additional 33 cent stamps was promised to participants who completed and mailed back their surveys by September 25, 2000. Participants printed their identification numbers (included on the original envelopes) on the back of their survey questionnaires to ensure confidentiality and allow the Graduate Department ITS Program to keep track of those whom were eligible for receiving stamps.

Two ramp meter questions were contained within the before Dane County Driver Survey. The questions and results are located below.

18. Are you familiar with ramp meters?

(Sample Size : 263)

Total Response: 251/263 = 95.4%

Never heard of them	⟵	⟶		Very familiar
0	1	2	3	4
51%	10%	11%	15%	13%

19. If you are not familiar with ramp meters (answered 0 for question 18) please skip to question 20, otherwise please describe what you think about ramp meters being installed in Dane County by circling the number that represents your feelings for each line:

(Sample Size : 263)

<<<<<	0	1	2	3	4	>>>>>
a. reduced highway safety? Total Response: 101/263 = 38.4%	2%	6%	28%	45%	19%	improved highway safety?
b. increased my driving times? Total Response: 100/263 = 38.0%	8%	13%	47%	22%	10%	reduced my driving times?
c. increased the number of accidents? Total Response: 103/263 = 39.2%	5%	9%	28%	36%	22%	reduced the number of accidents?

Before Ramp Meter Related Survey Findings
Several conclusions can be drawn from the results of the two ramp meter questions included in the 2000 Dane County Driver Survey. Specifically, 51.4 % of drivers polled have never heard of ramp meters. However, for those familiar with ramp meters, 64.4 % felt ramp meters will improve highway safety, 32.0% felt ramp meters will reduce driving time and 58.3 % felt ramp meters will reduce crashes. Therefore, most people indicated installing ramp meters in Dane County would have positive impacts on highway safety and mobility.

5.2 2002 Dane County Driver Survey (After Data)

The University of Wisconsin-Madison ITS Program developed a 45 question Dane County Driver Survey for the year 2002. The purpose of the survey was to: 1) assess drivers' opinions on travel conditions in Dane County, 2) assess drivers' opinions regarding ramp meter, service patrol, enhanced reference marker, and blue route alternate route signing implementation, and 3) determine user awareness and perception of the Dane County Transportation Operations and Safety Program.

The following general areas of research were included in the survey:

- General Perceptions about Driving in Dane County
- Knowledge and Perceptions of Beltline Highway Ramp Meter Installation
- Knowledge and Perceptions of Enhanced Reference Marker Installation
- Knowledge and Perceptions of Beltline Highway Service Patrol Implementation
- Knowledge and Perceptions of Blue Route Alternate Route Signing Implementation
- Knowledge and Perceptions of the Dane County Transportation Operations and Safety Program
- Demographic Characteristics of Sample

During the month of October, 2002 a total of 1,000 survey questionnaires were sent out to completely random drivers residing in Dane County. The deadline for drivers to mail back their completed surveys to the Graduate Department ITS Program was November 1, 2002. These results are compared to those of the 2000 Dane County Driver Survey.

In order to encourage Dane County residents to complete and mail in their surveys, two 37 cent stamps were enclosed within the envelopes containing the questionnaires along with a letter explaining the intent of the survey and its importance to Dane County drivers. In addition, a book of 10 additional 37 cent stamps was promised to participants who completed and mailed back their surveys by November 1, 2002. Identification numbers (included on the original envelopes) were printed on the back of the individual survey questionnaires to ensure confidentiality and allow the Graduate Department ITS Program to keep track of those whom are eligible for receiving stamps.

298 completed surveys were returned and used for analysis. 63 surveys were mailed back to the Graduate Department ITS Program "Return To Sender," indicating a change of address. The "unopened" surveys were subtracted from the original total. As a result, a response rate of approximately 31.8% was calculated.

Seven ramp meter questions were contained within the after Dane County Driver Survey. The questions and results are located below.

Ramp Meter Survey Questions

The next 7 questions refer to your knowledge and perception of the Ramp Meters installed on five separate entrance ramps to the Beltline Highway. A map showing the location of the ramp meters as well as a picture of a Ramp Meter has been provided below for your convenience. Please answer the questions by either circling your answer or writing in the information requested.

1. How effective do you feel the Ramp Metering has been in improving driving conditions on the Beltline Highway (please circle a number)?

(Sample Size : 284)

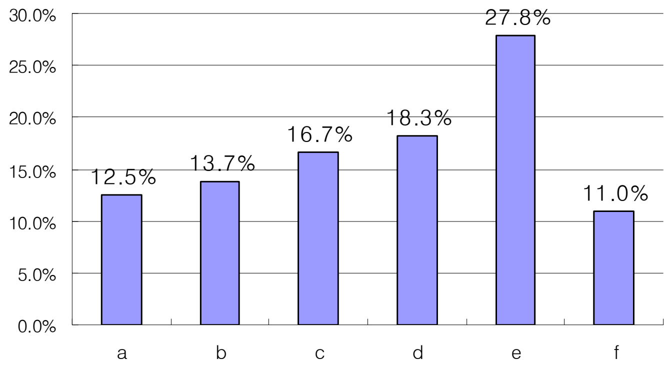
Not Effective	←	→		Very Effective
0	1	2	3	4
5%	12%	34%	39%	11%

2. Do you feel that the Ramp Metering installed along the Beltline Highway has (please circle a number):

(Sample Size : 284)

<<<<<	0	1	2	3	4	>>>>>
d. reduced highway safety?	3%	5%	24%	52%	16%	improved highway safety?
e. increased my driving times?	6%	15%	44%	28%	7%	reduced my driving times?
f. increased the number of accidents?	3%	6%	37%	40%	15%	reduced the number of accidents?

3. Which Ramp Meter location(s) have you used along the Beltline Highway in the past month? Please place an "X" in the space provided, where applicable.



a. Park St. Westbound from South Approach
b. Park St. Westbound from North Approach
c. Fish Hatchery Westbound from South Approach
d. Fish Hatchery Westbound from North Approach
e. Whitney Way Eastbound
f. None

4. If you answered "None" for question 8, please skip to question 11; otherwise how long would you estimate your waiting time (on average) at each of the Ramp Meters identified in question 8?

(sec)

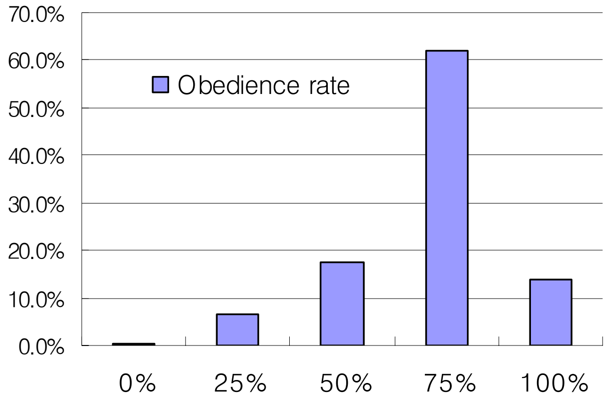
	N	Mean	StDev	Min	Max
a. Park St. Westbound from South Approach	81	63.48	88.04	0	480
b. Park St. Westbound from North Approach	86	53.73	71.42	0	300
c. Fish Hatchery Westbound from South Approach	98	65.74	97.33	0	600
d. Fish Hatchery Westbound from North Approach	113	62.87	78.56	0	360
e. Whitney Way Eastbound	148	91.1	129.1	0	600

* N=Sample Size

5. Do you take advantage of High Occupancy Vehicle (HOV) lanes on the metered ramps while carpooling? (Sample Size:217)

Yes	22.1%
No	54.4%
Not aware of HOV Lanes	23.5%

6. How well do you think drivers obey the Ramp Meters (please circle a number)? (Sample Size:287)



7. Do you think Ramp Metering would be useful at other on-ramp locations along the Beltline Highway or along other highways within Dane County? Please list below.

Location	Direction	# of recommendations
Midvale Road	EB	10
Gammon Road	EB	8
Monona Drive	WB	6
Stoughton Road	WB	5
John Nolen Drive	WB	3
Mineral Point Road	EB	3
Rimrock Road	WB	3

After Ramp Meter Related Survey Findings

50 percent of the respondents agreed that ramp metering is an effective tool that can improve driving conditions and 17 percent of the respondents disagreed that ramp metering can improve driving conditions on the Beltline Highway. It seems there was an upward swing in general knowledge of the ramp meters compared to the before data, when almost half of the respondents did not know what a ramp meter was.

68 percent of the respondents agreed that ramp metering is effective to reduce the number of accidents and increase highway safety on the Beltline highway. Approximately 35 percent of the respondents agreed that ramp meters can reduce driving time while only 21 percent felt that ramp meter increased driving time. When compared to the same questions asked in the before Dane County Driver Survey, there were very few shifts in motorist perception related to safety and mobility, with a slight shift (about 4%) indicating that ramp meters can assist in reducing the number of accidents.

Based on comparing survey responses and field measurements of ramp wait times, most respondents feel they are waiting longer in the ramp meter queue than they actually experience. On average, motorists felt they waited approximately 30 seconds longer than actually measured in the field.

According to respondents, among the five ramp meters on the Beltline, Whitney Way Eastbound is the location which is the most frequently used.

Approximately one and five respondents indicated use of the HOV lanes. Also, four out of five respondents indicated they did understand, or where not aware of the HOV lanes.

Over fifty respondents suggested installation of ramp meters at several other locations along the Beltline. Midvale and Gammon Road were the two tops locations where respondents thought ramp meters would be useful.

Feedback from the Dane County motorist survey indicates the overall perception of ramp metering is mixed. This is mainly due to the fact respondents are not accustomed to the ramp meters and there were some short-term problems in operating the system as initially envisioned. The main concerns are as follows: 1) vehicles are not able to reach highway speed from a stopped position; 2) lack of traffic enforcement; 3) traffic backs up onto arterial streets; and 4) timing of red/green interval is inadequate and functions during low-flow periods on Beltline.

Despite these inadequacies expressed by the survey respondents, they have also seen improvements to the Beltline since the implementation of ramp metering. One of the chief purposes of ramp metering is to prevent bottleneck occurrences on the Beltline. Appropriately, the respondents noticed an improvement during rush hour traffic, since it is easier to get on the Beltline and entrance ramp traffic has a more controlled, paced flow.

5.3 Agency Survey

To assess agency perception of the benefits and effectiveness of ramp metering a survey was administered to the following transportation and law enforcement agencies: the Wisconsin State Patrol-District 1 (based in DeForest), Madison Police Department, Dane County 9-1-1 and Madison Metro Transit. The sample size for this survey was 24, consisting of 1 sergeant, 6 state troopers, 1 lieutenant, and 16 9-1-1 operators.

Agency Survey Findings
The perception of effectiveness of ramp metering varied across those interviewed. Approximately 61% of the agency representatives interviewed indicated more than half of motorists complied with the ramp meters.

To determine the officers' familiarity with ramp metering on the Madison Beltline, they were asked to rank their perceptions ranging from "not at all familiar" (0) to "very familiar" (4). Approximately 33% of the officers indicated they are very familiar with ramp metering. The average score was 3.67 on the 0-4 point scale.

The surveyed officers were asked to describe the impacts ramp metering has had on the Madison Beltline by using a 5-point scale. The scale ranges from "reduced" (0) to "improved" (4) for the impact on freeway safety. Half of the surveyed officers claimed there is not much of an impact on safety.

The trend continued when asked to evaluate the impact of driving time on the Beltline with the installation of ramp metering. Approximately 59% of the surveyed officers did not notice an increase or decrease on driving time.

The respondents were also asked to indicate if ramp metering has had an impact on the number of crashes on the Madison Beltline. Once again, about 65% of the officers did not see a significant impact.

The next set of questions focused on the effect ramp metering has had on the time it takes to respond to accidents and the time required to clear. Approximately 64% of the respondents found the time to respond to accidents has improved with ramp metering. This improvement correlates with the use of High Occupancy Vehicle (HOV) lanes by emergency service providers. Only three respondents—one state trooper and two 911 operators - acknowledged the use of HOV lanes and of those, two use them in emergency situations. Additionally, about 96% found that the time to clear accidents has improved.

The last series of questions focused on the effectiveness of the design and installation elements of the ramp meters. These elements include the visibility of the signals, the appropriate location of the signage and the effectiveness of the enforcement pads. The scale ranges from (0) “not clear” to (4) “clear” and it is apparent that the signal visibility does not seem to be a significant problem for the respondents. The degree of appropriate signage ranges from (0) “not appropriate” to (4) “appropriate”. Once again, there does not seem to be significant concern regarding signage. The effectiveness of the enforcement pads ranged from (0) “not effective” to (4) “effective”. The enforcement pads do not seem to have the similar positive response as the location and appropriateness of the signage.

To gauge the need for ramp metering, agency respondents were asked if there were any other segments of the Dane County freeway system that might be improved with ramp metering. Recommended locations for ramp metering on the Beltline included Gammon Road, Mineral Point Road and Monona Drive.

There were several suggestions made by agency personnel for the improvement of ramp metering. One responder suggested the creation of a phone number to report malfunctions of the ramp meters. Many of the responders, especially the transit and 9-1-1 operators, suggested more enforcement should be used to curb violations.

6. Conclusions and Recommendations

6.1 Conclusions

Analysis of the field data confirms that in general, ramp metering has had a positive impact on the Madison Beltline based on a number of different evaluation criteria. Table 6.1 following table summarizes these benefits and their corresponding measures of effectiveness.

Table 6-1 Summary of Evaluation Findings

Evaluation Objective	Measures of Effectiveness
Reduce the number of crashes.	▪ While the entire Beltline from Stoughton Road to Old Sauk experienced a 57% reduction in crashes, the area identified as the eastbound ramp meter influence zone near Whitney Way experienced a significant reduction in crashes during metered and non-metered periods (86% for both periods). ▪ The westbound ramp meter influence zone in the vicinity of Park and Fish Hatchery showed a reduction in 50% of crashes during metered time periods, and an overall reduction of 27%.
Improve the ability to mitigate effects of traffic incidents.	▪ Results from the agency survey of law enforcement and transit personnel indicate that ramp metering contributes to a quick response to and clearing of incidents. ▪ About 96% of agency users found the time to clear accidents has improved because of the introduction of ramp meters along the Beltline. ▪ Approximately 64% of the agency respondents found that the time to respond to accidents has improved with ramp metering. ▪ Simulation shows that ramp meters can reduce delay by as much as 15% during a traffic incident.
Reduce average travel delay and improve the reliability and predictability of travel.	▪ Despite significant growth in traffic volumes, travel times increased slightly during three of the four metering periods, with a slight reduction in the westbound AM metering period. ▪ With the exception of the PM westbound metering period, ramp meters have generally been able to assist in maintaining consistent localized travel times (i.e., in the vicinity of the ramp meter location). ▪ Simulation indicates that ramp meters can reduce travel time delay by over 20% (over a 2-hour simulation period).
Maintain existing balance between freeway and arterial traffic loading.	▪ The Beltline has experienced significant growth in traffic. ▪ Results from the ramp counts indicate that motorists at some locations are seeking alternative routes to avoid using the metered ramps. ▪ Travel times on arterial roadways were not adversely impacted, with some showing a slight increase and others a slight decrease.
Reduce travel time variance and reliability across time and space.	▪ Three out of the four travel periods experienced a lower variability in travel speeds. ▪ The most significant finding is in the Westbound AM period where the variation of travel speeds was reduced from +/-10.9 seconds down to +/-3.8 seconds after ramp metering. ▪ The largest variations before and after ramp metering continue to be observed in the vicinity of Seminole and Verona.
Reduce vehicle emissions and improve air quality.	▪ Simulation shows a slight reduction in emissions after ramp meter installation ranging from 1-4%.
Reduce fuel consumption.	▪ Simulation shows a slight increase in overall fuel consumption (8%) and a slight increase in fuel efficiency (6%).
Improve motorist perception of the program.	▪ Most motorists feel they are waiting in the ramp meter queue longer than they actually experience. On average, motorists felt they waited approximately 30 seconds longer than actually measured in the field. ▪ Feedback from the driver survey indicates that the overall perception of ramp metering is mixed. Respondents noticed an improvement during rush hour traffic, since it is easier to get on the Beltline and entering traffic has a more

Evaluation Objective	Measures of Effectiveness
	controlled, paced flow. ▪ Only one in five respondents indicated they not understand, or where not aware of the HOV lanes.
Encourage driver compliance and reduce the violation rate.	▪ SOV lanes violations ranged from 0-10% while HOV lanes experienced a much higher violation rate of 5-35%. ▪ Approximately 61% of officers indicated that more than half of motorists complied with the ramp meters.
Reduce delay costs.	▪ Using the delay calculated savings from simulation; ramp meters have contributed to an overall delay savings of over $4,300 per hour (during peak travel hours).

The evaluation findings are generally positive, but somewhat mixed. For example, the evaluation team initially thought there would be a reduction of crashes, increase in freeway travel speeds, with a minimal impact on arterial operations. Factors such as large increase in traffic volumes and the location of the ramp meters contributed to the mixed evaluation results.

6.2 Recommendations

While noting the operational improvements to the Beltline as a result of ramp metering, survey responses and other data point to certain aspects of ramp metering that warrant further review and modification.

In particular, as observed in other parts of the country, the maximum benefits of ramp meters can be realized when installed as a system, where vehicles do not divert to an un-metered ramp immediately downstream to gain access to the facility. Should WisDOT consider ramp meters as a future strategy to enhance safety and mobility in the Madison area, a minimum of 3-4 consecutive interchanges should be metered to maximize the use of available freeway capacity. As with most projects, emerging traffic simulation packages can assist in determining locations that would provide the greatest benefit.

There is also room for improvement in the public perception of ramp metering, especially with regard to increasing awareness of the benefits to traffic flow and safety. Greater public acceptance of ramp metering would also lead to greater compliance and a reduction of ramp meter violations, further enhancing the effectiveness of ramp metering. The Department should consider additional outreach initiatives to better describe HOV lanes and their intended use. Also, addition law enforcement should be considered to reduce violations and to increase compliance.