Wisconsin Statewide Ramp Control Plan

WisDOT
Ramp Metering And Control Plan

July 2006

Produced by Wilbur Smith Associates
on behalf of the Wisconsin Department of Transportation

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Executive Summary

Ramp metering/control is an important component of Wisconsin's SmartWays program, which applies advanced technologies for traffic management and traveler information. The WisDOT web site described ramp metering in the following manner: "Since their implementation in Wisconsin, ramp meters have served a wide variety of purposes. Ramp meters are traffic signals on freeway entrance ramps that break up clusters of vehicles entering the freeway to make merging safer. Ramp meters can also store and spread out the volume of vehicles entering onto the freeway so it is less likely to become congested and the overall rate of travel is minimally affected." Ramp control gates are used at strategic locations primarily for closure of the freeway due to incidents or weather.

Task Description

The purpose of this project is, as a precursor to a Wisconsin's Statewide Freeway Ramp Control Plan, lead the development of an institutional and procedural plan for integrating the implementation criteria for ramp control strategies into statewide planning and programming processes. To accomplish this, Wilbur Smith Associates began with a literature review and interviews with existing ramp control operations. This led to the identification of several criteria. These criteria were assessed with sample locations. Simultaneously, existing WisDOT procedures were examined to best determine where this new process would fit within the organization. Costs were examined both for installation and operational impact. A spreadsheet model was created to provide some initial high level view of the applicability of ramp metering and control.

The study concluded that ramp metering operations are much more locally dependent than other operational strategies. Therefore, it is not appropriate to apply statewide criteria as a firm decision making tool. Rather, the spreadsheet tool can be used as an initial screening for applicability at the earliest planning stages. More detailed and appropriate modeling can than be conducted later on in the planning or early design stage to provide a more accurate indication of whether ramp metering will be effective.

Ramp control operations are the opposite. Rather than being designed to address very local concerns, they are best applied on a regional basis. A spreadsheet tool was developed for ramp control gates also, but the analysis indicated it may be better for WisDOT to make a decision on deployment based on larger regional operations (e.g., urban evacuation, snow belt areas, etc.).

Chapter 1
Literature Review

While providing a national review of literature, this chapter also focuses on a literature review of ramp metering/control for the following nine jurisdictions: Minneapolis/St. Paul, Portland, Seattle, Long Island, Detroit, Austin, San Diego, San Francisco Bay Area and Denver. In addition, Chapter 1 also includes information related to ongoing and planned evaluations of ramp metering/control warrants developed by Milwaukee's Traffic Operations Center and the Beltline evaluation in Madison.

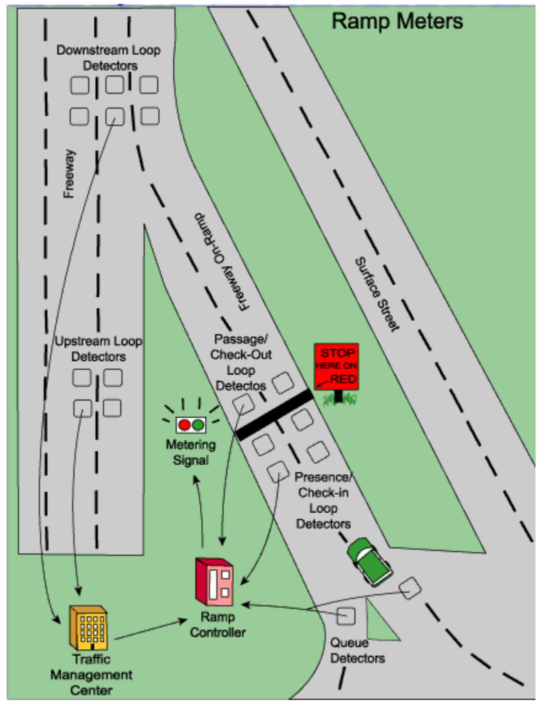


Figure 1-1 Typical Ramp Meter Schematic[1]

What is Ramp Metering?

Ramp metering is the use of traffic signals at freeway on ramps to control the rate of vehicles entering the freeway. The main purpose is to control traffic flow onto the freeway, in order to improve efficiency of the freeway itself. The signals can be set for different metering rates to optimize freeway flow and minimize congestion. Signal timing algorithms and real time data from mainline loop detectors can be used for more effective results. The ramp meters themselves vary depending on location, from Chicago's simple green light/red light Figure 1-1 to Minnesota's mounting one standard (red-yellow-green) traffic light on top of another. Figure 1-2 is an illustration of a typical ramp meter/control deployment.

Ramp metering is not a new freeway management technique. Various forms of ramp control were implemented during the late 1950's and through the 1960's in Chicago, Detroit and Los Angeles. By the early 1990's, ramp metering systems existed in twenty metropolitan areas within the United States, along with numerous cities around the world. In addition to on ramp metering, freeway to freeway connector ramp meters have been successful in several areas including Minneapolis, San Antonio, and San Diego[1].

Figure 1-2. Typical Freeway Ramp Meter Deployment[2]

The main reason for implementing ramp metering is to reduce traffic congestion and delays on freeways by limiting access to these freeways. There are a number of factors responsible for traffic congestion, some of these can include: incidents/accidents, lane drops, demand exceeding capacity, insufficient exit capacity, and interruptions in traffic flow caused by merging traffic. These factors alone or in combination can severely limit traffic flow on freeways and major arterials. Ramp metering/control can help reduce traffic congestion caused by three of the five factors listed above: lane drops, insufficient exit capacity, and interruptions in traffic flow caused by merging traffic.

In order to effectively use ramp metering, the ramp must possess characteristics suitable to metering. These include sufficient vehicle storage space on the ramp to limit or prevent the likelihood of vehicles backing up onto the arterial roadway, and adequate acceleration and merge distances downstream of the meter stop bar.

Figure 1-3 illustrates a typical ramp metering system consisting of various components. Often these components are elements within a larger freeway management architecture. Some of these components may be:

- Ramp Metering Signal and Controller
- Advance Warning Signage
- Presence Detector
- Passage Detector
- HOV Detector
- Queue Detector
- Mainline Detectors

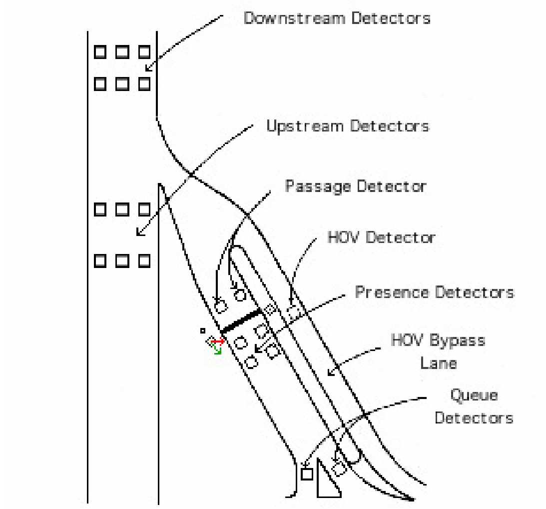


Figure 1-3. Metered Freeway Ramp[1]

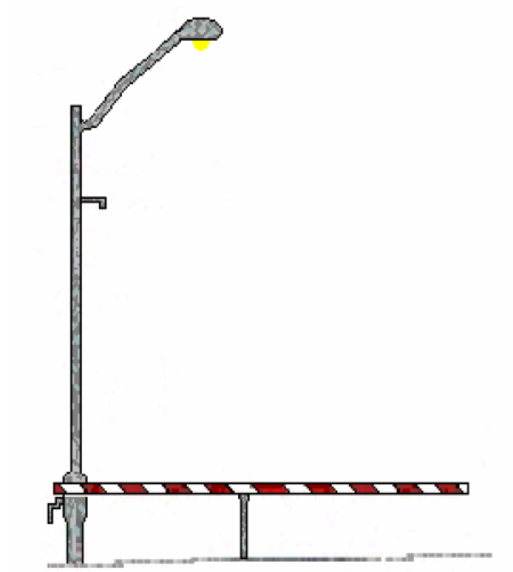


Figure 1-4. Example of Road Closure Gate

What is Ramp Control?

Ramp control provides traffic managers with the ability to open and close freeways, roadways, and ramps based on weather, security, or traffic problems. Ramp control gates can be manually, automatically, or remotely controlled from a central location, or from a vehicle at the gate/barrier location. Figure 1-4 above illustrates an automated road closure gate. This improves system efficiency and reduces personnel exposure to unsafe conditions during severe weather and other situations where roads must be closed. Ramp control systems can be integrated with surveillance systems allowing operating personnel to visually verify the safe activation of the closure system and driver information systems (e.g., DMS) that provide closure information to motorists in the vicinity of the closure.

Figure 1-5 highlights the states that have deployed or are planning to deploy Ramp Control or Roadway Closure Systems. The number on shaded states indicates the number of systems reported. A total of 17 states identified 25 separate Roadway Closure Systems. The majority of these systems are deployed on freeways or limited access highways.

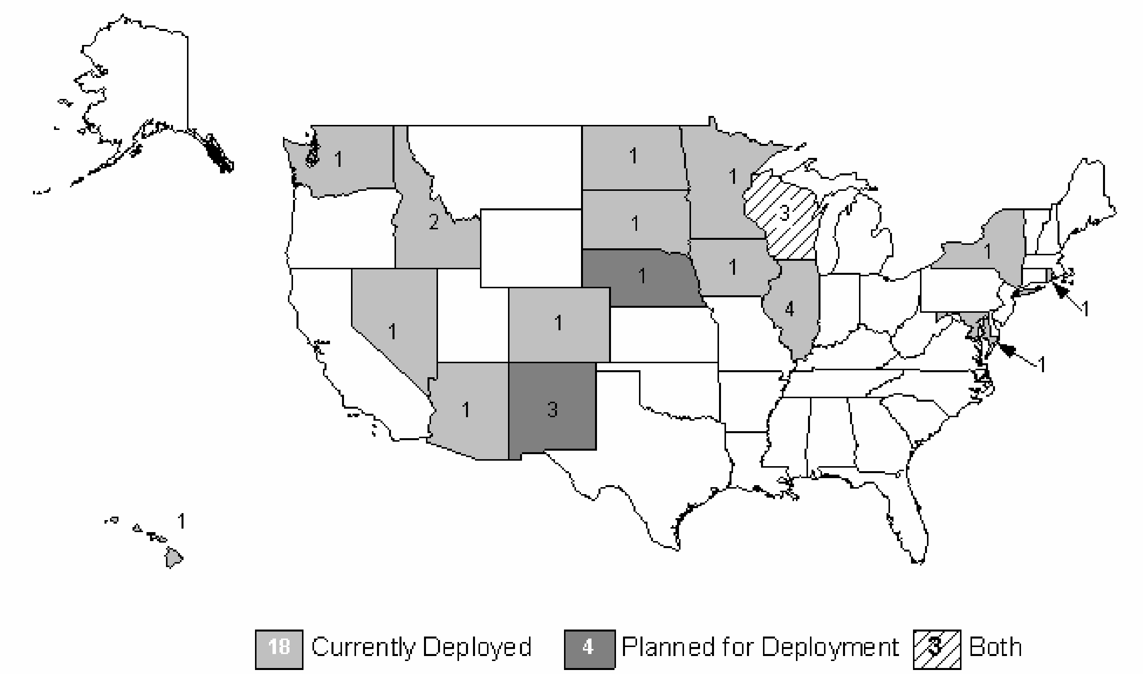


Figure 1- 5. States planning to or currently have deployed Roadway Closure Systems
Source: USDOT ITS website http://www.itsdeployment.its.dot.gov

Typically Roadway Closure Systems are used to restrict access to roadways during severe weather conditions or during special events. These systems may consist of automated or manual vertical swing arm assemblies similar to Figure 1-4. Other Roadway Closure gate types include Type III Barricade and Horizontal Swing gates. Figures 1-6 and 1-7 below are examples of these.

Figure 1-6. Type III Barricade[3]

Figure 1-7. Horizontal Swing Arm Traffic Gate[3]

Literature Review

The first step of Chapter 1 was to identify, collect and review existing literature related to ramp metering projects and experiences. Specifically, this project considered the nine case studies listed in the Scope of Work as well as recent, ongoing and planned ramp metering evaluation efforts in Wisconsin. The case studies reviewed were:

- Minneapolis
- Portland
- Seattle
- Long Island
- Detroit
- Austin
- San Diego
- San Francisco Bay Area
- Denver
- Wisconsin

Appendix B, Case Studies, contains excerpts from Gary Piotrowicz and James Robinson's *Ramp Metering Status in North America 1995 Update*[4] detailing their review of the ramp metering systems listed above. It is provided to allow the reader to easily review the ramp metering experiences of the cities listed above.

Much of the literature collected for this review was compiled using an Internet search. Other sources included outreach to various State Department of Transportation officials (Washington, Oregon, New York, Illinois, etc.) involved in ramp metering and control, papers presented at professional conferences, and resource manuals produced by Federal Highway Administration (FHWA).

The literature review also identified a number of additional ramp metering resources not used in this project but which might be useful in subsequent WisDOT efforts. These additional resources are listed in Appendix A of this report.

The literature review considered the geographic and traffic criteria for implementation, reasons for each jurisdiction's decision to implement a ramp meter system, the design of the system including ramp configuration, when the system was deployed, and an evaluation of the Measures of Effectiveness (MOEs) after implementation. Table 1-1 provides an overview of many of the issues considered in the literature review for ramp metering.

Table 1-1. Ramp Meter System Information by City

	Study Roadway	Ramp Design	Operations	Reason for Implementation	Enforcement	Hours of Operation
Minneapolis	I-35	2-lane HOV Bypass	Mostly central control, few fixed	Minimize local street impacts	Regular Enforcement	Weekdays Peak Periods Off Peak Varies
Portland	I-5		Fixed	Improve safety and efficiency, minimize local street impacts		
Seattle	I-5	2-lane HOV Bypass	Area Wide Metering Strategy	Improve safety and efficiency, minimize local street impacts	Regular enforcement Violation rate < 2%	Weekdays 6:30am-9:00am 3:00pm-6:30pm
Long Island	Multiple	1-lane 1-lane with HOV 2-lane no HOV	Traffic Responsive and Central Control	Minimize Local Street Impacts	Minimal Enforcement, typically only when a new ramp is opened	Weekdays Peak Periods
Detroit	I-94		Central Control			
Austin	I-35					Am peak
San Diego (no response)	-					
San Francisco (no response)	I-80					
Denver	I-25	HOV Bypass	Central Control	Improve safety and efficiency		Weekdays Peak Periods
Milwaukee	US-45		Traffic Responsive and central control	Improve traffic flow during peak periods, and other incident related activities		Weekdays 6:00am-9:00am 3:00pm-6:30pm Off peak operations also
Chicago	System wide	1-lane	Central control, manually monitored	Improve safety and efficiency	Minimal Enforcement – minimal violations	Weekdays Peak Periods
Phoenix	Multiple	1-lane 2-lane HOV Bypass	Area wide and capable of central control but operate on fixed time	Improve current Freeway Management System and breakup platoons	Heavy fines for violation $619 Heavy congestion – violation rate approx 45% Normal conditions violation rate approx 10%	Weekdays 6:00am-9:00am 4:00pm-7:00pm 24-hour/day in construction zones

Sources: References 1, 4, 5, and Outreach efforts

Table 1-2 below provides a brief summary of common MOEs recorded from each of the case studies. Due to the lack of consensus in the establishment of common ramp metering warrants, not all MOEs were measured for each case study.

Table 1-2. Common MOEs from Various Case Studies

	Study Roadway	Increase in Average Speed	Reduction in Travel Time		Occurrence of Traffic Accidents	Change in Freeway Volume Peak Period	Initiation of Ramp Meter Program
			From	To	% Change		Year
Minneapolis	I-35	26%	-	-	- 27%	25%	1970
Portland	I-5	61%	23 min	9 min	- 43%	-	1981
Seattle	I-5	-	22 min	11.5 min	- 39%	86% (NB) 62% (SB)	1981
Long Island[A]	Multiple	9%	-	-	- 15%	2%	1989
Detroit	I-94	8%	-	-	-50%	14%	1982
Austin	I-35	60%	-	-	-	7.9%	Late 1970's
San Diego[B]	-	-	-	-	-	-	1968
San Francisco	I-80	-	2.5 min to 3.5 min		-	14%	1974
Denver	I-25	57%	37% Decrease		-5%	-	1981
Milwaukee	US-45	6% to 13%	5% Decrease		-16%	-	1969

A: The INFORM (Information For Motorist) Project covered a 40 mile long by 5 mile wide corridor at the center of which was the Long Island Expressway (LIE).

B: No detailed evaluation of the ramp metering system has been conducted since the early installation, but vehicle throughputs of approximately 2200 vph to 2400 vph are common on San Diego's metered freeways.

Additional information gathered from ramp metering officials in some of the Case Study Cities are provided in Table 1-3 on the following page. The table is an overview of lessons learned, best practices, implementation criteria, effects ramp metering has on traffic patterns, and ramp configurations.

Table 1-3. Additional information gathered from ramp metering officials in some of the Case Study Cities

	Lessons Learned	Best Practices	Criteria for Deploying Ramp Metering	Example of Ramp Metering being used to change routes, travel times, or modes	Ramp Configurations
Seattle	Conduct more extensive public outreach; improve communications between public and DOT; employ more extensive "Fuzzy Logic" Algorithms that include both arterial and mainline traffic information.	Meter vehicles along shoulder of ramp during peak periods – during peak periods ramp operates as a two lane ramp, during off peak times ramp operates as a single lane ramp.	Number of Accidents (no threshold number set); evaluation of local conditions (qualitative, not quantitative); lane capacity ≈ 1500 vphpl; ramp metering implement ≈ 20% occupancy.	More HOV users if HOV Bypass ramp is available (typically will try to add a park-and-ride lot in the area of the HOV Bypass ramp); park-and-ride lots are usually joint ventures of the State DOT, local government, and transit.	- Single Lane - Dual Lane - HOV Bypass - Multi-lane (more than 2 lanes)
Long Island	Heavy enforcement when deploying a new ramp meter.	Pretimed meters operating during AM and PM peak hours.	Number of Accidents (no threshold number set); evaluation of local conditions (qualitative, not quantitative); follow CALTRANS Ramp Meter Design Guidelines for geometric guidelines.		- Single Lane - Single Lane with HOV Bypass - Dual Lane no HOV Bypass
Portland	NO RESPONSE				
Phoenix	NO RESPONSE				
San Diego	Effective tool for improving overall travel times of commuters; when adding new meters, ensure additional resources are also added to the system (staff, maintenance contracts, etc.).	Using a traffic responsive system where metering rates are adjusted at each ramp dependant on the local conditions at each ramp.	Follow CALTRANS Ramp Meter Design Guidelines.	N/A	Single lane, dual, and triple lane configurations with SOV and HOV lanes.
California (Statewide)	Ramp metering is a very effective tool for relieving traffic congestion, reducing travel time, and accidents.	Working closely with local officials and the public to ensure they are well informed of existing and future ramp metering plans.	Follow CALTRANS Ramp Meter Design Guidelines.	Metering encourages some drivers to use alternate routes.	Single lane, dual, and triple lane configurations with SOV and HOV lanes.
Detroit	Ramp metering has improved the flow of traffic over the condition of not having metering.		No set criteria, just installed along entire corridor, not just individual ramps.	N/A	System is currently not operational; hopes are to have the system working again in 2 to 4 years.

Results

The review of existing ramp metering systems revealed a great deal of information related to: the criteria used to select a ramp metering site, ramp configuration, the type of ramp metering system, and enforcement issues. This technical memorandum also considered geographic and traffic criteria, measures of effectiveness used to evaluate traffic performance, current ramp metering deployments around the country, and the goals and strategies often sited for ramp metering. Each of these items is addressed below relative to national practices. The application to Wisconsin is addressed at the end of this chapter.

When to Use Ramp Metering

It is important to remember from a transportation facilities standpoint, freeways and arterials operate quite differently, with ramps being the common connection point. On arterials, platoons are encouraged, when these platoons created by properly functioning arterials attempt to enter or merge with a congested freeway, traffic flow breakdowns are likely to occur. Ramp meters are a tool used to limit or control platoons merging onto a freeway.

Recurring congestion is the predictable occurrence of slow downs in traffic flow. Typically it occurs during peak hours in the same location on a daily basis. Ramp metering is the primary traffic management tool to reduce the impacts of recurring congestion on freeways. Metering is also used during non-recurring congestion (incidents, debris, etc.) to help manage flow in the vicinity of, and upstream of, a temporary bottleneck. However, metering is primarily used as a proactive tool to delay the onset of, and reduce the time period of, recurring congestion[4].

As a traffic management tool, it can be used for other purposes. Specifically, it can be used to promote specific policies or travel demand strategies. This report addresses at a higher level these issues concerning when ramp metering should be used to support a travel demand policy. The reason is the metrics are much less direct and the calculated effectiveness is not as well documented. For example, with respect to metrics, when ramp metering is implemented to reduce congestion on the corresponding freeway, removing incidents and seasonal variations results in a direct cause and effect. That is, the active management of the ramp traffic directly impacts the freeway operations. Conversely, if ramp metering is used as an incentive to have people change travel times, then there are many other variables that have to be considered. Are you trying to delay their trip 15 minutes, 30 minutes, or an hour? Do people not make their trip? Do they use a different mode? Do they choose a new destination? The active management of the ramp may affect all of these, but none of them can be directly measured and attributed solely to the ramp metering.

From our literature review a number of common strategies were noted as keys to determining when ramp metering should be used. Some of these strategies include: geometric considerations, traffic criteria, and availability of alternative routes. Each of these strategies is addressed in the following sections.

Why Use Ramp Metering?

Ramp metering is used to reduce congestion or improve merge operations on heavily congested urban freeways. Because there is not uniform evaluation criteria used nationally, it is difficult to accurately compare all systems, but a review of the case studies has revealed in each study area, average speeds and vehicle throughput increased, while travel times and peak period accidents declined for freeway users.

The *Twin Cities Ramp Meter Evaluation Report – Appendix to the Final Report* provides a general evaluation of measures of effectiveness (MOEs) used in Ramp Metering evaluation studies conducted worldwide. Table 1-4 provided below lists common MOEs used in many of the evaluation studies along with the trends caused by ramp metering. The first seven MOEs reveal travel conditions for freeway users tend to improve, while the remaining MOEs show travel conditions for drivers on the arterials typically worsen. Specific examples of MOEs are provided in Table 1-2 of this document as well as many of the references provided at the end of this document.

Table 1-4. List of Common MOEs with Corresponding Trends[5]

MOE	Trend
Freeway mainline speed	Increases
Accident rate/frequency	Decreases
Freeway mainline occupancy	Decreases
Overall travel time/delay time	Decreases
Freeway mainline volume/flow/stability of flow	Increases and stabilizes
Fuel savings	Increase
Benefit/cost (B/C) ratio	>1.0
Ramp delays	Increase
Arterial vehicle volume	Increases, but insignificant
Overall travel demand	Increases
Public/motorist survey results (qualitative)	Mixed

In general, ramp metering is used to improve traffic conditions on freeways and encourage motorists on arterial roadways to alter their commute by using other routes, commuting during non peak hour travel times, ride share (if HOV ramp meter bypass lanes exist), or use other modes of transit. A notable exception to this was seen in the case study for Seattle, Washington. This case study revealed an example of ramp metering being used to reduce commuter diversion through a residential neighborhood and encourage commuters to either stay on SR-520 or get on it earlier in their commute.

Another example, also from Seattle, Washington, reveals that in many instances where a new ramp meter is deployed, and also includes an HOV Bypass Lane, many commuters choose to car pool. In a number of cases, the State DOT, in partnership with local government and Transit, will jointly fund the construction and operation of a park-and-ride lot for commuters wishing to carpool.

Ramp Metering Deployments

Ramp meters are currently present in more than thirty cities worldwide with more than 3,000 ramps being metered every day. Figure 1-8 is a map with the number of ramp meters in operation in the U.S. (1999)[6].

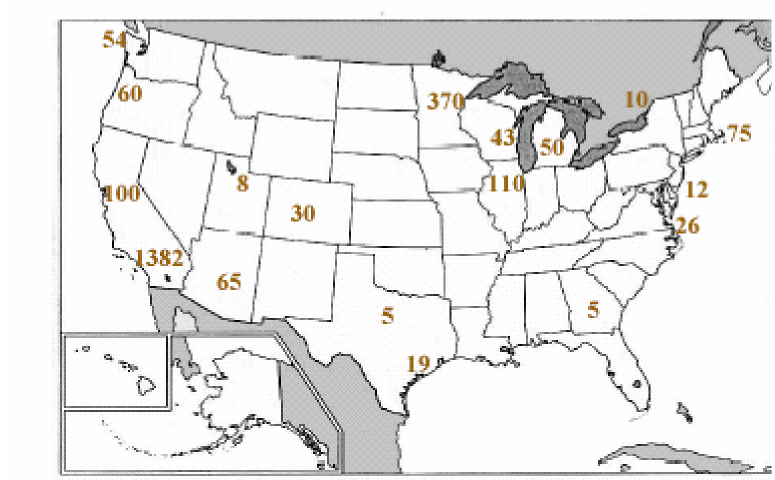


Figure 1-8. Ramp Meter Deployment in the US (1999)

According to Piotrowicz and Robinson, as noted in *Ramp Metering Status in North America 1995 Update*, from the years 1989 to 1995 the number of ramp meters in North America increased from nearly 1600 to over 2300. From the USDOT's ITS Deployment Tracking 2002 survey results, nearly 2200 ramp meters are in use in 28 jurisdictions throughout the US. The following Table 1-5 lists the total number of ramp meters in use from each of the 28 US agencies who replied to the survey. It is important to note this table does not include ramp meters currently in jurisdictions that did not respond to the survey or ramp meter deployments in the rest of North America.

Table 1-5. Ramp Meter Deployment – 2002 USDOT's ITS Deployment Tracking Survey

Metropolitan Area	Agency	Ramp Meters
Allentown, Bethlehem, Easton, PA	Pennsylvania Department of Transportation-Allentown	14
Atlanta, GA	Georgia Department of Transportation	5
Beaumont-Port Arthur, TX	Texas Department of Transportation	1
Chicago, IL; Gary, IN; Lake County, IL	Illinois Department of Transportation	113
Columbus, OH	Ohio Department of Transportation	15
Dallas, Fort. Worth, TX	Texas Department of Transportation Fort Worth District	5
Denver, Boulder, CO	Colorado Department of Transportation	30
Detroit, Ann Arbor, MI	Michigan Department of Transportation	60
El Paso, TX	Texas Department of Transportation-El Paso District	1
Fresno, CA	Caltrans District 6	35
Houston, Galveston, Brazoria, TX	Texas Department of Transportation-Houston District	128
Los Angeles, Anaheim, Riverside, CA	Caltrans District 7	20
Los Angeles, Anaheim, Riverside, CA	Caltrans District 8	147
Milwaukee, Racine, WI	Wisconsin Department of Transportation	118
Minneapolis, St. Paul, MN	Minnesota Department of Transportation	419
New York, NY; Northern New Jersey, NJ; Southwestern Connecticut, CT	New York State DOT-Long Island Region 10	85
New York, NY; Northern New Jersey, NJ; Southwestern Connecticut, CT	Port Authority of New York and New Jersey	1
Philadelphia, PA; Wilmington, DE; Trenton, NJ	Pennsylvania Department of Transportation District 6-0	6
Phoenix, AZ	Arizona Department of Transportation	122
Portland, OR; Vancouver, WA	Oregon Department of Transportation	110
Sacramento, CA	Caltrans District 3	80
Salt Lake City, Ogden, UT	Utah Department of Transportation-Region 2	23
Salt Lake City, Ogden, UT	Utah Department of Transportation-Region 1	1
San Diego, CA	Caltrans District 11	288
San Francisco, Oakland, San Jose, CA	Caltrans District 4	191
Santa Barbara, CA	Caltrans	1
Seattle, Tacoma, WA	Washington State Department of Transportation Northwest Region	120
Washington , DC	Virginia Department of Transportation	24
Total		2,163

Source: United States Department of Transportation Website

Geometric Considerations

A number of states have design guidelines accounting for geometric considerations for metered entrance ramps. Common amongst the designs are certain characteristics that make ramps suitable for metering. The three primary considerations are the availability of storage space, adequate acceleration distance and merge area beyond the meter, and sight distance.

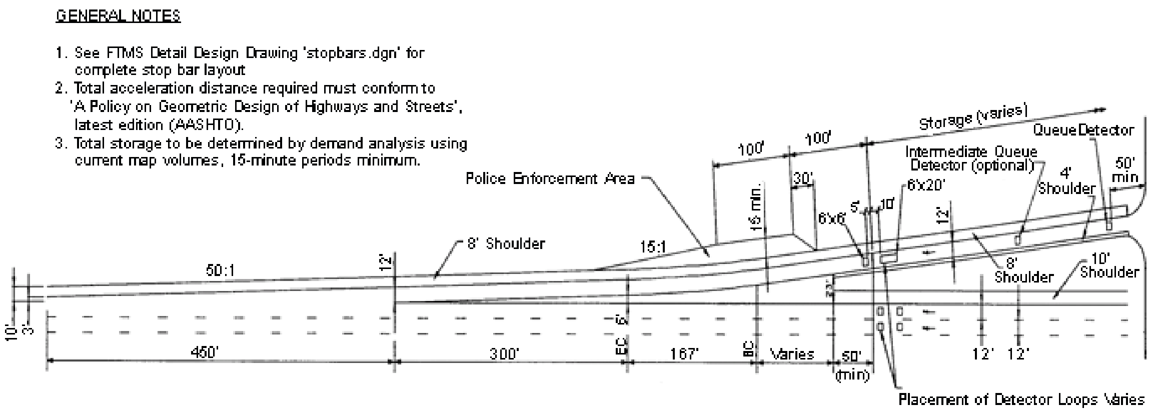


Figure 1-9. Wisconsin DOT Ramp Meter Design Guidelines[3, 7]

Ramp storage requirements can depend on ramp demand volumes and metered rates, ramp entry flow patterns (e.g., platoons caused by adjacent upstream signals), and availability of surface street storage. The availability of adequate vehicle storage can often be addressed by using two or more lanes along the ramp. This can be accomplished by restriping or reconstructing ramps to allow for two or more lanes. Our literature review revealed that consensus has not yet been reached on the most appropriate way to release vehicles from multiple lane ramps. Currently it is possible to find jurisdictions releasing vehicles simultaneously, intentionally staggered, and independently (randomly). As noted in the 1995 update of *Ramp Metering Status in North America*, one loop ramp in Minneapolis was widened to four lanes approaching the ramp meters. The meters release vehicles from two lanes at a time, alternating between the right pair and the left pair. Downstream of the meter the vehicles merge into one lane before reaching the freeway. Northern Virginia and Seattle are two systems that release vehicles simultaneously, while Chicago releases vehicles one at a time.

Wisconsin DOT guidelines require the ramp to provide storage for a minimum of 10% 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 SOV lanes. For ramp meters designed in conjunction with ramp reconstruction, the ramp should accommodate a minimum of 10% of the *design* year projected peak hour volume. For ramp meters retrofitted to existing conditions, a storage minimum of 5% of the current peak hour volume may possibly be used[7].

The distance downstream of the meter must be adequate to permit vehicles to accelerate to freeway speeds from a stopped condition. The acceleration characteristics of heavy trucks and small economy cars, and the grade of the ramp are factors that must be considered. Many agencies have lengthened acceleration lanes to provide for safe merging.

The third consideration is sight distance. Because of the curvature on many ramps, it is difficult to obtain minimum stopping sight distance requirements. Additionally, unless the public is well informed, drivers generally are not expecting to stop on an entrance ramp. Therefore, advance warning signs are usually needed to make drivers aware of the forthcoming stop. Blank out signs or static signs enhanced with flashing lights are the most common forms used. In addition to advance signing, at high accident ramps, INFORM (Long Island, New York) also uses strobe lights in the red lens to help emphasize the stop indication. Many states have standardized advance warning signs and other ramp metering considerations.

Additional geometric considerations include:

- Ramp Width – If more than one metering lane is desired, adequate width is required for side by side (tandem) metering and/or preferential HOV bypass lanes.
- Grade – Ramp grades should not be restrictive during adverse weather or for certain types of heavy vehicles.
- Merge Area – The present design should facilitate a smooth merge for vehicles accelerating after being stopped at the meter.

In January 2001, Texas did not have guidelines for designing freeway entrance ramps with explicit consideration of ramp metering. TxDOT initiated the *Design Freeway On-Ramps for Metering*[8] to address this need. Researchers at the Texas Transportation Institute performed an in depth study of current ramp metering design and operations practice in Texas and in other states. The purpose of this study was to acquire an understanding of all key elements related to ramp metering in Texas. Then the researchers developed spreadsheet based analytical tools and simulation models for studying all key design variables. The researchers also utilized hardware-in-loop simulation to verify the results of these models. These tasks led to the development of design criteria for ramp metering in Texas as summarized in the report.

Figure 1-10 provides a brief snapshot of the Optimum distance from the center of an upstream signalized intersection to ramp meter for various traffic demand levels. Figure 1-11 shows the distance from meter to merge point for three ramp grades as proposed in the study.

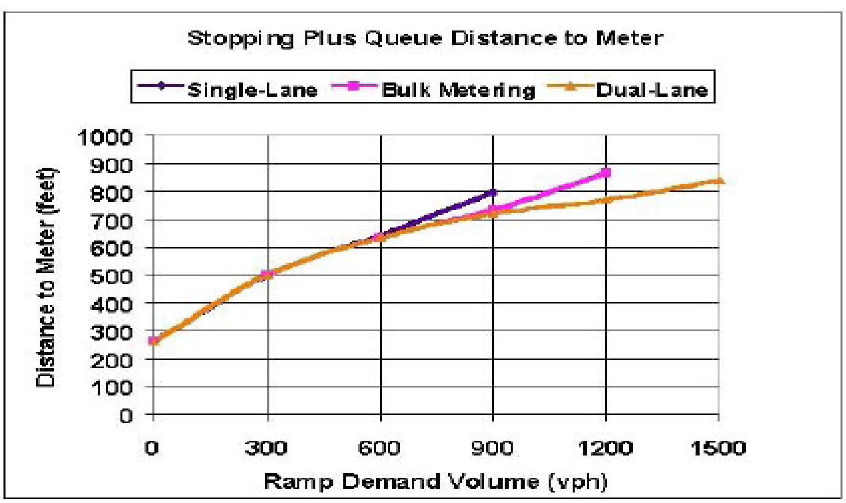


Figure 1-10. Optimum distance from the center of an upstream signalized intersection to a ramp meter for various traffic demand levels[8]

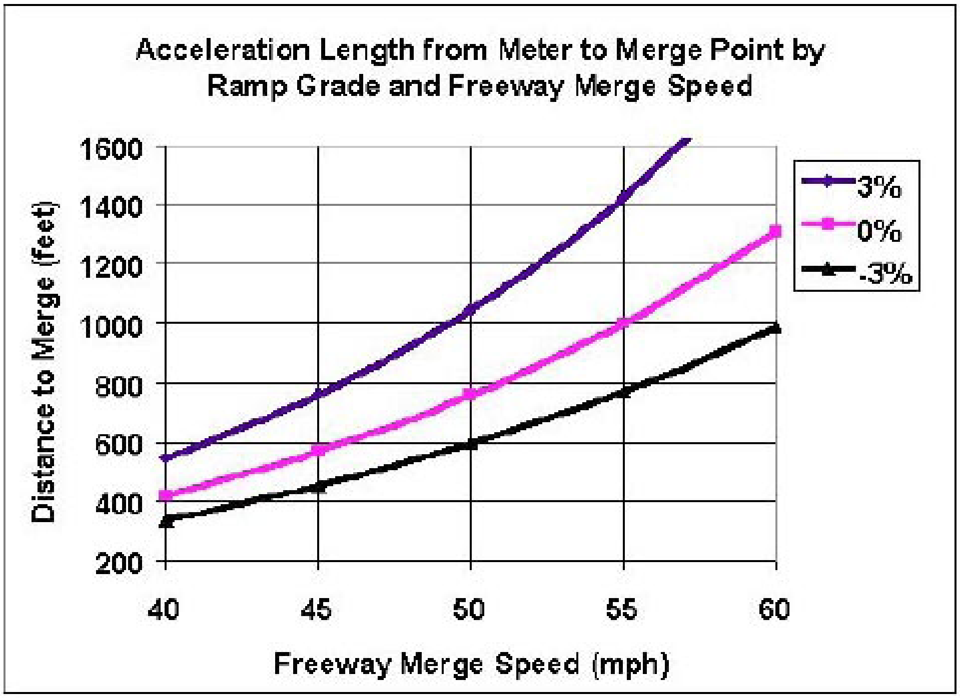


Figure 1-11. The distance from meter to merge point for three ramp grades[8]

Additional on ramp design information related to this study can be found in reference 15.

Traffic Criteria

Generally, there are no specific warrants for ramp metering, because of the many local factors involved. The Texas Department of Transportation (TxDOT) compares the peak sum of the ramp and all freeway mainline volumes to a preset table and determines if ramp metering is warranted at such locations. Similarly, the Arizona Department of Transportation (ADOT) determines that the peak sum of the ramp volume and the rightmost mainline lane volume must be equal or greater than 1,800 vehicles per hour (vph) to warrant ramp metering. If the rightmost mainline lane volumes are not available, ADOT uses the standard developed by TxDOT.

The *Chicago Area Expressway Surveillance and Control Final Report*[9] provides a discussion on Occupancy Based Metering which proposes metering rates for on ramps based on the measurement of vehicle occupancy in an individual lane. This report produced the Figure 1-12 below that illustrates the relationship between lane volume, lane occupancy, and traffic flow conditions.

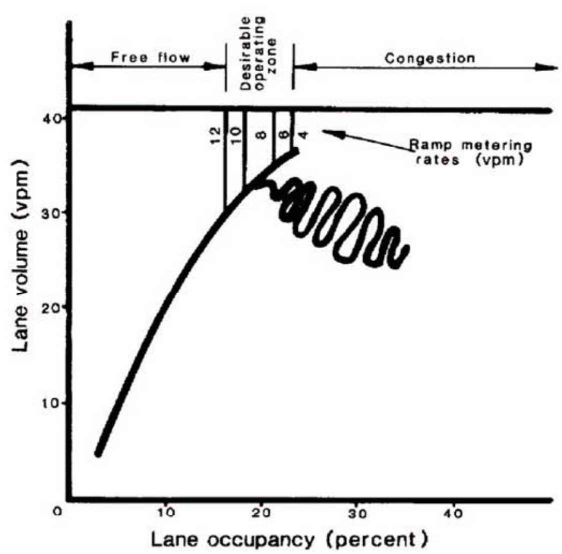


Figure 1-12. Typical Volume Occupancy Plot[7]

The Chicago study revealed that free flow conditions typically exist until the lane occupancy rate of approximately 16% is reached. At this point, ramp metering should begin in an effort to help prevent the freeway from reaching lane occupancy rates above 27% or congested flow, as shown in Figure 1-12. When ramp metering is operating prior to congestion occurring, occupancy increases represent volume increases until congestion develops.

In Cassidy and Rudjanakanoknad's[10] study, *Increasing Capacity of an Isolated Merge by Metering its On-Ramp*, they conclude breakdowns always occurred at or shortly before the time measured occupancies rose to 27%, supporting the conclusion of the Chicago study.

From Wisconsin's *Ramp Meter Retiming Procedure* document, ramp metering periods for existing systems are determined by reviewing the volume to capacity (v/c) ratio of the freeway. Based on the Highway Capacity Manual (HCM), congestion levels are critical when the v/c ratio reaches 0.7. Thus, it is common practice to begin metering when the freeway reaches a v/c ratio value of 0.7. The user must also consider freeway occupancy greater than 18%, freeway speed reduction, freeway LOS, mainline volume, downstream bottleneck conditions, the merge influence area, and ramp diversion when determining ramp metering periods[11]. It is important to note the above criteria outline when an existing ramp metering system should be turned on but it is also reasonable to use the same criteria for determining when a ramp metering system should be deployed.

Below are some general guidelines for when to deploy ramp metering, suggested in both Piotrowicz and Robinson, as well as the *Twin Cities Ramp Meter Evaluation – Appendix to the Final Report*. They note historically, freeway sections that warrant ramp metering have the following characteristics:

- Peak period speeds less than 30 mph;
- Vehicle flows between 1,200 to 1,500 vphpl;
- High accident rates;
- Significant merging problems.

Outreach efforts revealed Washington State Department of Transportation uses the four characteristics listed above as part of their criteria for determining when to deploy ramp metering. They also rely on detector data collected from their system to measure lane occupancy, using this information in their decision process to determine when ramp metering could have a beneficial impact on traffic flow. Washington State DOT did note in most cases, the Department prefers to implement ramp metering along a corridor instead of a single ramp. This is to reduce the likelihood of commuters using the adjacent ramps as bypasses for the metered ramp.

Availability of Alternative Routes

Another major consideration when considering deployment of ramp meters is the availability of alternate routes on adjacent roadways to allow drivers to avoid queues at the meters. Piotrowicz and Robinson noted in *Ramp Metering Status in North America 1995 Update*, that extensive evaluations of existing metering systems showed adjustments in traffic patterns, after metering was implemented, took many forms. However, it was possible to predict the likely impacts of metering before it was installed. Factors entering into the analysis included trip length, queue length, entry delay, and especially the availability of alternate routes. The impact of attractive and efficient alternate routes was seen as potentially a key factor in the effectiveness of a ramp metering system. The probable new traffic patterns, including diversion, could then either be accommodated in the design and operation of the local transportation system, or become part of a decision that metering was not feasible.

Piotrowicz and Robinson went on to say metering may in fact divert some short trips from the freeway. In concept, freeways were not intended to serve very short trips, and diverting some trips may even be desirable if there are alternate routes under utilized. Diverting traffic from high volume, substandard, or other problem ramps to more desirable entry points should be an objective of metering where it is feasible. Such an action would require a thorough analysis of the alternate routes and the impacts of diversion on those routes, and improvements on the alternate routes when and where they are needed.

Goals and Strategies of Ramp Metering

Depending on the goals and objectives of the implementing agency, several types of ramp metering strategies can be pursued. Several factors influence how agencies choose the best strategy for their cities, but the decision is mainly driven by the public, local politicians, and geometric conditions of the ramps. The types of ramp metering strategies include[7]:

1. Emphasis on Safety – Under this scenario, safety is the main objective, and metering rates are typically very restrictive (imposing high metering delays). This reduces the traffic flow turbulence on the freeway, and therefore the number of accidents at the merge areas. Often viewed as too restrictive and controversial, currently there are no agencies adopting this strategy (although most use the goal of increased safety in their decision on ramp metering).
2. Optimize Travel Safety and Efficiency – Metering rates are less restrictive than Strategy 1, since some emphasis is placed on maximizing the capacity of the freeway. Minneapolis-St. Paul and San Diego are the primary cities implementing this strategy.
3. Minimize Local Street Impacts – When queue storage is limited on the ramps, as in the case of Houston (TX) and Arlington (TX), more provisions need to be made to ensure no queues develop on the arterials. However, such compromises decrease the effectiveness of ramp metering. Nevertheless, studies[4, 12] show that some positive benefits are obtained.
4. Combination of Strategies 2 and 3: Basic Freeway Management – Due to public and/or political pressure, most cities adopt this strategy as a compromise. Since the public is wary of queues and delay at the ramps, metering rates are adjusted at some cost to the freeway and overall transportation efficiency.

Table 1-6 below provides examples of the ramp metering goals and strategies employed by various cities around the United States.

Table 1- 6. Ramp Metering Goals and Strategies employed by Various Cities around the United States

	Emphasis on Safety	Optimize Travel Safety and Efficiency	Minimize Local Street Impacts	Combination of Strategies 2 and 3
Minneapolis		X	X	
Portland		X	X	
Seattle		X	X	X
Long Island			X	
Denver		X		
Milwaukee		X		
Chicago		X		
Phoenix		X	X	
San Diego		X		

The Role of Micro Simulation on Ramp Metering Design

New ramp metering strategies must be evaluated and tested, but experimenting in the field with real traffic is considered politically risky. Therefore, researchers and professionals often rely on simulation models. Many simulation studies have been conducted to estimate the effects of ramp metering, but in some cases simulation does not correspond well with empirical results. Part of the discrepancy is caused by the assumptions in some models, such as uniform driver aggressiveness and somewhat fixed demand. Simulated investigations suggest that metering can be beneficial provided that the control algorithm is precise, that queues do not spill back onto surface streets, and that surface streets have excess capacity to accommodate diverted vehicles. In contrast, results from deployed systems indicate that diversion is minimal, and that even without alternate routes, metering can be successful. Simulated models suggest metering can obtain speed increases upwards of 4% and reduced travel times up to 26%, in accordance with empirical results[1].

How to Implement Ramp Metering

In this section of the document, we look at the design and operational considerations that should be given to a new ramp metering deployment. The amount of funding available, existing or planned transportation infrastructure, and the complexities of the existing arterial signal system, are a few of the considerations the system operator and designer should be aware of. Once the decision has been made to implement ramp metering and the potential ramp locations identified, consideration should be given to the expected arrival rate of vehicles to the ramp, available storage capacity, potential for providing an HOV bypass lane, the type of ramp metering system to be used, and how enforcement will be handled.

Important groups or constituents to consider before implementing a ramp metering system include: the public, the media, local government and political officials, Law enforcement, and managers/operators of the arterial street network.

If ramp metering is new to the user community, a public information program using the media and public information meetings is often employed to describe the benefits as well as how to respond to metered signals. Local news media, both print and electronic, can have a profound effect on the success of ramp metering systems. It is important that a media relations plan be developed to help ensure that positive support is secured.

Although a support base and consensus may be built at the staff and agency level, it is important to build support with elected officials as well. Benefits of ramp metering are real and measurable in the overall system, but may not be apparent to the individual driver who experiences delay at an entrance ramp or must reroute due to a ramp closure. Citizen complaints can have an adverse effect on the success of ramp metering projects.

Enforcement must be supported by the judicial system. A standard ramp traffic signal that meets the requirements of the Manual On Uniform Traffic Control Devices (MUTCD) is a legally enforceable device. It is important to ensure that the proper laws and ordinances are in place and that judges to whom appeals of citations may be taken are informed of the system goals, objectives, and operating characteristics prior to system turn on. Where geometrics permit, police enforcement areas may be incorporated into the design of metered ramps.

Finally, by altering entry ramp flow, ramp metering can change the interaction of the freeway system with surface street traffic movement – for example, traffic may spillback from metered ramps into the surface street traffic stream, so it is important that managers/operators of the local arterial street network be involved.

Design

As mentioned earlier, the geometric configuration of the ramps is a key factor in deciding the ramp metering strategy. Since vehicles queue on the ramps, ample storage room must be available. Increasing ramp storage capacity can be addressed using one of the following approaches[5]:

- Increasing the Length of the Ramps – One simple way to provide more vehicle capacity is by increasing the length of the ramps. However, long ramps are expensive and space consumptive. In urban areas, there is typically not enough room to build long ramps. Furthermore, long ramps may increase violation rates, especially if queues are constantly backed up to the ramp entrance[4]. Denver is an example of a city that recognized the need for longer ramps to accommodate longer vehicle queues. Ramps designed for ramp metering in the city's first deployment were generally considered to be too short. When ramps were designed subsequent to the initial deployment, they were lengthened[12]. Many of the metered ramps along Shirley Highway (I-395) in Virginia are single lane designs as well as along the Katy Highway (IH-10) in Houston, Texas.

Figure 1-13. Single Lane Ramp Metering[13]

- Two Lane Ramps – Another simple way to increase ramp storage capacity is by adding another lane to the ramp. Similar to longer ramps, constructing a two lane ramp can be an expensive and difficult effort, especially in urban areas[7]. During peak periods in Seattle, some drivers of the single lane on ramps shown in Figure 1-13 use the shoulder as a second metered lane as shown in Figure 1-14. Dual lane metering is used in Denver, Portland, Northern Virginia, and Texas.

Figure 1-14. Dual Lane Ramp Metering[13]

- High Occupancy Vehicle (HOV) Bypass Lane – When the on ramp has two or more lanes, certain agencies prefer to dedicate one of the lanes as an HOV bypass lane, instead of metering all lanes. HOV bypass lanes are sometimes more attractive over two or more lane ramp meters because they also promote carpooling and improve transit operations. The disadvantage of HOV bypass lanes is the possible increase in violation rates[7]. Seattle reports their only real violations occur when drivers avoid the queues in the regular lanes by using the bypass lane. Other cities using HOV Bypass lanes include San Francisco/Oakland, Minnesota, and Las Vegas. Signage for a HOV Bypass is at right in Figure 1-15.

Figure 1-15. HOV Bypass Sign – Seattle

The Minneapolis-St. Paul area has long, two lane ramps that can store large numbers of vehicles. However, delays at the ramps have been known to be long, as high as 20 minutes. Interestingly, violation rates at these ramps remain low. Nevertheless, the Minnesota Department of Transportation (MnDOT) was able to implement Strategy #2 (Optimize Freeway Safety and Efficiency) from the Goals and Strategies of Ramp Metering section of this report, largely because of the favorable ramp geometrics.

Operations

There are many different options available when deciding how to operate a ramp meter system. This document will consider the following types of ramp metering systems: Fixed Time, Local Traffic Response Operation, System Wide Traffic Response Operation, Demand-Capacity Control Strategy, and Local Predictive Algorithms.

- **Fixed Time –** This is the simplest form of ramp metering control where equal amounts of green time are given to all vehicles regardless of the freeway traffic conditions. This type of system performs the basic task of breaking up platoons into single vehicle entries to the freeway as well as setting a maximum rate of vehicles entering the freeway system. Portland is an example of a U.S. city using fixed time ramp metering.
- **Local Traffic Responsive Operation –** This form of ramp metering determines metered rates using the actual freeway conditions adjacent to the ramp. Detectors are placed in the freeway to measure the real time traffic conditions from which the

metering rates are set. Local traffic responsive control also allows ramp metering to manage demand rates when incidents occur on the freeway, i.e. reduce the metering rate at ramps upstream of the incident and increase the rate at ramps downstream. Most current ramp metering systems have this capability, but many choose not to use this feature because of infrastructure restrictions, funding constraints, or other system priorities.

- **System Wide Traffic Responsive Operation –** Similar to local traffic responsive operations, system wide traffic responsive operations use detectors in or along the freeway to monitor traffic conditions. However, system wide traffic responsive operates on the basis of total freeway conditions, not just freeway conditions adjacent to the ramp. Centralized computer controlled systems can handle numerous ramps in a traffic responsive scheme and feature multiple control programs and overrides. Control strategies can also be distributed among individual ramps. A significant feature of system control is interconnection that permits the metering rate at any ramp to be influenced by conditions at other locations. Denver showed that this type of control has significant benefits when properly applied[4].
- **Demand-Capacity Control Strategy –** In addition to detecting traffic conditions on the freeway network, the integrated controllers monitor traffic conditions on the alternative arterials. If traffic volumes on the city streets are too high, the meter delays may be reduced to encourage motorists to use the freeway instead[5]. Other cities using demand-capacity control strategy include Houston and Minnesota.
- **Local Predictive Algorithms –** This is sometimes referred to as "Fuzzy Logic Control." Traffic responsive controllers normally react to, rather than prevent, congestion. As mentioned, traffic responsive controllers usually apply metering rates based on traffic data from the previous minute, which may be too late in the case of an accident/incident. Furthermore, traffic responsive controllers are not capable of interpreting erroneous or imprecise traffic data, which often occurs with freeway loop detectors. Fuzzy logic controllers manage to solve these problems by having short range predictive capabilities, and can be utilized to smooth out and process imprecise or erroneous information[5]. Seattle is an example of a jurisdiction using local predictive or Fuzzy logic. Our outreach research determined Seattle is currently considering upgrades for its current algorithms.

Table 1-7 of this document identifies the types of ramp metering systems used by many of the cities listed in the case studies reviewed in this report. Additional information related to the types of ramp metering systems and ramp metering rates can be found in references: 1, 4, 5, 6, 7, and 10 located at the end of this report.

Since each of the ramp metering systems discussed has its own strengths and weaknesses, Table 1-7 below provides general guidelines for some types of ramp metering systems given common applications.

Table 1-7: General Guidelines for Types of Ramp Metering

	Application	Pretimed Local	Traffic-Responsive Local	Pretimed System wide	Traffic-Responsive System wide (Note 1)
1.	Achieve smoother flow at merge (safety improvement – preserve merge capacity)	Applicable	Applicable	Applicable	Applicable
2.	Spot congestion problems – sufficient control for one meter to satisfy	Applicable if congestion time period stable	Applicable	Applicable	Applicable
3.	Congestion requiring control distributed over several meters	Not Applicable	Not Applicable	Applicable if congestion time period stable	Applicable
4.	Scheduled special events	Applicable if one meter can satisfy and congestion time period stable	Applicable if one meter can satisfy	Applicable if congestion time period stable (**Note 2**)	Applicable
5.	Highly variable mainline demand	Not Applicable	Applicable if one meter can satisfy	Not Applicable	Applicable
6.	Congestion due to spillback from exit ramp onto mainline	Applicable if one meter can satisfy and congestion time period stable	Applicable if one meter can satisfy	Applicable if congestion time period stable	Applicable
7.	Congestion due to incidents	Not Applicable	Applicable, but system wide preferred	Not Applicable	Applicable
8.	Congestion due to construction	Not Applicable	Applicable, but system wide preferred	Applicable (**Note 2**)	Applicable
9.	Use in combination with other controls: • Closure • CMS • Route Guidance	 Unlikely to be Applicable Not Applicable Not Applicable	 Applicable Not Applicable Not Applicable	 Unlikely to be Applicable Not Applicable Not Applicable	 Applicable Applicable Applicable
10.	Backup Mode	Backup to Traffic – Responsive – Local	Backup to Traffic – Responsive – System wide	Backup to Traffic – Responsive – System wide	Not Applicable

Note 1: Assumes that pretimed system wide and local traffic-responsive modes are available.
Note 2: Applicable only if rates and times are alterable through communications.
Source: Traffic Control Systems Handbook, FHWA, February 1996

Enforcement

As with other traffic control devices, the effectiveness of ramp metering is directly related to the user's willingness to comply with the system's directions. As a part of the public education program, it should be made clear to users that ramp meters are a part of the traffic control system and disregarding the system carries the same penalties as not obeying traffic signals at local intersections. The case studies review revealed, in cities where public

Figure 1-16. HOV Bypass Enforcement

education was actively promoted, violation rates were lower. It is important to note, like any other traffic regulation, enforcement is needed. Effective enforcement requires good enforcement access, a safe area to cite violators, adequate staff, support by the courts, and good signs and signals that are enforceable. Enforcement needs must be considered and accommodated early during the project development and design stages. HOV Bypass Enforcement personnel as demonstrated in Figure 1-16, should also be included early on in the planning and design of ramp metering projects. Compliance is critical to the success of a ramp metering system. Compliance rates have generally been good in most areas across the country. However, violations are contagious and can multiply quickly. The result can lead to an extremely ineffective ramp metering system.

In Seattle, WSDOT launched the "HERO" program, which allows motorists to report violators via a toll free number. The violators will then receive warnings by mail. Initially, the program resulted in a significant reduction in the violation rate. Over time, however, as violators realized that no further action would be taken, the program lost its effectiveness[5]. Today, violations have been confined primarily to users jumping the queue by using the Bypass lane.

Results

Survey of Previously Used Ramp Metering Implementation Criteria

The literature review provided only limited information about specific criteria used by jurisdictions to determine if ramp metering would be implemented. Piotrowicz and Robinson noted in *Ramp Metering Status in North America 1995 Update*, that a number of attempts have been made in the past to develop a formal set of ramp meter warrants, but due to the unique nature of each individual location, it was difficult to determine a single set of conditions due to the wide range of factors involved. They also noted ramp metering should be only one element of a larger overall freeway management program.

The Manual on Uniform Traffic Control Devices (MUTCD) does provide some broad guidelines on when the installation of ramp meters may be appropriate. The MUTCD simply states that entrance ramp signals may be justified when the total expected delay to traffic in the freeway corridor, including freeway ramps and local streets, is expected to be reduced. Minimum volume warrants were considered, but not used because freeway capacity does vary according to geometric, traffic and driver characteristics. Freeway operating conditions provide the most guidance. Candidate freeways for ramp metering historically have the following peak period conditions:

- Peak period speeds less than 30 mph;
- Vehicle flows between 1,200 to 1,500 vphpl;
- High accident rates;
- Significant merging problems.

Minnesota and Seattle both report considering these criteria as part of their decision process when determining if a ramp or series of ramps should be metered. Seattle and Chicago also reported using detector data to measure lane occupancy and using this information as another indicator for determining when ramp metering might be beneficial.

Other candidates for metering include new and reconstructed facilities that may become overloaded shortly after completion. There is agreement among operating agencies that it is best to implement metering before conditions get severe. More restrictive metering rates can then be applied gradually as demand increases over time to help spread the peaks and thus maintain operational efficiency[4].

In Minneapolis/St. Paul, high accident locations and freeway operating conditions were the two most frequent factors used to identify candidate ramps for metering. Metering some ramps may also be required to complete a system, to prevent undesirable shifts in travel patterns, to address the equity issue, and/or to improve the quality of a merge operation[4]. Seattle reported ramp metering was initially implemented in an attempt to both improve safety and the efficiency of their roadway system. As time went on and the system matured, additional metering projects were also considered based on local traffic impacts.

Benefits/Cost

According to Piotrowicz and Robinson, ramp metering is "one proven method of maximizing exiting roadway capacity." While consensus may not have been developed with respect to establishing general criteria for implementing ramp metering, the literature review reveals most case studies commonly report similar benefits and costs related to deploying ramp metering. Below is a description of the common benefits for freeway users attributed to the implementation of ramp metering.

Metering shortens the duration of congestion and improves overall traffic conditions. There is evidence[1, 4, 5, 12] that metering increases throughput, as many metered highways sustain peak volumes well in excess of 2,100 vph (flows up to 2,450 vph have been achieved). Data from the Minneapolis, San Diego, Seattle, Detroit and Denver Studies show mainline volumes well in excess of 2,100 vphpl[4]. By eliminating the stop and go behavior associated with congestion, metering can also result in up to 50% increases in speed and up to 30% reductions in accidents. Though traffic diversion to the surface network is an important metering concern, empirical results suggest no more than 5-10% of vehicles will be diverted[1]. According to *Evaluation of Ramp Meter Effectiveness for Wisconsin Freeways, A Milwaukee Case Study,*[14] both Minneapolis and Chicago reported only minimal traffic diversion as a result of new ramp meter deployment.

In Portland, City officials were very concerned about entrance metering creating problems on parallel streets. Before the meters on I-5 were installed, the city and state agreed that if volumes on adjacent streets increased by more than 25% during the first year of operation, the state would either abandon the project or adjust the meters to reduce the diversion below the 25% level. Following meter installation, the 20% increase in local street volume was not substantial. Evaluations of the impact of metering on adjacent streets have been conducted in Los Angeles, Denver, Seattle, Detroit and other cities. Significant diversion from the freeway to surface streets did not occur in any of these locations. Formal and informal agreements are common between state and local jurisdictions in connection with metering projects and close advance coordination between jurisdictions is highly recommended[4].

Additional benefits can include:

- Reductions on impacts of recurring congestion due to heavy traffic demand;
- Reductions in fuel consumption from stop and go travel;
- Improvements in air quality and other societal goals (environmental conservation, increased transit/carpooling, etc.);
- Delaying or preventing the occurrence of freeway slow speed operations;
- Breaking up of vehicle platoons;
- Promoting easier and safer merging from ramps;
- Reducing emergency or vehicle breakdown response time;
- Encouraging motorists on shorter trips to use arterials; and
- Encouraging motorists to shift travel times or change travel modes[5].

The following is a list of some disadvantages associated with ramp metering[5]:

- Delays and increased emissions at the ramps – Although the overall travel time is improved and overall emissions are reduced, ramps experience increases in delay time and emissions. The Twin Cities, Long Island, Seattle, Zoetemeer Netherlands, and the M6 Motorway in England all reported increased ramp delays as a result of ramp metering[5]. Furthermore, time spent waiting at the ramps is normally perceived to be longer, lowering its perceived benefits by the motorists.
- Queues extending to the arterials – City agencies have worked hard to prevent such occurrences, because consistent interruption of local traffic will reduce the benefits of the ramp metering program. Depending on the geometric configuration of ramps and metering strategies used, this problem can be easily avoided. *Ramp Queues? Not in My Backyard!* By Glenn Havinoviski[12] provides an in depth discussion on ramp queues and queue detection systems designed to reduce the occurrences of spill back onto the arterial network. Seattle reported they still experience some spill back as a result of not

being able to coordinate their ramp metering system with the signals at the ramp terminals.

- Inequity issues – This is one of the main causes for public opposition to ramp metering. Ramp meters are believed to be a disadvantage to citizens that are: 1) traveling on short trips without any alternative routes, and 2) living near the city centers, because freeway systems near the city centers are more likely to be congested, triggering the traffic responsive ramp meters to impose higher delays. To gain public support, good educational efforts, along with certain compromises must be made. In Detroit, the initial metering was operated only in the outbound direction to minimize the city-suburb equity problem. Once the effectiveness of the metering was established, the system was expanded with fewer objections. This strategy will also be used in Atlanta where northbound I-75, leaving the city during the evening peak, will be the first section metered.
- Potential increase in single occupancy vehicle (SOV) use – A good, successful ramp metering campaign that dramatically improves freeway operations may encourage motorists to travel in SOV. But contrary to this opinion, Seattle experienced a 10 to 15 percent increase in HOV lane usage. While further studies should be performed to gain conclusive evidence, implementation of ramp metering along with good corridor travel demand management (TDM) strategies may be able to discourage SOV.

In a recent study by the Minnesota Department of Transportation, ramp metering was found to have the following benefits:

- 9% increase in freeway throughput on average, with a 14% increase during peak hours
- Annual savings of 25,121 hours of travel time
- Reduced travel time variability, resulting in an annual savings of 2.6 million hours of unexpected delay
- Annual savings of 1,041 crashes, or approximately 4 crashes per day
- Net annual savings of 1,161 tons of emissions

Table 2 provides information on benefits realized by other cities that have implemented ramp metering programs. While research is limited on the effect ramp metering has on emissions, in studies where it was considered (Denver, Detroit, and Long Island), an overall improvement in emissions was found.

The only criteria category found to be worsened by ramp metering was fuel consumption, with an annual increase of 5.5 million gallons of fuel consumed[15].

Implementation Challenges

The main challenge to the implementation of ramp metering is public opposition. 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 the future advantages. In addition, ramp metering takes time to produce benefits, and often must be adjusted after installation to respond to actual results, further increasing 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 away from the central business district (CBD). Drivers attempting to access the freeway nearer the CBD may find their metering rates extremely restrictive because entering drivers have already filled mainline capacity further upstream. As mentioned in the costs section, equity issues can be addressed by adjusting the metering rates.

Finally, ramps must have the capacity to handle queues at meters without causing undesirable spillover onto the arterial network. Also, ramp metering usually works better if the arterial network has some extra capacity to accommodate the small portion of traffic that is diverted[1].

Why Use Ramp Control

Figure 1-17. I-90 Ramp Gate[6]

Figure 1-18. Iowa Ramp Closure Gate

The purpose of using Traffic Gates at freeway on ramps, as shown in Figures 1-17 and 1-18, is to minimize the utilization of law enforcement vehicles and personnel as temporary roadway barriers. Traffic Gates allow for easy closure of freeway entrance ramps during planned incidents such as sporting events and unplanned incidents such as weather related or freeway emergencies. Traffic Gates are also used on some reversible lane facilities around the country including the Kennedy Expressway (I-90/94) in Chicago and the Shirley Highway (I-395) in Virginia. The Washington Dulles International Airport Access Road, connecting the airport with I-66 and I-495, uses traffic gates on the slip ramps connecting the Access Road and the Dulles Toll Road that run parallel to each other. The slip ramps are used by local transit buses and law enforcement to allow these vehicles to use the less congested Washington Dulles International Airport Access Road instead of the Dulles Toll Road. Another common use of ramp control is in states where road closures due to severe weather occur regularly. Some of these states include South Dakota, Minnesota, Iowa, and Wyoming.

When to Use Ramp Control

Ideally, the decision to place a Traffic Gate on a particular freeway on ramp should be made as part of a system wide implementation plan based on a history of incident rates and severity, and on frequency of closures due to severe weather. Lacking a formal implementation plan, the decision to install Traffic Gates may be made on a project by project basis based on the same factors. Each District's Freeway Operations Unit should make this decision with input from local law enforcement and maintenance agencies[6].

A decision on the type of gate (Vertical Swing Arm, Horizontal Swing Arm, or Type III Barricade) to install is dependent on a number of issues including available funding, maintenance, communications (automated versus manual deployment), and expected frequency of use. Due to remoteness of some ramp closures, some states chose simple horizontal gates because of lower costs versus vertical swing gates and fewer maintenance issues. Manually deployed gates are also frequently used in more remote and lower frequency of use locations due to the costs associated with communications for automated gates. Automated vertical swing gates are often used in high frequency use cases (Chicago, Northern Virginia) because of safety issues (high vehicle volumes) and the daily raising and lowering of the gates (Chicago and Northern Virginia).

Design Considerations

Ramp control has always been available with the use of personnel – either law enforcement or maintenance workers. Rather than posting expensive personnel at ramps, areas of recurring problems first began pre-positioning type III barricades at the ramp. Personnel could then pull the barricades across the ramp and leave. This has since been upgraded in many locations with permanent gates that can be more quickly and efficiently moved into place. The two most common types are cattle gates that swing horizontally across the ramp, or railroad arms that can be lowered across the ramp.

As noted above, at select locations, ramp control is used to control access to special lanes – typically HOV or reversible lanes. In many of these cases, automated gate closure systems that can be operated remotely have been installed. The REVLAC project in Chicago is on the extreme end. With the reversible lanes on the Kennedy Expressway (I-90/94) changing directions several times a day, a complicated and sophisticated automated system was designed and installed to allow safe remote operation while minimizing exposure of maintenance personnel to high volumes of traffic[16].

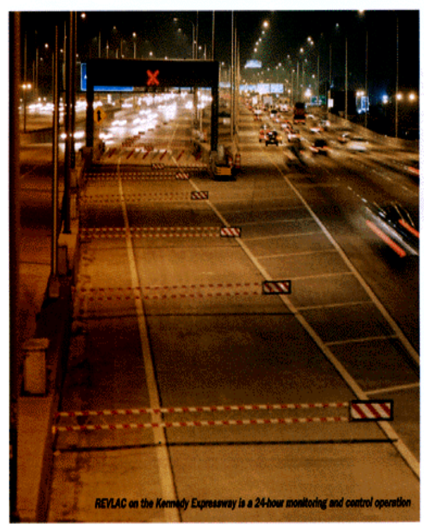


Figure 1-19. REVLAC on the Kennedy Expressway[16]

In the majority of the installations, the gates are designed to fit across the entire ramp entrance as the Figure 1-19 photograph illustrates. As they are typically used only in extreme circumstances, there have been few warrants developed. Availability of alternate routes, traffic volumes, etc., is not as relevant compared to whatever event has created a situation requiring a full closure of a freeway. Similarly the goals and strategies are typically to prevent motorists from driving into a hazardous situation.

For application in HOV and reversible lanes, the goals are equally as simple. In the first case it is a question of enforcement. In the second it is a safety hazard (preventing motorists from driving into oncoming traffic).

How to Implement Ramp Control Gates

The typical application is very simple and inexpensive. From pre-positioned type III barricades to the cattle gates and railroad arms, the implementation cost is typically under $5,000. Design decisions are usually based on an approved standard with modifications in the field to provide adequate coverage.

For the more complex applications, the decision process, design, and warrants are significant. When applied for enforcement (e.g., HOV or tolling), the ramp control system is usually a small part of a larger project and all costs and design have been addressed within the larger project. Again, the goal is simply enforcement. When applied for travel demand management, no warrants or criteria have been developed. The application is relatively rare and is typically created out of a larger study addressing the greater regional or local transportation issues.

Conclusions

Generally speaking, ramp metering systems have been successful in improving safety, reducing congestion and travel times, and increasing speeds and vehicle throughput. While the benefits of ramp metering are well documented, it is still clear one of the major obstacles facing jurisdictions is balancing the benefits of protecting freeway flow at the expense of arterial operations. Public education campaigns and strong media relations are important components for improving public acceptance of new ramp metering programs. Table 8 provides a summary of the Annual Benefits of the Ramp Metering System (Year 2000 Dollars) as documented in the *Twin Cities Ramp Meter Evaluation Final Report.*

Table 1-8. Annual Benefits of the Twin Cities Ramp Metering System (Year 2000 Dollars)

Performance Measure	**Annual Benefits**	**Annual $ Savings**
Travel Time	25,121 hours of travel time saved	$247,000
Travel Time Reliability	2,583,620 hours of unexpected delay avoided	$25,449,000
Crashes	1,041 crashes avoided	$18,198,000
Emissions	1,161 tons of pollutants saved	$4,101,000
Fuel Consumption	5.5 million gallons of fuel depleted	($7,967,000)
Total Annual Benefits		$40,028,000

Source: ***Twin Cities Ramp Meter Evaluation Final Report, February 2001.***

Studies similar to the Twin Cities ramp meter evaluation are difficult to conduct, as most jurisdictions are reluctant to turn off their ramp metering system for any length of time. In Denver, however, an interesting unplanned "evaluation" of the system occurred in the Spring of 1987. To accommodate daylight savings time, all of the individual ramp controllers were adjusted one hour ahead. Unfortunately, the central computer clock was overlooked. The central computer overrode the local controllers and metering began an hour late. Traffic was the worst it had been in years. This oversight did have a bright side for the Department of Transportation. Since this incident, the media has been even more supportive of ramp metering[4].

According to Piotrowicz and Robinson, as noted in *Ramp Metering Status in North America 1995 Update*, if agencies were given the opportunity to go back and start their ramp metering programs again, the two things most would do differently would be to provide adequate vehicle storage and improve public relations. This helps underline the importance of good design and the role the public plays in the success of any ramp metering program.

Keys to Successful Ramp Metering Implementations

While each locality may be different, there are some common keys to success all jurisdictions should be aware of when implementing a ramp metering program. These include, but are not limited to: proper site selection, secured funding, manageable project scale, gaining the public's and media's support, sufficient storage capacity, synergy, avoid conflicting solutions, eliminate technical problems, consistent enforcement, and continuous improvement. Below is a brief discussion of each key[5].

- **Select the right place –** In order to realize significant positive benefits of ramp metering, it is necessary to implement ramp metering in freeway sections that actually need it. As discussed in Section 3 of this report, appropriate locations typically have the following characteristics: peak period speeds less than 30 mph, flow of 1,200 to 1,500 vphpl, high accident rates, and significant merging problems.
- **Secure funding –** Before embarking on a ramp metering program, make sure that the local politicians and city officials are committed to funding the program. In some cases, public-private partnerships can forge a more secure funding situation.
- **Start small and simple –** Cities trying to implement ramp metering for the first time should start with a few ramps, with a fixed time control, adopting a more conservative strategy.
- **Excellent public support –** All implementing cities believe that public education and support are critical to the success of their ramp metering programs.
- **Ample storage capacity –** Most cities would like to have longer and wider ramps to prevent queues from extending beyond the ramps onto the arterials. If long queues with backups onto the arterials occur on a consistent basis, good queue detection systems and adopting a more conservative strategy are necessary.
- **Synergy –** Use other forms of Intelligent Transportation Systems (ITS) to eliminate disadvantages found in ramp metering alone (i.e., ramp delays or increases in arterial volumes). Agencies may couple ramp metering with ramp queue wait time signs or an Advanced Traveler Information System (ATIS) that can inform motorists of crowded ramps, or provide motorists with options of different travel modes, times, or routes.
- **Avoid conflicting solutions –** Mainline freeway HOV lanes and ramp meters are two freeway management solutions that may not work well together. In some cases, mainline HOV lanes are believed to dilute the benefits of ramp metering. Without HOV bypass lanes or direct HOV connectors, metering may impose unnecessary delays to buses and carpools.

- **Eliminate technical problems –** Make sure the system is free from technical breakdowns, to sustain high public trust and compliance rates.
- **Consistent enforcement –** A study entitled "Motorist Behavior and Opinions Toward High Occupancy Vehicle Lanes at Ramp Meters," showed that consistent police enforcement, though costly, is the most effective enforcement strategy[18].
- **Continuous improvement –** Upgrade the fixed or traffic responsive controllers to central or fuzzy logic controllers. Central control offers greater benefits because it can monitor an entire system, while fuzzy logic controllers eliminate the possibility of processing and applying imprecise or erroneous traffic data.

Proposed Ramp Metering Implementation Criteria

The literature review and interviews with other regions have demonstrated that the criteria are not standardized in definition or application. Therefore it is not possible to simply apply nationally acceptable criteria directly to Wisconsin. This report takes the best of what other states have used to create a best case criteria for Wisconsin. Should national standards evolve, the criteria used in Wisconsin should be re-examined.

Historically, the freeway ramps which are most likely to benefit from the addition of a properly designed ramp metering system typically exhibit slow moving traffic (<30 mph), low vehicle throughput (1,200 to 1,500 vphpl), high accident rates, and significant problems in merge areas. Many jurisdictions, including Seattle, Chicago, and Minneapolis use a 20% - 30% occupancy threshold as another indicator of when ramp metering should begin. Below is a preliminary list of ramp metering implementation criteria to use when considering deployment of a ramp meter system. These criteria are preliminary at this point; further evaluation of these and other criteria will be undertaken in subsequent efforts of this project.

1. Volume Criteria – Vehicle flow rates of 1,200 vphpl coupled with slow moving traffic along the freeway lanes.
2. Ramp Volume Criteria – Ramp volumes of at least 240 vph (400vph for two lanes).
3. Speed Criteria – Multiple ramp metering case studies listed 30 mph or less as the common minimum freeway speed to warrant ramp metering.
4. Safety Criteria – While no specific number or accident rate is mentioned in any of the previous reports, a reduction in accidents at the merge is often cited as the reason for the ramp metering and used in the calculation of benefits.
5. Ramp Geometric Criteria – There are a number of geometric criteria well established for ramp design. The three primary criteria include storage space, adequate acceleration distance and merge area beyond the meter, and sight distance. FHWA's Freeway Management and Operations Handbook - Chapter 7, along with Wisconsin's Intelligent Transportation System Design Manual - Version 2, provide ramp requirement guidelines for the design of a ramp metering system.
6. Funding Criteria – Before attempting to implement a new ramp metering project, an evaluation of potential funding sources should be completed to determine if there is sufficient support for the project.
7. Alternate Route Criteria – The presence of an alternative route for motorists on the arterial network to avoid the delays on entrance ramps created by a ramp meter[14].

Pre-Deployment of Infrastructure

In all of the literature review, there was no discussion of the need to install portions of the ramp metering systems in advance of the full installation. Wisconsin DOT is dealing with this exact issue as some ramps in the Southeast Corridor, which is currently under design, may warrant ramp metering in a few years but not at project opening. If there is an advantage to installing some equipment or systems during the construction, WisDOT would like to study the issue at this phase.

There are three basic subsystems to a ramp metering system. The first is electronics, which includes communications. In general, installation of a communications network is very expensive and is done in conjunction with other efforts. If the only need for the communications network is the ramp metering control, that is a relatively small amount of data that could likely be accomplished with leased phone lines. If there are CCTV and other high bandwidth systems, the communications system should either be installed with them, or as a separate project in advance of them. In general, ramp metering and control does not warrant the pre-deployment of a significant communications infrastructure. Additionally, the identified annual maintenance costs for ramp meters helps illustrate that electronics that are installed well in advance of their need become out of date and deteriorate due to exposure to the elements without preventative maintenance and active monitoring. A similar argument can be applied to support subsystems such as cabinets and signs. Introduction of these subsystem elements prior to need is not desirable due to maintenance and related issues.

The other subsystem is the pavement. The ramp meters and control systems typically do not require changes in the geometry of the ramps, so no geometric or pavement changes are required in advance of installation. The exception may be the inclusion of an enforcement pad. If it is cheaper and easier to install with the construction of the ramp pavement, then this additional pavement can be installed with the other construction. Without major loadings from traffic, the pavement should last well for many years and may be used by law enforcement or maintenance forces for other purposes in the mean time. The decision on whether to do this should be based on economic analysis by WisDOT for each design job that may require ramp metering.

Ramp Control Criteria

The literature review has shown there is minimal documentation on the criteria used for ramp control gates. Later chapters will develop some criteria from what is available for review by WisDOT. The criteria will focus on incident related criteria requiring the lower type of ramp control gates. Applications such as reversible lanes are more specific to their individual conditions. While these lower end systems are of minimal cost compared to the higher end systems, if there is no perceived need for the gates, their benefit is still zero.

Again, more complex applications should be studied individually as part of specific local operational traffic studies. At that time, costs and benefits should be compared and a systems engineering approach adopted to determine what form of ramp control is best.

Chapter 2

Develop and Apply Methodology

What is Systems Engineering?

Systems engineering is an approach to building systems that enhances the quality of the end result[1] (Building Quality Intelligent Transportation Systems Through Systems Engineering, FHWA-OP-02-046, by Mitretek Systems, Inc., April 2002). It combines technical activities and management activities to produce a disciplined approach to building systems by considering the entire life cycle of the system. The structured approach is highly recommended for complex systems like ITS. Ramp metering is one key element of the overall traffic management system.

Systems Engineering can best be illustrated by the "Vee" diagram, shown below. The "Vee" development model presents the system development lifecycle stages in chronological order. The left side of the "Vee" is the definition and decomposition of the system into components that can be built or procured. The bottom of the "Vee" is the construction, fabrication and procurement or development of the component items. The right side of the "Vee" integrates the components into subsystems, and then into the final system.

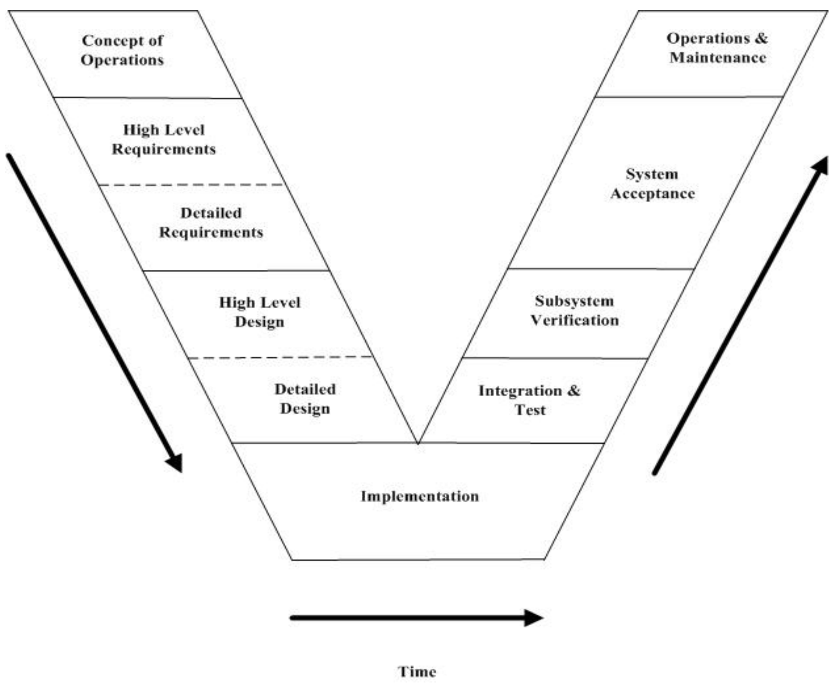


Figure 2-1 Systems Engineering "Vee" Diagram
from NHI Course No. 137024 "An Overview of Systems Engineering"

Each stage of the left side must consider the corresponding stage directly across on the right side. For example, when developing the 'Concept of Operations,' which identifies the roles and responsibilities of the agencies involved, the 'Operations & Maintenance' concerns must be addressed and satisfied.

How will it be applied?

This project effort is to prepare a planning methodology for implementation of ramp metering; therefore, it will not address specific design and implementation specifications. However, it will address the following stages:

- Planning—Preparation of a concept of operations defining the manner in which the system will be used, including agency roles and responsibilities.
- High Level Requirements—Derivation of requirements that define what the system will do.

These activities cover the first two stages on the "Vee" diagram ('Concept of Operations' and 'High Level Requirements'). The products of this study can then be built upon during the design and construction stages for future ramp metering installations.

The 'Concept of Operations' is the stage in which the need for the system is identified. The needs are identified by considering each applicable stakeholder and determining where the existing or legacy system is not meeting those needs. In the case for this project, since a ramp metering system exists, the needs will be based upon when and where expansion of ramp metering is appropriate. The 'High Level Requirements' stage is an analysis determining simply what the system must do (i.e. integrated into MONITOR for operators to be able to actively manage from workstations and be maintainable by WisDOT resources).

Concept of Operations

There are many different interpretations of how to define a "Concept of Operations." This likely is because each industry has a different definition of Operations and is exacerbated by the lack of consistency within the transportation industry. Additionally, the systems engineering process, while it applies to almost all activities, is most applicable in the design and implementation of complex systems. When applied to smaller, less complicated systems, the process becomes more condensed and less segregated.

Definition

The definition used for Concept of Operations by the National Highway Institute (NHI) Course No. 137024 "An Overview of Systems Engineering" is as follows:

> "A document that defines the environment in which the system is to operate – the environment includes the relationship between the system and the agency's responsibilities, the physical environment, and expectations (performance and life)."

For the planning application of ramp metering criteria, the Concept of Operations needs to identify those environments that are important to planning. That is, details of the environment for operations (e.g., timing, geometry, etc.) do not need to be addressed in the concept of operations. They are addressed as part of the criteria. The issues relative to planning are higher level – who controls the systems, when should they be deployed.

High Level Description

Ramp metering has been under the exclusive control of WisDOT since its inception. There was coordination with the local jurisdictions, but ongoing operations have been solely the responsibility of WisDOT. This includes all maintenance and operations. The deployed systems are generally on the high end of the design spectrum. This is due to some dual lane control and HOV bypasses. Control is centralized through a developed traffic management system in Milwaukee and a stand alone in Madison. Red and green lights are used to manage the traffic with one vehicle allowed per green. The long term intent of WisDOT is that all ramp meters will be controlled through the Milwaukee Traffic Operations Center (TOC).

Figure 2-2. Eastbound Beltline Ramp Meter at Whitney Way

For ramp control gates, WisDOT owns the property, but the local police have access and are the general users of the gates, not DOT staff. The majority of the ramp control gates are vertical swing gates that are manually operated. Much work has been done in coordinating and assessing performance of the ramp control gates[1,19].

Figure 2-3. WisDOT ITS Design Manual

The stakeholder vision has been determined through stakeholder involvement, in previous project work. Studies for the Beltline implementation[2] along with the MONITOR and TIME[3] programs in the Southeast corridor, have already accomplished much of this. In general, the focus remains on the freeways – reducing congestion and improving safety.

As the single most important stakeholder for ramp meters, WisDOT (as per this study and other ongoing efforts) would like to see increased use of ramp meters for improved freeway operations where appropriate. WisDOT recognizes the need to work with the public and to deploy in a logical fashion with the involvement and education of many.

For ramp control gates, the general consensus is they have value and are relatively low cost.[19] Those interviewed in Chapter 1 in this study were from operating agencies that use the ramp gates. They do raise the issue of adequate alternate route signing to aid motorists in finding the next available entrance ramp.

Identify Stakeholders

As mentioned, the single greatest stakeholder is the Wisconsin DOT. As owners and operators of these systems, they have paid for their installation, maintain them in working order, and are the agency held accountable by the public for their use. However, within WisDOT, operations are currently split. Table 2-1 identifies primary and secondary stakeholders. The current primary stakeholders are those responsible for the operations of the ramp meters. That is, those actively using the ramp meters, those responsible for enforcing the ramp meters, and those responsible for maintaining the ramp meters. Additionally, the traveling public is always a primary stakeholder as they are the ones that use the ramp meters. They are also the ones that hold the public agencies accountable for their continued operation.

Table 2.1. Wisconsin Statewide Freeway Ramp Control Stakeholders

Primary	Secondary
WisDOT Southeast Region – MONITOR	Other sections within WisDOT (e.g., planning, design, construction)
WisDOT Southwest Region – Traffic Operations	Local municipal law enforcement
Law enforcement 1. County Sheriffs 2. State Patrol	Local municipal traffic engineering departments
Maintenance crews (ramp control gates)	Local emergency response agencies (fire/paramedic)
Traveling Public	Public transit agencies
	Regional and adjacent traffic management systems

The secondary stakeholders are those directly affected by the operations of the ramp meters. This includes the local jurisdictions that handle traffic from ramp congestion or on alternate routes, as well as other sections within the primary stakeholder organizations that may be interested in the operations (e.g., planning, design, etc.).

Finally, other Traffic Management Systems should also be included. Currently, there are no interfacing signal control systems that require coordination. MONITOR does have access to the Integrated Corridor Operations Project (ICOP) involving traffic signal coordination; however, the signal systems and MONITOR are not actively sharing real time information. WisDOT does plan to expand the ICOP program and eventually integrate the two systems together. Future consideration of coordination with Minneapolis or through the GCM corridor is important.

Vision

The vision should be developed as a collective vision from all of the stakeholders. As no meeting is specifically planned to assemble the stakeholders, a draft vision will need to be created to share individually with the stakeholders for their concurrence or comment.

The needs previously expressed in Wisconsin concerning ramp metering and control were generally focused on improving freeway operations. Specifically for ramp metering, this involved identifying locations where the freeway congestion is created by ramp traffic. Safety is a large factor in reducing congestion and should be considered as part of this analysis. Ramp control gates were generally addressed as another incident management tool.

The following is a draft vision statement for the consideration of the stakeholders:

Utilize traffic operations and incident management tools to reduce congestion, primarily on freeways, and improve safety of the entire motoring public in Wisconsin.

Goals

There is also not sufficient time within this project to properly conduct stakeholder meetings to collectively determine the goals of a statewide ramp control program. Therefore, a set of draft goals is developed for the written review and comment of the stakeholders. These goals are generally universal in nature (they should address both ramp metering and ramp control inclusively). The following goals are offered as an initial starting point:

1. Improve safety on the overall system
2. Reduce congestion on the overall system – including arterials

These goals are specifically high level. While they are focused on the consideration of ramp metering, these same goals apply to most other traffic management considerations. This should not detract from the value of this step within the systems engineering process. It is important to identify these goals and the following objectives for best determining the eventual criteria.

Objectives

At the highest level, these goals lead to a variety of objectives that address additional issues and concerns. These goals and objectives are conveyed in Table 2.

Table 2-2. High Level WisDot Goals and Objectives

Goal	Objective

Improve Safety	o Reduce the number of incidents
	  ○ On the freeway
	  ○ On the local arterials
	o Reduce the severity of incidents
	  ○ On the freeway
	  ○ On the local arterials
	o Reduce the impact of incidents
	  ○ On the freeway
	  ○ On the local arterials

Reduce congestion	o Increase congested freeway travel speeds o Minimize ramp queue delays o Increase arterial vehicle throughput o Reduce the impact of incidents

Engineers have to constantly make decisions trading one objective for another. If one objective is to make a car go faster, a bigger engine is one solution. However, another objective is to improve fuel mileage, which typically decreases with engine size. The same conundrum faces those making decisions on operational tools. The series of objectives are not necessarily mutually supportive – meeting one objective may be at the expense of another. The systems engineering process is one way of applying a logical process to this decision tree. The systems engineering process is robust enough to address qualitative issues and requirements, though possibly not as well as other decision tree models or less formal negotiations. The objectives identified will need to be weighed and balanced in a separate decision process to determine what the priorities are for WisDOT.

Metrics

Within the Systems Engineering process, each objective should map to specific metrics that can be analyzed to determine success. The following metrics have been identified to track performance and help determine relative project success:

1 **Lower accident rates – both on the freeways and local arterial system**
- To determine if safety has been improved
- Available through WisDOT

2 **Average freeway speeds (by time of day or at least for peak hours)**
- To determine if congestion is being reduced
- Available on monitored sections of freeways or in spot studies

3 **Lower accident severity – both on the freeways and local arterial system**
- To determine if safety has been improved
- Available through WisDOT

4 **Travel volumes through a corridor – both on the freeways and local arterial system**
- To determine if total throughput has increased
- Available on freeways through WisDOT
- Available on arterials through WisDOT, local agencies, or through manual counts

5 **Travel times through a corridor (through surveys or probe vehicle tracking)**
- To determine if congestion on arterials is improving
- Available only as additional survey efforts

Operations

As mentioned earlier, a concept of operations can mean many things to many people. For a very detailed/specific effort, it could be down to the level of actual maintenance procedures. For a statewide planning level study such as this, the operations are addressed at a much higher level.

Several different parameters need to be reviewed concerning operations. The first is practice and procedures. This refers to the activities around how ramp metering functions are processed, information flow, administration and security (who handles what, whose responsibility is it). As mentioned previously, the Southeast Region's Traffic Operations Center (MONITOR) has the ownership, operations, and maintenance responsibilities of the ramp meters in Southeast Wisconsin. The meters are operated by time of day or upon operator activation. Metering rates are observed and stepped up from initiation as demand dictates. A similar operation is in effect in the Southwest Region. There is a single computer. The ramp meters are turned on by time of day and monitored and controlled from the single computer. In both systems, meters are turned on in advance of the congestion to help delay and mitigate its impact. All systems have queue detectors to ensure operators are aware of when the ramps back up onto the arterial system. Long term vision is to have the operators at MONITOR handle all ramp meters in the State. Currently, all data and control rests locally with the two different systems.

Ramp control gates are much simpler (in terms of technology) and are used more sporadically. They are used as needed for incidents by local law enforcement. As they are not automated, there is no computer data on operations or information flow beyond radio calls. The radio traffic is monitored at the Southeast Region's Traffic Operations Center and could be included in the MONITOR system as operator inputs.

As mentioned, the primary purpose of ramp metering is to mitigate congestion. While typically all ramp meters are turned on at the same instant, their operations are generally focused on congestion at each individual location – as opposed to system wide traffic management. This also applies when individual ramp meters are turned on for addressing concerns during an off peak incident.

Ramp gate operations are strictly on an as needed basis. If there is a major incident on the freeway, local law enforcement, in conjunction with WisDOT staff, makes the determination to use the gates. Law enforcement or WisDOT maintenance staff will operate the gates in the field.

The key points of ramp meter operations are as follows:

- Time of day
- Local responsive
- Minimal impact on arterials
- Currently controlled at region level – eventual single statewide control

High Level Requirements

The following requirements are written in order to define the system by which planning level decisions are made as to the implementation of ramp metering. The requirements are discussed by various applications, but numbered consecutively.

<u>Deployment</u>

Deployment considerations are generally described as "why" and "when". Again, the detailed design phase addresses the "how". The first requirements address the criteria created later in this document. The criteria fall into two general categories. The first is operational – those that are directly related to the existing or anticipated traffic conditions. The second are more subjective, addressing other issues WisDOT may need to address such as modal split or corridor applications.

1. The ramp meter shall meet at least two of the criteria.
2. Traffic criteria (speed, volume or safety) shall use existing or planning numbers for at most a ten year horizon.
3. Others shall review subjective criteria throughout the planning process.

<u>Operational</u>

The requirements for operations are based on how WisDOT will operate the systems and relate back directly to the goals and objectives. The focus remains on keeping freeway traffic moving. These requirements are relative to ramp metering, not the total traffic management center. Software and user interfaces are not appropriate to address at this level.

4. Ramp metering shall not increase traffic on local arterials significantly.
5. Queue detection shall be installed and used to determine when ramp traffic is about to impact arterial traffic and take appropriate actions.
6. Freeway traffic monitoring sensors shall be installed and used to monitor freeway congestion before, during, and after ramp metering.
7. Ramp meter control shall allow operators to select variable timing rates.

Performance and Effectiveness

Performance addresses how the system operates for users – both the WisDOT staff and the motorists that use the ramp meters. Performance is mainly addressed by the design details. As such, there are no meaningful planning level requirements. Effectiveness addresses how well the ramp meters and control gates address the goals and objectives. Wherever possible, this should be done with before/after studies. However, it is also appropriate to monitor existing ramp meters to see if conditions have changed and the ramp meters are no longer effective. The largest problem with this issue is that per the Minnesota Study[5], turning off the ramp meters caused an increase in traffic accidents. With this study as a reference, it would be difficult for a public sector agency to choose a day to turn the meters off to test the results. Any accidents on that day could possibly be blamed on the lack of ramp meters. Therefore, any testing and verification is probably best accomplished with modeling.

8. The ramp metering operations shall demonstrate how well they achieve the goals and objectives of the system at initiation and on a recurring basis.

Environment

The physical environment refers to the actual implementation of the ramp meter. Again, this is for actual operations or detailed design – requirements do not belong at this level. However, interagency cooperation and coordination can be addressed at this stage. Some of the elements remain vague at this point, simply because the exact needs of the other agencies are not known at this time.

9. WisDOT shall share planning level data with other stakeholders as requested.
10. Real time coordination and information sharing shall take place with adjacent operating agencies as mutually agreed.
11. WisDOT and participating local operating agencies shall coordinate actual operations of ramp meters and control as mutually agreed.

Methodology for Preliminary Ramp Meter Site Selection

From Chapter 1, a set of proposed ramp metering implementation criteria were presented as a guideline intended to assist state planners and engineers in determining when it might be appropriate to consider deploying ramp metering on freeway ramps. This section will discuss some of these criteria in greater detail, as well as describe an overall process for determining applicability of ramp metering at the planning level.

Proposed Ramp Metering Decision Process

The following diagram, Figure 2-4, illustrates the proposed decision process related to ramp metering. The process is divided into three steps – concept of operations, criteria, and design issues. In each step, several issues are discussed and decisions made as to whether to proceed.

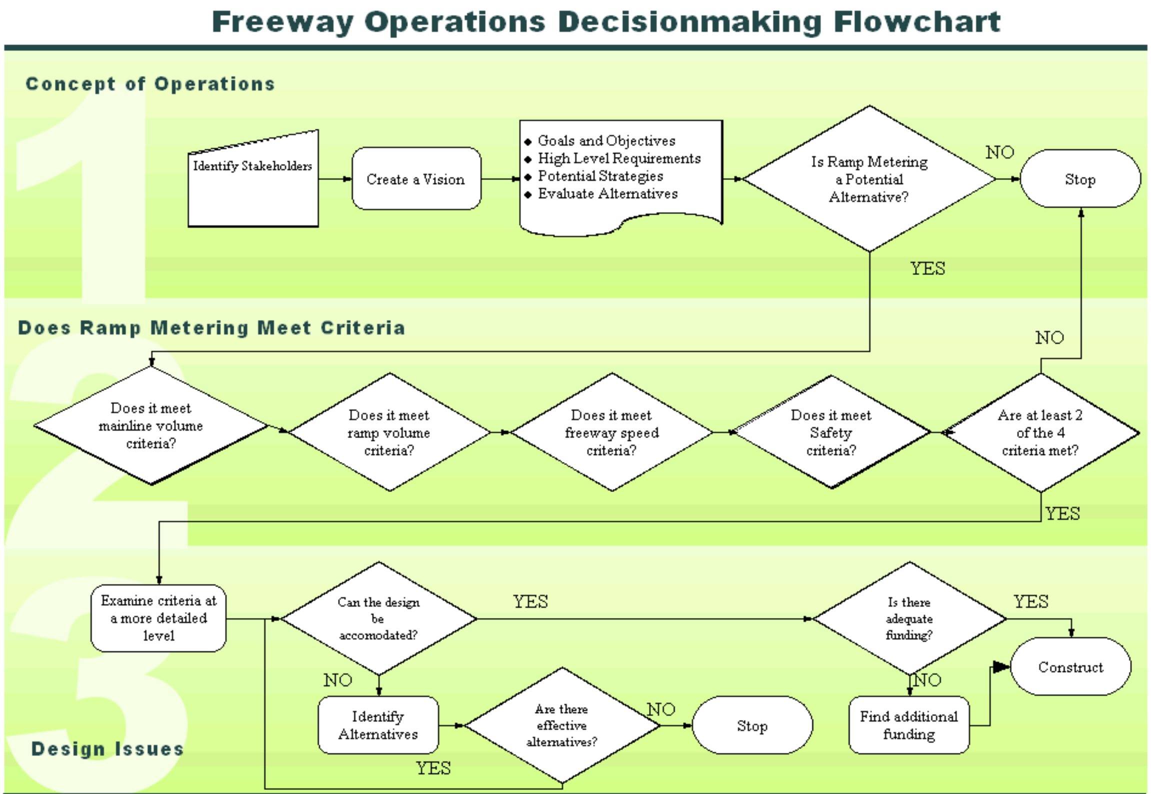


Figure 2-4

Earlier in this chapter, the Concept of Operations was addressed specific only to ramp metering. The operations identified in the first step relate to the overall operations of the system in question. Ramp metering is only one tool and may not apply to this particular situation. For the purpose of this project, we are assuming that step one has already been accomplished and ramp metering has been selected.

The second step deals with the first section of criteria identified in the following section. These are specific measurable data that can be applied and are based on previous engineering efforts.

The third step addresses other issues that are part of the overall DOT planning/programming/design process. The process assumes that additional analysis will be conducted on the potential ramp meter locations. The criteria used before this point are fairly high level. The criteria used in the design portion are fairly detailed. It is recommended that some additional analysis or modeling of the ramp meters would create more accurate and useable information leading into design.

Proposed Ramp Metering Implementation Criteria

The proposed ramp metering criteria were identified in Chapter 1. These criteria are really divided into several classes of criteria. The first are those that are related directly to traffic conditions. This represents directly measured traffic performance measures. The second are design criteria. At this point, typically the decision has been made to include operational tools such as ramp metering, and it is the responsibility of the design engineer to accommodate these requirements. However, many times the design criteria are excessive for the available geometry. In this case, the ramp meter may be warranted, but may become cost prohibitive.

Traffic Criteria

Historically, the freeway ramps that are most likely to benefit from the addition of a properly designed ramp metering system typically exhibit slow moving traffic, low vehicle throughput, and ramp volumes that meet a minimum volume threshold. High accident rates and significant problems in merge areas must also be considered. The following is a list of the traffic related criteria:

1. Mainline Volume Criteria – Vehicle flow rates of at least 1,200 vphpl (approximately 20-30% occupancy).
2. Ramp Volume Criteria – Ramp volumes of at least 240 vph (400 vph for two lanes).
3. Speed Criteria – A mainline speed of 30 mph or less at peak times.
4. Safety Criteria – Significant merge related accidents (80 accidents per 100mvm).
5. Alternate Route Criteria – The presence of an alternative route for motorists on the arterial network to avoid the delays on entrance ramps created by a ramp meter (yes or no based on engineering judgment).
6. Corridor Criteria – In most implementations, ramp metering is addressed at a corridor level. A single isolated ramp meter is rare, and even rarer is a series of ramp meters with a non metered ramp in between. (Yes or no based on engineering judgment.)

Many of the criteria identified in the literature review also had maximums for some of the thresholds. Only the minimums are used in this process. The decision was that maximum thresholds represent operational change points for the ramp meter owner, but should not change the decision process for considering ramp metering.

From the literature review, while many states used the thresholds provided above, the agencies varied on how many were applied at once. For some locations, it was all of the first three, for others a single criterion was enough. It is recommended that at least 2 of the first four criteria must be met to justify ramp metering. In order for criteria 6 to be met, at least 2 of the ramps within a corridor must meet the previous criteria. If a single ramp within a corridor meets the criteria, the assumption should be that other geometric improvements are more warranted to address the operational concerns.

Design Criteria

There are a number of design requirements for proper ramp meter installation. It may be that the design engineer is unable to address all of these requirements in a cost effective manner. If that is the case, then ramp metering, though warranted, may not be implemented due to physical constraints. Additionally, agencies constantly have to address issues relative to balancing costs of a project. Assuming funding for a project is limited, the appropriate engineers within the agency will have to make the decision on what aspects of a project must be cut to realize the budget.

7. Ramp Geometric Criteria – There are a number of geometric criteria well established for ramp design. The three primary criteria include: storage space, adequate acceleration distance and merge area beyond the meter, and sight distance. FHWA's Freeway Management and Operations Handbook - Chapter 7, along with Wisconsin's Intelligent Transportation System Design Manual - Version 2, provide ramp requirement guidelines for the design of a ramp metering system.
8. Funding Criteria – Before attempting to implement a new ramp metering project, an evaluation of potential funding sources should be completed to determine if there is sufficient support for the project.

Each of these criteria will be discussed in greater detail in Chapter 3. This will include the origin and reasons why each is used as possible criteria for ramp meter deployment.

HOV lane criteria are not recommended. HOV lane use is more of an operational consideration and should be addressed within the design process. It is noted from previous experience that any implementation of HOV lanes requires additional consideration and operational commitments from all participants. This would include formal commitments from local transit for usage, and local law enforcement for enforcement.

Ramp Control Criteria

Ramp control was previously defined as a means of restricting access to a ramp. In general, ramp control gates as used in Wisconsin have been either type III barricades or vertical swing gates. It should be noted that any ramp with a ramp meter for the purpose of this report should be considered as under ramp control. There are circumstances where a ramp may need to be closed at its entrance instead of at the meter, but this raises operational concerns beyond the scope of this project.

In the literature review, including examination of the WisDOT ITS Design Manual, there have been no specific criteria for determination of when to use ramp control gates. It appears that decisions to install gates are more based on policy. The other major decision seems to focus on what type of gate to use. South Dakota has accomplished some good work in identifying the operational issues with several gates and calculating the costs of several different types of alternatives.[6]

In the South Dakota project, the most frequent use of the gates was once every two years. The greater concern was that the design did not prove effective enough (e.g., poor visibility) or the gates were not in working order.

With a lack of guidance from previous work, it is proposed to divide ramp control into three categories with individual criteria. The first category is Daily Use. The next two categories both address occasional use, and are listed as Occasional Short Term and Occasional Long Term. Occasional permanent could be considered another category, but under this circumstance the operating agency should provide safe and secure physical barrier along with designated signage for alternate routes.

Daily Use

Daily use gates are those on high volume ramps that require control several times a week. Examples are entrances to reversible lanes, HOV, HOT, or ramps whose peak hour usage has been deemed to severely affect operations of the main freeway section. These gate systems can be as simple as vertical swing gates like that currently used in Milwaukee on I-94, up to fully automated systems like the REVLAC system on the Kennedy expressway in Chicago. The exact design of the ramp control system should follow a Systems Engineering process to determine which gate system is best for that particular application. The criteria for permanent ramp control systems are as follows:

1. Adverse freeway operations criteria – if the merging section between the ramp and the mainline causes safety and congestion issues only during certain periods, and a suitable alternate is available, ramp control should be instituted. It should be noted that poor geometrics are best addressed with improved geometrics, and further analysis may yield specific thresholds (e.g., minimum vphpl on the freeway, minimum ramp volume /freeway volume ratio, etc.) that better indicate when ramp control is warranted.
2. Reversible criteria – if the ramp is associated with a reversible lane system (either the ramp is reversible or the mainline section it feeds is reversible) some ramp control system is required.
3. Tolling criteria – if cash transactions are required to use the ramp, some form of control is necessary on the ramp.

Criteria 2 and 3 do not currently apply within Wisconsin. While neither operation is expected in the near future, the criteria are included here for future reference.

Occasional Short Term

In the South Dakota study, it was noted that many gates had never been used in their life. It should be noted that the minimal costs involved (no more than $5000 per site) may be quickly justified the first time they are used in place of a maintenance vehicle and worker or law enforcement vehicle.

Short term for this project is defined in hours. Any time the freeway is restricted for a period that is a portion of a single shift, it should be considered short term. With this definition, it is relatively easy for an agency to block a ramp with agency personnel. Assuming the cost of a staff and vehicle are approximately $150/hour, and a closure averages half a shift (5 hours), the direct value is assumed at $750 per closure. Considering personnel shortages, especially in rural areas, this value may be significantly more if no agency has the personnel and vehicle to spare. With a short term closure, any traffic entering the freeway would experience a significant delay, but not one that isolates and confines a person to the region requiring them to seek shelter for overnight protection. The criteria for Occasional Short Term ramp control systems are as follows:

4. Usage criteria – If a ramp experiences as many as 1 closure per year for a period of less than 8 hours. Systems Engineering will determine what type of closure is best (e.g., Type III barricades vs. swing arm).
5. Corridor criteria – Ramps should be grouped into corridors. As incidents are sporadic and may happen at any location within a corridor, if any ramp within a corridor meets the usage criteria, all ramps shall have control installed. Any closure within the corridor can easily happen at another location next time, and may require several advance ramps to be closed also.
6. Heavy usage criteria – If the individual ramp experiences as many as four closures per year for a period of less than 8 hours, some additional automation shall be investigated in the Systems Engineering process.

Occasional Long Term

Long term for this project is defined in days. Any time the freeway is restricted for a period that is less than a month or several weeks. Typically, this is for major snowstorms that may have mainline sections closed for less than a week. With this definition, agencies do not have the resources to staff the closure, but do have the resources to place more formal traffic control from regional yards. The criteria for Occasional Long Term ramp control systems are as follows:

7. Usage criteria – If a ramp experiences as many as 1 closure per 3 years for a period of more than 8 hours but less than 2 weeks. Systems Engineering will determine what type of closure is best (e.g., Type III barricades vs. swing arm) and any design details (e.g., lighting).
8. Corridor criteria – Ramps should be grouped into corridors. As incidents are sporadic and may happen at any location within a corridor, if any ramp within a corridor meets the usage criteria, all ramps shall have control installed. Any closure within the corridor can easily happen at another location next time, and may require several advance ramps to be closed also.
9. Heavy usage criteria – If the individual ramp experiences as many as four closures per year for a period of more than 8 hours and less than two weeks, some additional automation shall be investigated in the Systems Engineering process.

Preliminary Application to the SE Corridor

Five ramps were identified in the scope of work for an initial application of the criteria. These sites were selected by WisDOT along the I-94 North-South Corridor.

Eight criteria were developed in the previous section. The first seven are specific to individual ramp variables. The eighth criterion deals with corridor vs. local implementation.

Proposed Ramp Metering Implementation Criteria

From the previous section, the following Table 2-3 summarizes the criteria for ramp metering.

Table 2-3. Criteria and Decision Factors for Ramp Metering

Criteria	Decision factor
Freeway volume	1200 vehicles per hour per lane for any hour
Ramp volume	240 vehicles per hour per lane for any hour
Freeway speed	Hourly average speeds of less than 30 mph
Safety	To be determined on ad hoc basis until additional research can develop agreed thresholds
AT LEAST TWO OF THE FIRST FOUR CRITERIA MUST BE MET	
Ramp geometry	Is there sufficient room to design a proper ramp meter implementation?
Funding	Is this an addition to an existing operation? If not, is there sufficient funding for a new operation? If there is, are construction funds identified?
Alternate route	Is there a suitable alternate route to another ramp (engineering judgment)?
Local vs. Corridor	Within what corridor does the ramp reside? Is there existing metering in the corridor? Are there plans for (more) metering in the corridor? How many of the ramps in the corridor have, or plan to have, metering?

For the volumes, 2004 Average Annual Daily Traffic (AADT) values for both mainline freeway and ramps were obtained from WisDOT. All sections of I-94 are three lanes in each direction for the five ramps selected. It is assumed that traffic is equally distributed over all three lanes to get a daily traffic per lane, so the AADT was divided by three. Without hourly volumes, a peak hour factor is used. For most urban/suburban expressways, a range of .08 to .095 is assumed (Highway Capacity Manual). For this analysis, 0.09 was used. The resulting number is the vehicles per hour per lane (vphpl). A similar analysis was applied to the ramp volumes. All five interchanges have single ramp lanes, so the peak hour factor is used to translate daily volumes to hourly. Speed data was obtained from the Southeast Region's MONITOR system on these sections of freeway. Where two number appear in a cell, it is because there was a significant directional difference. If only one number is in the cell, an average was used.

Ramp geometry and alternative route availability could require a very detailed analysis. For example, in a dense urban area with older freeway geometrics, the available land for the proper installation of ramp metering (e.g., equipment, lanes, enforcement, etc.) may not be possible to determine exactly without a full engineering analysis. Some cases of extreme lack of right of way are easy to identify, as well as some interchange geometrics are large enough that they can easily accommodate any ramp metering operation. Without the time and budget to conduct a more detailed engineering analysis, the best judgment of the engineer shall be used. It may very well be that later engineering design indicates the judgment was wrong, so the implementing agency should prepare for this contingency.

Funding is split into two categories. First, if the agency has existing operations in the area, and the new ramp meter can be easily accommodated within the existing software and personnel operations, then the marginal cost is minimal (but will be considered). If the ramp metering installation requires a new software package and communications in order to operate it, then it becomes a much more expensive decision. The decision should have to address this concern over the expected life cycle. For the five interchanges listed, all fit within a current TOC jurisdiction that already operates ramp meters. Table 2-4 looks at bi-directional averages for the following interchanges except where directional differences are significant. Additionally, accident data was only available for two of the five interchanges.

Table 2-4. Sample Application of Design Criteria

Criteria \ Interchange	STH 20	STH 158	CTH C	CTH KR	CTH K
Volume (1200<=VPHPL) (2004 data)	774	822	987	833	955
Ramp Volume (2004) (240<=VPHPL)	**750/520**	**320/270**	**280**	150	**460** / 220
Speed (freeway speeds of 30 mph or less)	65	65	65	65	65
Safety	**98 / 88**	**95** / 49	?	?	?
Ramp Geometry (see WisDOT ITS design manual)	Ok	Ok	Ok	Ok	Ok
Funding	Yes	Yes	Yes	Yes	Yes
Alternate Route (is one available?)	Frontage Road	Frontage Road	Frontage Road	Frontage Road	Frontage Road
2004 Local Criteria Met?	Yes	Yes/No	No	No	No
Future Local Criteria Met?	Expected	Expected	Expected	Not Expected	Expected
Current Corridor Criteria	No	No	No	No	No
Future Corridor Criteria	Yes	Yes	Yes	Yes	Yes

One interchange meets the criteria for the current conditions. Actual peak hour volumes were used. When compared to AADTs, the peak hour volumes showed a wide variation in values indicating that a simple application of a 9% peak hour factor was less valid. This makes estimates of design year volumes more difficult. Initial analysis of speed data did not appear to warrant ramp metering in most circumstances. As the speed data set requested was limited, a more formal analysis of speed data may show different results.

As discussed previously, there are no national standards on accident rates for ramp metering criteria. In the following chapter, an initial criteria of 80 accidents per hundred million vehicle miles is established for Wisconsin. The analysis describes how this should be considered a starting point, as a more detailed analysis is required for developing statistically significant values. As additional accident studies examine this issue further, the ramps may meet the new criteria.

From the current high level design analysis, all have sufficient right of way to build appropriate ramp metering, and with the current I-94 North-South Corridor project, all are assumed to have sufficient funding. Frontage roads are available at all locations for alternate routes. The corridor criteria is not met with current conditions, but is expected to apply with design year data.

Summary

The ramp metering criteria identified in this report were developed from the collective national practices. They have been broken into different types of criteria that apply in different ways (not every decision is made from formal calculations using empirical data).

The initial high level application of these criteria demonstrated that the process can function and deliver reasonable results. While only one of the five interchanges met the criteria based on empirical data, three more were within a small percentage of meeting the criteria, and are certainly expected to meet the criteria with the future design year data. As this is the strongest and most direct justification for ramp metering operations, this should be viewed positively for the corridor. The other more anecdotal criteria have proven their validity in other locations and have been useful for guiding WisDOT to a more stable and proven ramp metering operation.

Chapter 3
Assess Operational Feasibility

Identify Decision Making Process

A decision making process was outlined in Chapter 2 and is repeated here for convenience. Figure 3-1 presents the freeway operations decision making details in flowchart format.

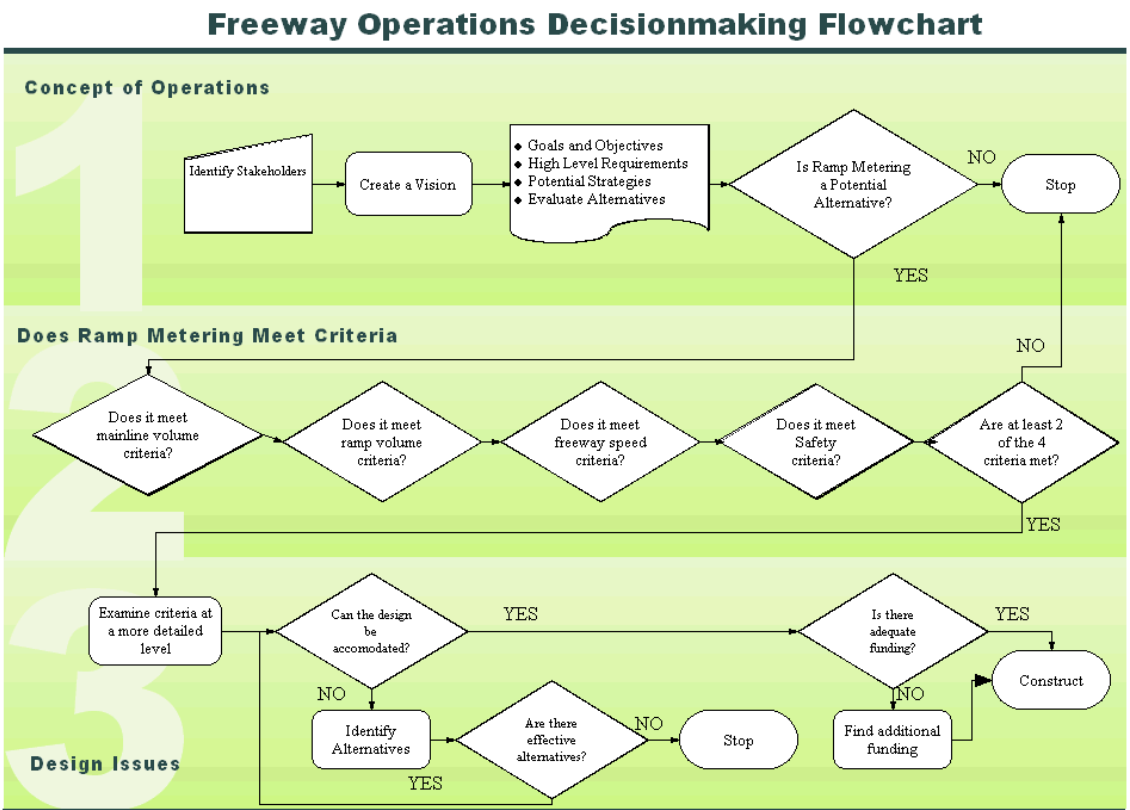


Figure 3-1. Freeway Operations Decisionmaking Flowchart

Concept of Operations

The complete process was discussed in Chapter 2. In summary, the decision process is really divided into three steps. The first is the planning level, or Concept of Operations. At this level, a wide range of options is considered. As part of the Systems Engineering process, the operational concerns need to be identified and potential solutions discussed with the stakeholders. Operational concerns can include the following:

- Specific accident types (location, type, severity, etc.)
- Specific congestion (daily or peak hour)
- Any special event management needed
- Impacts of large traffic generators nearby

To meet those operational needs, a wide variety of solutions should be proposed and discussed within the Systems Engineering process:

- Increase number of lanes
- Improve other geometric features (ramp merges, reduce curves, etc.)
- Ramp metering
- Surveillance
- Traffic patrols
- Dynamic speed enforcement
- Lane control
- Corridor signal coordination
- Others

At this level, the improvements should be exclusively focused on whether they solve the freeway operations problems that have been identified. Typically, cost is not considered here.

Criteria

The flow chart above is specific to ramp meters. The middle section could be repeated for any number of specific operational applications, including geometric changes. For this project, only those criteria specific to ramp metering are considered.

There are two types of criteria – traffic related and traffic management related. Those that are traffic related are based on empirical data, e.g., travel speeds. Those that are management related are more policy oriented. The traffic related criteria are discussed first.

Volume Criteria – Vehicle flow rates of at least 1,200 vphpl.

The purpose of these criteria is to identify freeway segments that are about to reach the critical stage of breakdown where throughput and speed both begin to decline at the same time. Piotrowicz and Robinson[4], as well as Mn/DOT's Twin Cities Ramp Meter Evaluation – Appendix to the Final Report[5], both state freeways typically exhibiting these criteria are candidates for ramp metering.

According to the *Highway Capacity Manual – 2000*[20] and Figure 3-2 diagram to the right, as flow increases from zero, density also increases, since more vehicles are on the roadway. When this happens, speed declines because of the interaction of vehicles. This decline is negligible at low and medium densities and flow rates. As density increases, these generalized curves suggest that speed decreases significantly before capacity is achieved.

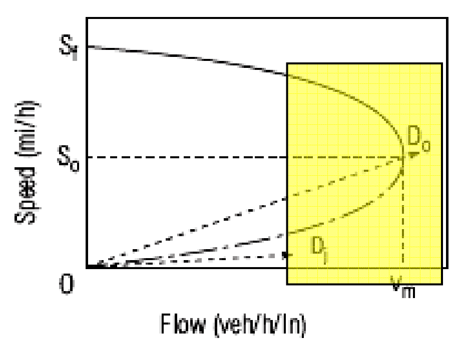


Figure 3-2. Speed, Density and Flow Relationship

Capacity is reached when the product of density and speed results in the maximum flow rate. This condition is shown as optimum speed So (often called critical speed), optimum density Do (sometimes referred to as critical density), and maximum flow v_m.

The volume criteria is a guideline for predicting when flow rates will enter the portion of the graph (an estimate) associated with the significant decreases in speed which coincides with the critical density of the lane. Under these criteria, 1,200 vphpl would be located just to the left of the shaded area.

Ramp Volume Criteria – Ramp volumes of at least 240 vph (400vph for two lanes).

The purpose of these criteria is to identify freeway on ramp segments that are about to reach critical breakdown. The Highway Capacity Manual – 2000 uses much higher service volumes for single lane on ramps as shown in Table 3-1 below than is described in these criteria.

Table 3-1. Approximate Capacity of Ramp Roadways[1]

Free-Flow Speed of Ramp (mph)	Capacity (pc/h)	
	Single-Lane Ramps	Two-Lane Ramps
> 50	**2200**	**4400**
>40-50	**2100**	**4100**
>30-40	**2000**	**3800**
>= 20-30	1900	3500
<20	1800	3200

The Highway Capacity Manual – 2000, Exhibit 25-3. Approximate Capacity of Ramp Roadways

The main reason for the higher capacities given in the Highway Capacity Manual – 2000 is the analysis did not account for the arrival of vehicles in platoons, this is often the case with on ramp situations. Page 25-11 of the Highway Capacity Manual – 2000 states: *For the purposes of this chapter, procedures are not modified in any way to account for the local effect of ramp control, except for the limitation the ramp meter may have on v_R. Research[5] has found that breakdown of a merge area may be a probabilistic event based on the platoon characteristics of the arriving ramp vehicles. Ramp meters provide for uniform gaps between entering ramp vehicles and may therefore reduce the probability of a breakdown on the freeway mainline.*

Mn/DOT's Twin Cities Ramp Meter Evaluation – Appendix to the Final Report[5], the Freeway Management and Operations Handbook[7], and CALTANS Ramp Meter Design Manual[21] each use these criteria for suggesting when ramp volumes warrant metering.

From Applications of Freeway Ramp Metering in Alabama[22], the authors state: *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.*

Speed Criteria – Multiple ramp metering case studies listed 30 mph or less as the common minimum freeway speed for ramp metering.

As noted in the volume criteria, the purpose is to identify freeway segments that are about to reach the critical stage of breakdown where throughput and speed both begin to decline at the same time. Piotrowicz and Robinson[4], as well as Mn/DOT's Twin Cities Ramp Meter Evaluation – Appendix to the Final Report[5], both state freeways typically exhibiting these criteria are candidates for ramp metering. Both are based on long term observation.

Safety Criteria – Accident rates in the vicinity of the ramp of 80 per hundred million vehicle miles of travel.

None of the other sources gave explicit safety thresholds for implementing ramp metering. Not only were there few details on accident statistics used in ramp meter decision making, but statistics on accident rates in similar sections of expressways were difficult to find. Two sources of relevant data were located; first, from the I-95 Master Plan Study, they provide an Accident Rate Comparison for urban, divided roadways with full access control, similar to the Wisconsin section of road. A second source of data was the Minnesota DOT website. While the volumes may be higher for I-95, use of the accident rate (instead of total accidents) accounts for this.

Candidate Safety Improvement Locations (CSILs) have been identified by the Maryland State Highway Administration (MSHA) at or near each of the nine interchanges between I-695 and MD 272. For the most part, these CSILs are categorized as being of secondary concern since the accident rate does not significantly exceed the statewide average rate for similar facilities. CSILs of primary concern were identified elsewhere.

A total of 3,178 accidents were reported by police for the five-year period beginning on January 1, 1995 and ending on December 31, 1999. The overall accident rate for the corridor, 38.0 accidents per 100 million vehicle miles traveled (MVMT), was 15 percent below the average rate of 44.8 acc/100 MVMT for similar state maintained highways. Fatal and injury accident rates were approximately 20 percent below the statewide average rate. The accident rate for rural sections of I-95 is 34.6/100 MVMT compared to the average statewide rate of 39.7 acc/100 MVMT. A comparison of accident rates for urban highway segments is shown in the following figure.

Although I-95 is generally a safe facility, as reflected by the current average accident rate, sections of the corridor have, in the past, had significantly higher accident rates than the statewide average. These sections include congested areas near interchange ramps, weaving areas, and the Toll Plaza. As travel demand on I-95 increases and congested periods become longer, opportunities for motorists to enter, exit, and change lanes on the facility will be reduced, increasing the potential for accidents over longer sections of the facility.

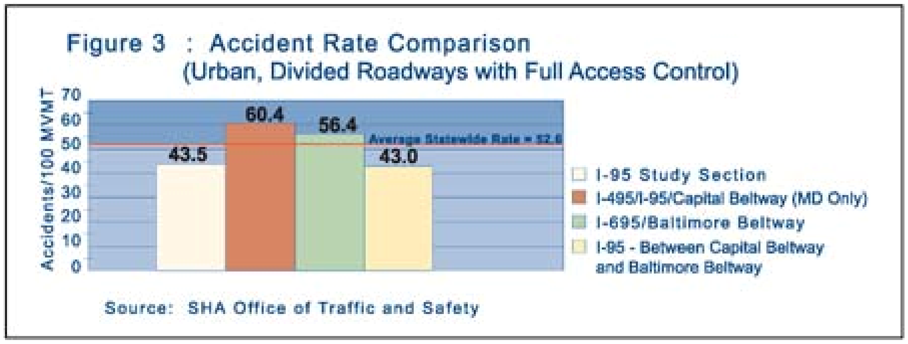


Figure 3-3. Accident Rate Comparison

From Minnesota, an average accident rate is provided for urban interstate corridors (approximately 1.9685 accidents per million vehicles). Since Minnesota uses Million Vehicle Miles as opposed to Maryland's 100 Million Vehicle Miles, the Minnesota data must be multiplied by 100 to match Maryland's data.

I-494 experienced an accident rate of 2.5 accidents per million vehicle miles; 127 % higher than the state average for urban interstate corridors, while I-35W experienced an accident rate of 1.6 accidents per million vehicle miles; 45 % higher than the state average for urban interstates corridors.

The accident rates for each interstate were calculated by counting the number accidents at 494/35W in the Minnesota law enforcement accident reports from 2000-2002, dividing by three for a yearly average, and dividing by the vehicle miles calculated from the 2002 AADT reports. The Traffic Safety Fundamentals Handbook distributed by the Mn/DOT Metro Division Office of Traffic Engineering lists the accident rate on urban interstate freeways as 1.1 accidents per million vehicle miles or 110 accidents per 100 million vehicle miles.

Accident statistics were made available for I-94 in Kenosha and Racine Counties. This information was provided by WisDOT and is summarized in Table 3-2. The formula used to calculate the accident Rate per Hundred Million Vehicle Miles (RHMVM) is as follows:

RHMVM = (Accidents * 100,000,000) / (AADT * 365 * Distance)

Table 3-2 – WisDOT I-94 Accident Statistics

Direction and Limits	Distance	AADT	Accidents	RHMVM
STH 50 to STH 20 (Eastbound)	13.56 miles	33,300	83	47.79
STH 50 to STH 20 (Westbound)	13.56 miles	34,500	61	34.44
Near STH 158 (Eastbound)	1.64 miles	33,400	19	95.03
Near STH 158 (Westbound)	1.64 miles	33,800	10	49.42
Near STH 20 (Eastbound)	2.84 miles	34,500	35	97.87
Near STH 20 (Westbound)	2.84 miles	36,000	33	88.43

The rates are generally in between those shown in Maryland and Minnesota. For this very simple analysis, a threshold must be chosen. Since the threshold for volumes represents level of service B (before congestion occurs), the accident rate should be at a similar level. Without a solid reference for Wisconsin, we will assume an average of the 110 for Minnesota and the 53 for Maryland and use 80 accidents per hundred million vehicle miles as a starting point for further analysis.

Corridor Criteria – Ramp meters are almost exclusively deployed along an identified corridor rather than in isolation, so a determination is needed on whether the section under consideration is part of a corridor.

Most jurisdictions have implemented policies allowing ramp metering only on a corridor wide basis. All agencies more or less deploy ramp meters corridor wide, since metered interchanges can drive traffic to unmetered interchanges. It also reflects the system wide approach to managing congestion represented by ramp metering[22]. Some jurisdictions that have policies restricting ramp meter deployments to corridors only include Michigan, Washington, and Arizona. Other jurisdictions have policies that dictate all ramps within their network will be metered (San Diego and Long Island).

The main reasons for restricting ramp metering to corridor wide applications include:

1. Avoids rerouting or cut through traffic (using local arterials) from a metered ramp to an unmetered ramp,
2. Increases the effectiveness of metering by limiting the amount of traffic entering the system at more than one location,
3. Develops a system wide approach for addressing the issue of freeway throughput and travel times.

Even though most jurisdictions use a corridor wide approach to ramp meter deployment, there are a number of local or individual ramp constraints to consider, including: geometrics, ramp volume, vehicle arrival rates at ramps, vehicle storage capacity on ramp, funding and traffic control devices located on arterials near ramps. These constraints may negate the benefits of ramp metering on selected ramps.

These criteria are dependent on definition of the corridor. If existing definitions are used for other purposes (e.g., construction) they can usually be used directly. Considerations in defining corridors include the following:

- Major interchanges
- Major changes in development
- Jurisdictional boundaries
- Major changes in road geometry

Design Issues

The third level of the process relates to the engineering design of the ramp meters. At this point, individual requirements are addressed within the constraints of the ROW. The responsibility rests with the design engineers to find appropriate means of accommodating these requirements. As discussed above, it is possible that an individual requirement may not be able to economically be addressed within the constraints of the project. As the flow chart indicates, the implementing agency can try to find alternatives to the requirement or make decisions about increasing resources. Depending on the results, the ramp metering system may or may not end up being deployed.

Ramp Geometric Criteria

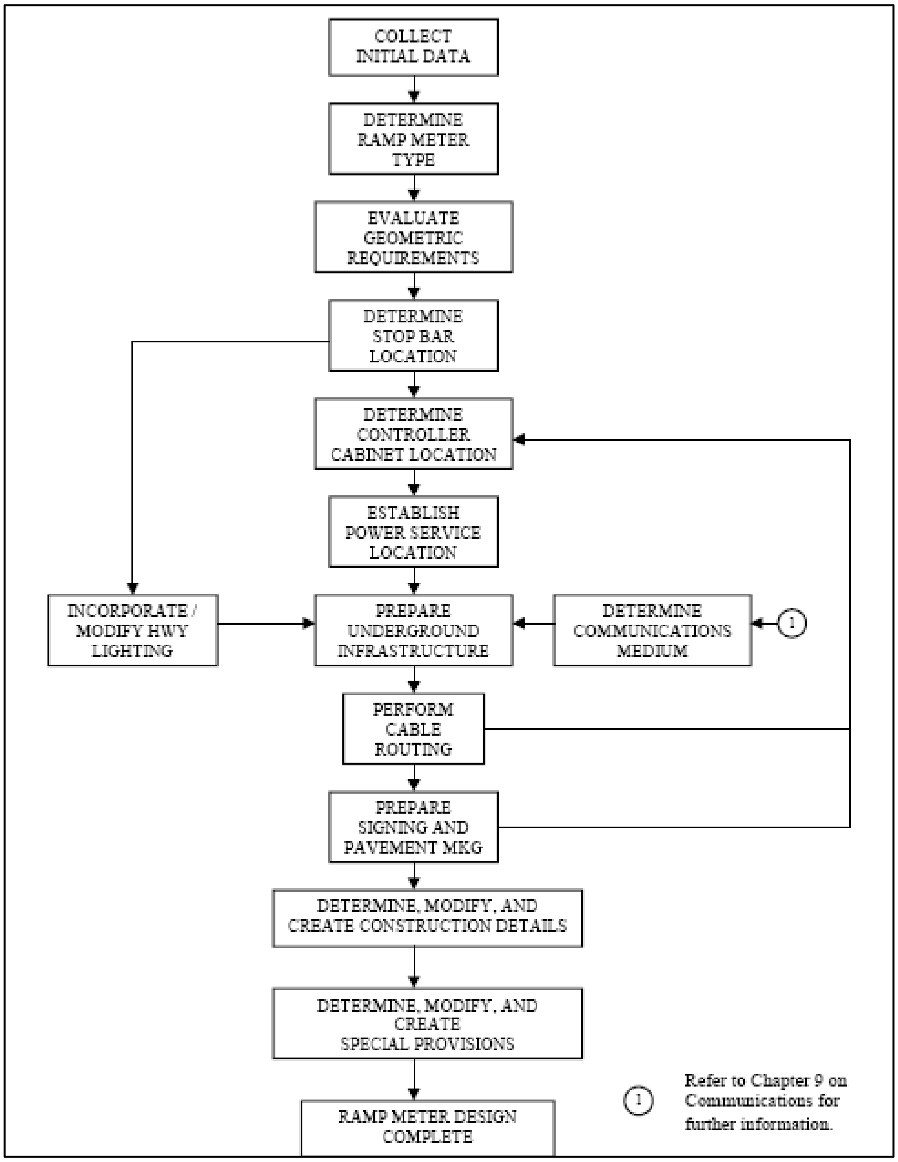
There are a number of geometric criteria that have been well established for ramp design. The three primary criteria include storage space, adequate acceleration distance and merge area beyond the meter, and sight distance. FHWA's Freeway Management and Operations Handbook - Chapter 7[7], along with Wisconsin's Intelligent Transportation System Design Manual[3] - Version 2, and CALTANS Ramp Meter Design Manual[21] provide ramp requirement guidelines for the design of a ramp metering system. As well, the Texas Transportation Institute published the findings of a study they completed titled, "Designing Freeway On-Ramps for Metering"[8], where they developed a number of guidelines related to the geometric design of ramp metering system deployments.

FHWA's Freeway Management and Operations Handbook - Chapter 7 provides a detailed discussion on design related considerations for ramp metering deployment. They cite a number of design manuals produced by various states including Wisconsin and California. In the case of Wisconsin, FHWA references the ramp meter design process flow diagram shown as Figure 3-4 on the following page.

Section 3.3 of the Wisconsin manual provides a detailed discussion of this process. Chapter 3 of this manual is an excellent resource for ramp meter design guidelines, in particular, Section 3.6 Geometric Considerations. This section provides guidance on ramp meter widths for single, dual and multiple lane (SOV and HOV) configurations, freeway connector ramps, enforcement zones, and a number of figures illustrating typical ramp meter design guidelines.

Another excellent resource for geometric guidelines for the design of ramp meters is CALTANS Ramp Meter Design Manual. Chapter 1 provides detailed information describing when ramp metering is warranted, when single lane or multi lane configurations are most suitable, what is the appropriate ramp metering storage lengths required, when HOV preferential lane deployment might be useful and other design considerations. Figure 3-4 presents the flow of the ramp meter design process.

Figure 3-4. Ramp Meter Design Process



The following design criteria also fall into two classes – those based on empirical data and those on observation. The majority are empirical requirements that are simply included in the design process as geometric needs. Those on observation include such items as alternate routes, where no specific item needs to be included in the roadway design, but which issue must be addressed.

The deployment of a ramp metering system to improve traffic flow in the network requires sufficient storage space, acceleration and sightline distances. The determination of minimum ramp length to provide safe, efficient and desirable operation requires careful consideration of several elements described below[22]:

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.
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 3-5[8] 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.

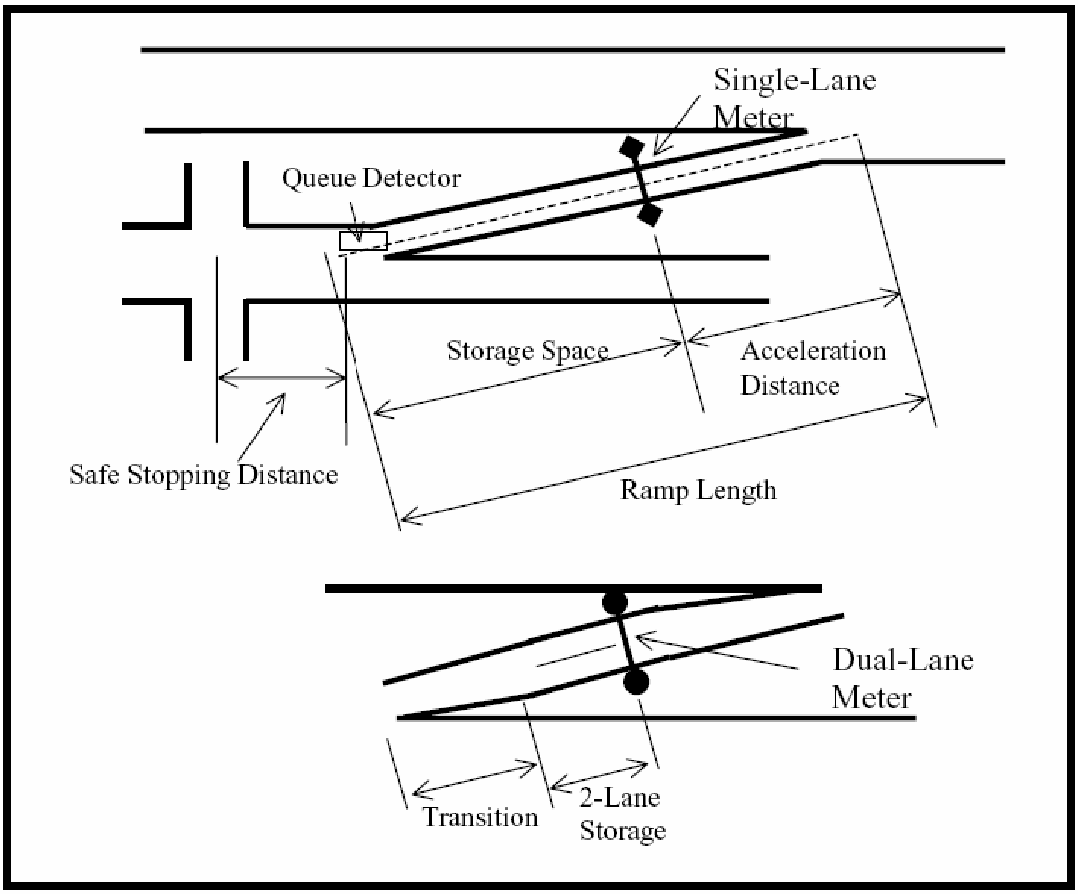


Figure 3-5. Distance Requirements for ramp meters

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 75 feet long, and the length of dual lane storage should be sufficient to store a minimum of four cars per lane 102 feet.

Storage Length - Sufficient space must be provided to store the resulting cyclic queue of vehicles without blocking an upstream signalized intersection

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 approximately 30 feet be considered for locations where there are significant percentages of trucks, buses or recreational vehicles.

Figure 3-6[8] provides the maximum queue length distribution for locating the excessive queue detector based on 95th 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[1].

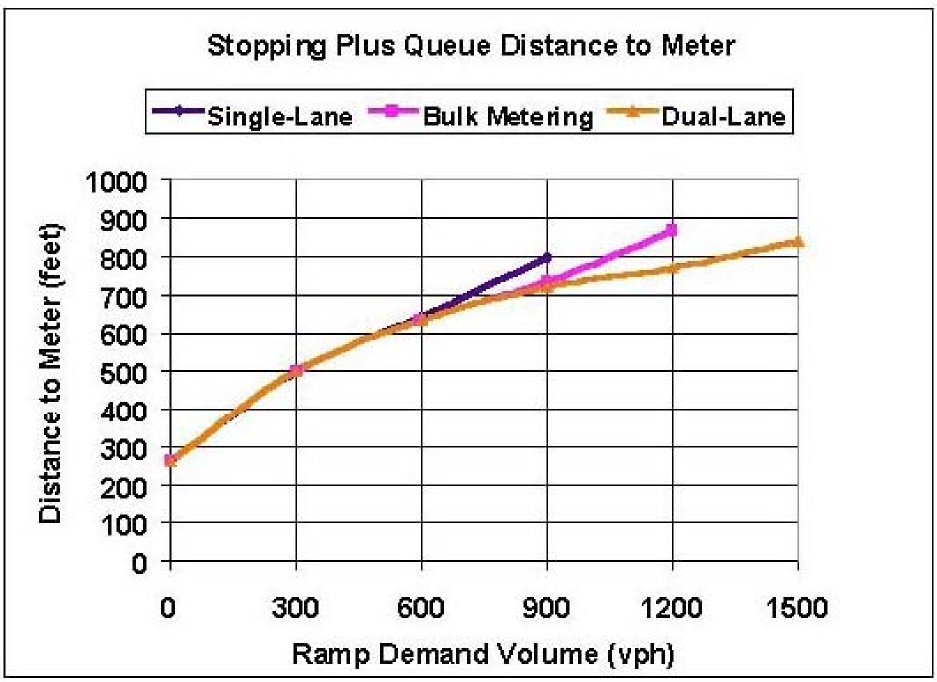


Figure 3-6. Ramp Demand Volume

This figure illustrates the stopping plus storage distance requirements of a ramp during peak hour conditions. The calculations include a minimum stopping distance of 250 feet plus the maximum storage length before ramp demand for each configuration is reached. For example, the single lane configuration reaches maximum ramp demand at 900 vph, this corresponds to an intersection to meter distance of approximately 800 feet of which 250 feet is suggested for adequate stopping distance leaving approximately 550 feet for storage. The storage length of design vehicle is 25 feet, this distance will be sufficient for storing up to 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 approximately 425 feet (5 vehicles x 25 feet + 12 vehicles x 25 feet).

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

American Association of State Highway and Transportation Officials (AASHTO) provide speed-distance profiles for various classes of vehicles as they accelerate from a stop to speed for various ramp grades. Figure 3-7[8] 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[22].

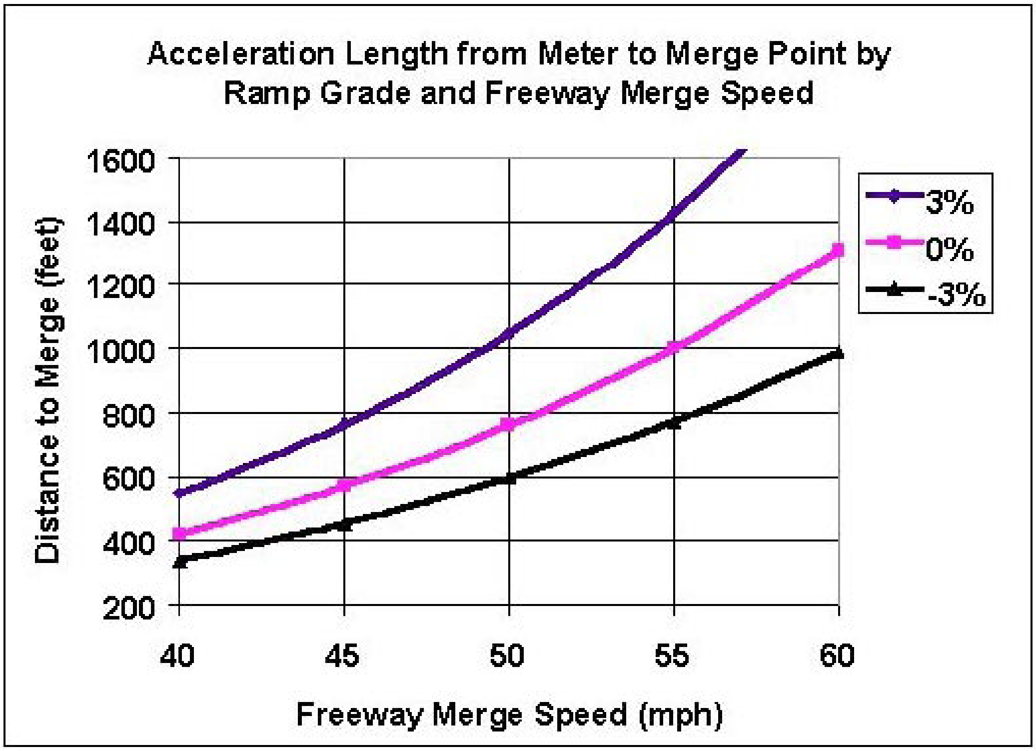


Figure 3-7. Acceleration length from meter to merge point

Stop Bar Sight Distance - Sufficient room must be provided for vehicles discharged from the upstream signal to safely stop behind the queue of vehicles being metered.

Once the storage length and acceleration length requirements have been established, the placement of the stop bar can be determined. The designer must remember that motorists typically leaving an upstream signalized intersection will likely encounter the rear end of the queue as they approach the ramp 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 35 mph or higher. Left turn speeds are usually no higher than 20 mph. 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[22].

For a 35 mph frontage road design speed, the minimum separation distance is calculated to be 240 feet from the basic AASHTO stopping sight distance equation[23]:

$X = 0.278vT + v2/(254f_v) = 0.278 * 55 * 2.5 + 552/(254*0.34) = 73$ m 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 27 mph left turn speed, the AASHTO stopping distance is 145 feet as measured from the centerline of the cross street[22].

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 20 mph, a lane change distance of 80 feet is assumed plus an added stopping distance of 97 feet. Adding a half of the street width, or 45 feet, produces a distance from the centerline of the cross street 225 feet. The distance to the back of the queue should also be some distance downstream of any turnaround lane entrance, which may be nearly 100 feet from the cross street curb line[22].

The minimum desired distance from the centerline of the cross street to the back of the design queue should be about 245 feet. A more desirable distance would be about 330 feet permitting two lane changes for right turn vehicles from the cross street and higher ramp approach speeds[22].

Ramp Meter System - Sufficient room must be provided for the equipment that encompasses the ramp meter system (e.g., signal heads, signs, etc.).

The WisDOT ITS Design Manual addresses all aspects of placement of signs and equipment relative to a ramp metering system, going into so much detail as illustrating the wiring[3]. Poles, detectors, wiring, signage, enforcement areas, etc. are all provided for the design engineer. Considerable work has already been invested in this effort so as to provide minimum setbacks, and optimal operations. This also includes decisions on HOV operations, number of lanes, applications on curved ramps, etc.

Also mentioned in this reference are the funding criteria that will be addressed later.

Alternate Routes Requirement - The presence of an alternative route for motorists on the arterial network to avoid the delays on entrance ramps created by a ramp meter may be required.

Metering may, in fact, divert some short trips from the freeway. In concept, freeways are not intended to serve very short trips, and diverting some trips may even be desirable if there are alternate routes that are under utilized. Diverting traffic from high volume, substandard, or other problem ramps to more desirable entry points should be an objective of metering where it is feasible. Such an action does require a thorough analysis of the alternate routes, the impacts of diversion on those routes, and improvements on the alternate routes when and where they are needed.

In Portland, City officials were very concerned about entrance metering creating problems on parallel streets. Before the meters on I-5 were installed, the City and State agreed that if volumes on adjacent streets increased by more than 25 percent during the first year of operation, the State would either abandon the project or adjust the meters to reduce the diversion below the 25 percent level. Following meter installation, the increase in local street volume did not have a substantial impact. Evaluations of the impact of metering on adjacent streets have been conducted in Los Angeles, Denver, Seattle, Detroit, and other cities. Significant diversion from the freeway to surface streets did not occur in any of these locations. Formal and informal agreements are common between State and local jurisdictions in connection with metering projects, and close advance coordination between jurisdictions is highly recommended[4].

In some cases, there may not be feasible alternate routes, due to barriers such as rivers, railroads, or other major highways. Metering still can and does operate effectively where diversion is not an objective of the system. The systems in Denver, Northern Virginia, and Chicago, for example, operate under a non diversionary strategy. In these systems, metering is sometimes terminated at least until the queue dissipates. Non diversionary strategies may also be implemented by the use of non restrictive ramp metering[22].

Significant benefits in freeway flow and accident reduction still result from non diversionary metering. The onset of mainline congestion consistently begins later in the peak period and ends earlier. On many days, the mainline does not breakdown at all. Accidents and accident rates are also reduced. For example, in Denver, it was observed that many drivers entered the freeway earlier in the morning. Peaks or spikes in volumes were thus leveled out over a longer period of time resulting in better utilization of freeway capacity[24].

The determination of the need for an alternate route, and the availability of that alternate route are open to review and analysis. The implementing agency must determine under which strategy they operate ramp meters, and then determine if alternates are necessary. Additionally, no one has sufficiently defined what makes a good alternate. The assumptions are that the routes should be marked routes with sufficient capacity and within a certain lateral distance of the expressway. No specific thresholds are mentioned in any of the literature, so this will require a more detailed examination of each individual system.

Design Issue Resolution

If the design engineer cannot meet all of the requirements identified above, then another round of systems engineering is required. It may be that a simple relaxing of a non critical standard or alternate operational strategy may better address the original needs, goals, and objectives. This would require the design engineer to reexamine their work to see if the alternate requirements can be met. If they cannot be met, then the decision goes on to whether it meets the traffic management criteria identified above. If the policy makers have selected this approach, some form of accommodation will be necessary. This may be in the form of altered needs or increased funding.

If the design engineer can physically accommodate the ramp metering system, then the next decision is funding. While a planning level assessment should have been made earlier, the design engineer must identify any design changes required by the ramp metering at this point. This should include O&M requirements for any operations focused features. As with other design issues (including many geometric issues), the decision makers must determine if they still have adequate funding to properly build the project. If they do not, then decisions must be made on either cutting certain aspects of the project or soliciting additional funding.

Funding

As part of the initial data collection efforts, availability of adequate funding for ramp meter deployment is a major consideration. This is true whether it is for building a new ramp, extending and/or widening an existing ramp or simply installing ramp meter equipment on an existing ramp. Before attempting to implement a new ramp metering project, an evaluation of potential funding sources should be completed to determine if there is sufficient support for the project. This would include analysis of O&M and whether this is an extension of an existing system or a new system that requires a central server, software, etc. The level of available funding can affect the extent to which a ramp or series of ramps can be modified, affecting ramp width, length, acceleration lanes, HOV treatment and enforcement.

Installation costs varied widely and depended in large part on the existing communication infrastructure and the extent of ramp modifications required to accommodate ramp metering.

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 $30,000 - $50,000 per installation. Virginia reported metering hardware itself is on the order of $10,000 - $15,000, but again that does not include communications. New York reported an average installation cost of about $80,000 per meter including all communications, and this is consistent with Arizona DOT's estimate of approximately $90,000 for an isolated installation.

On the next page is Table 3-3[22] listing the average installation cost and maintenance cost (per year) for various ramp metering systems. The range in costs for installation typically represents installations with and without communications included.

Table 3-3. Average Installation and Maintenance Cost

City	Average Installation Cost	Average Maintenance Cost (yr)
Phoenix	**$50,000 to $90,000**	**$2,000 to $3,000**
Caltrans (statewide)	**Varies**	**$3,000**
Detroit	**N/A**	**$2,500**
Minneapolis	**$10,000**	**$1,000**
Long Island	**$80,000 per ramp**	**$2,000**
Northern Virginia	**$10,000 to $15,000**	**$5,000**
Seattle	**$30,000 to $50,000**	**$3,000**
Milwaukee	**$30,000 to $50,000**	**$2,000**

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. Utilities were not included in these costs.

Wisconsin DOT has updated the costs of ramp meters with the recent Marquette Interchange Project. Costs used in this project indicate the following:

- 1 lane SOV ramp meter including communications costs around $75,000.
- 2 lane SOV or 1 SOV/1 HOV including communications costs around $84,000
- 2 lanes SOV/1 HOV ramp meter with communications costs around $103,000.

The average yearly maintenance costs for ramp meters, including utilities, are estimated at $1,482.29. When considering life cycle costs, with an average life span of 15 years, the average replacement cost is estimated at $17,500.

Also under consideration is the staffing costs incurred with each additional ramp meter. The maintenance costs for a ramp meter should all include the time and material for the field support staff to ensure the physical system is in working order. The additional staff are those operating and managing the additional ramp meters.

For managing the ramp meter, this would include maintaining data in asset management databases, time required for purchasing components, answering questions related to the ramp meter, etc. The majority of these are in the order of minutes per year. The exception is when first installed, there are always public meetings to attend and letters and phone calls that have to be answered. A conservative assumption is that a one time cost of 10 hours of management is incurred per ramp meter – 4 to attend meetings and 6 to answer questions by phone and mail. As ramp meters are rarely installed by themselves, this number is conservative. However, in developing a per location cost, this will be the number used. If management is assumed to cost a fully loaded $125/hour, this results in a one time cost of $1,250 per ramp meter. The other administrative costs can be assumed very conservatively at 1 hour per year for a technical staff person. At a fully loaded $100 per hour, this would result in an annual cost of $100 per ramp meter.

Operational costs are those related to the actual operations of the ramp meter. On a daily basis, an operator is typically responsible for turning on and checking all ramp meters once in the morning, and once in the evening. This would include verifying the meter turned on, was operating as expected, and eventually the meter was turned off. In between, time is spent verifying rates and operations. Over a three hour rush period, this could be estimated as follows:

- Turn on ramp meter – 0.5 minute
- Verify initial operations – 1 minute
- Verify rates while operational for 2 hours – 1 minute
- Turn off ramp meter – 0.5 minute

Daily, this equates to 3 minutes in the morning rush, and 3 minutes in the afternoon rush for 6 minutes (.1 hours) per day. If there are approximately 250 operational days per year, this equates to 25 hours per year. In addition, it can be assumed that once or twice a year, a ramp meter will experience a problem that requires some additional analysis (e.g., sensors are not working properly). This could be estimated at 2 additional hours per year.

Each ramp meter would require an additional 27 hours of technical staff time per year, at an assumed fully loaded rate of $100 per hour. This equates to $2700 per year per ramp meter.

Total estimated staffing costs per additional ramp meter are a one time cost of $1,250 and an annual cost of $2800 (equivalent to 28 hours of staff time). This could also be interpreted in terms of ramp meters per staff person. With 2000 working hours a year (minus vacation), 2000/28 is 71.5. This means that for every 72 additional ramp meters, an additional staff person is required (or for every 36, a part time person is required).

Application for I-94 at STH 20

The following picture illustrates the interchange at I-94 and State STH 20 in Southeastern Wisconsin. The lines show the locations of all roadways. The interchange is a diamond interchange with available frontage roads on both sides.

Figure 3-8. Arial View of STH 20 Interchange

Application of Traffic Criteria

The identified above are applied at a more detailed level.

Traffic Volumes

The threshold is at least 1200 vehicles per hour per lane (vphpl). The volumes at this location are shown in two different formats. The first are 2004 counts which are from WisDOT maps found on the WisDOT website. The ramp volumes have not been adjusted for trucks, as have the freeway volumes. This minor discrepancy is ignored for this exercise. By adding and subtracting ramp volumes in the direction of travel, the mainline volumes are determined. For this analysis, the mainline volumes are calculated at the merge point. This is typically lower than other volumes because the exiting traffic for the off ramp at that interchange has already been removed from the volumes, and the merging traffic has not yet joined from the on ramp. I-94 is three lanes in each direction in this section. An assumption is made that travel is equally distributed among the three lanes. This determines the daily volume per lane. As discussed in Chapter 2, from the Highway Capacity Manual, the peak hour factor that is most appropriate is .09 (9% of the traffic occurs in the peak hour). When combined, the results are shown in the following Table 3-4. The second method is through 2004 direct calculation of peak hour volumes. The first values are from average annual total volumes, the second from average weekday volumes. There is a significant discrepancy between the two numbers.

Table 3-4. I-94 Mainline Volumes at STH 20

Section	2004 AADT	VPL (3 lanes)	VPLPH (.09)	2004 Peak Hour Volume	2004 VPHPL
WB I-94	**30,500**	**10,167**	**915**	**2340**	**780**
EB I-94	**29,500**	**9,833**	**885**	**2310**	**770**

These volumes do not meet the criteria. However, the projected future volumes as part of the SE freeway study are not yet available. When they are available, the same analysis will be applied to them to determine if project volumes warrant ramp metering.

Ramp Volumes

The threshold is at least 240 vehicles per hour (vph) with an assumed one lane ramp. Again, the volumes at this location are provided in two formats. The first is from 2004 average annual counts from the WisDOT website. As discussed previously, the ramp volumes have not been adjusted for trucks. As discussed in Chapter 2, from the Highway Capacity Manual, the peak hour factor that is most appropriate is .09 (9% of the traffic occurs in the peak hour). When combined, the results are shown in the following Table 3-5. The second is directly calculated average weekday peak hour volumes. Again there is some discrepancy between the two values.

Table 3-5. I-94 at STH 20 Ramp Volumes

Section	2004 AADT	VPH (.09)	2004 VPH
WB I-94 entrance ramp	**8,800**	**792**	**750**
EB I-94 entrance ramp	**6,900**	**621**	**520**

In both cases, these volumes meet the criteria.

Freeway Speeds

The threshold is less than 30 mph. As this section of freeway has surveillance detectors with speed traps, direct data is available. In discussions with the staff at MONITOR, a spreadsheet was created with average weekday speeds by 15 minute periods for July 2005. As a considerable amount of data is available, there are many iterations that could be calculated (e.g., weekends, just Sunday, just Friday, average for the year, etc.). For the purposes of this report, the simplified approach was used.

The data matching this simplified request shows average 15 minute speeds routinely staying above 50 mph, and never falling below 45 mph. These speeds do not meet the criteria.

Safety Criteria
As discussed previously, there is no guidance from other locations on thresholds or metrics used in determining safety. Without sufficient investigation beyond this project, no solid analysis can be provided at this moment. However, in the interest of providing a starting point for Wisconsin, a simple analysis was completed to develop an initial threshold of 80 accidents per 100 mvm.

The accident rates calculated in Chapter 2 are 98 EB and 88 WB. Both directions exceed the threshold.

Corridor Criteria
At the time of this report, WisDOT had made no decision on whether ramp metering was applicable throughout the SE corridor. These criteria cannot be applied currently.

Ramp Geometry

Full determinations of exact lengths are best properly addressed during the formal design process. Not all geometric detail is available. Still, minimum values for many of the geometric requirements were discussed above. The following are determined as best as possible from available data.

The three main requirements are storage length, acceleration length, and stopping length. Charts with values per various conditions were discussed above. Based on values common to Wisconsin, minimum values for each can be calculated: Using basic assumptions such as 60 mph speed, the minimum values for each are as follows:

- 550 feet for a minimum storage length from Figure 3-6
- 440 feet for acceleration length for 3% grade at 45 mph from Figure 3-7
- 330 feet for a stop bar distance from the formula listed with the stop bar sight distance criteria discussed previously in this chapter

This combines for a total of 1320 feet from the arterial edge of pavement to the merge point on the freeway. From available data, the current westbound on ramp is 1850 feet long, and the eastbound on ramp is 1450 feet long. Both provide adequate minimal distances. However, the current ramps will be shortened in the near term due to an additional lane being constructed. The current planned lengths are 1520 feet for the westbound ramp, and 1000 feet for the eastbound ramp. Therefore, in the future, the eastbound entrance ramp may not be of sufficient length to allow proper installation of ramp meters.

For the ramp metering system itself, there currently exists a fiber optic backbone along the I-94 ROW. This ties into the existing ramp metering system at MONITOR. Therefore, the system level requirements are minimal.

The WisDOT ITS Design Manual does not specify a total footprint for the off pavement components of a ramp metering system. There is great detail on the requirements and specifications, but no summary. Assuming on pavement portions do not take additional ROW, and cable runs and signs do not take additional ROW, the largest components are the cabinet and the enforcement area. The cabinet is assumed to be a large 4'x6' base for 24 square feet. The enforcement area is variable per type of ramp, but is calculated at 2850 square feet. The aerial photo shows this interchange to have sufficient room for this equipment.

As determined above, these design requirements appear to have been met with minimal additional cost or effort.

Alternate Route

The requirement described above was relatively ambiguous as to exactly what defined an alternate route. In this case, frontage roads are available on either side of the freeway within several hundred feet. These frontage roads are continuous to the interchanges on either side of STH 20. The frontage roads are two lanes and paved. No determination of truck loading limits is available.

In general, this design requirement appears to be met.

Funding Requirement

Again, full costing of the system requires a detailed design approach under the separate SE corridor project. The analysis above has illustrated that the cost should be on the minimal side. The interchange is large and open with plenty of ROW. There are existing communications nearby and an operating system in which the ramp meters would be included. No anticipated rerouting of roads or new retaining walls is expected.

From the section following Table 3-2, an estimated impact cost of $75,000 is used. This is expected to be minimal compared to the mainline reconstruction work.

Summary

Two of the four base level traffic criteria are met with the available 2004 data. Thus, for the traffic criteria, these ramps meet the criteria. The remainder of the criteria do appear to be met, so that there are no impediments to installation of the ramp metering if the future numbers show they are warranted.

Application for I-94 at STH 158

The following picture illustrates the interchange at I-94 and STH 158 in Southeastern Wisconsin. The lines show the locations of all roadways. The interchange is a diamond interchange with available frontage roads on both sides.

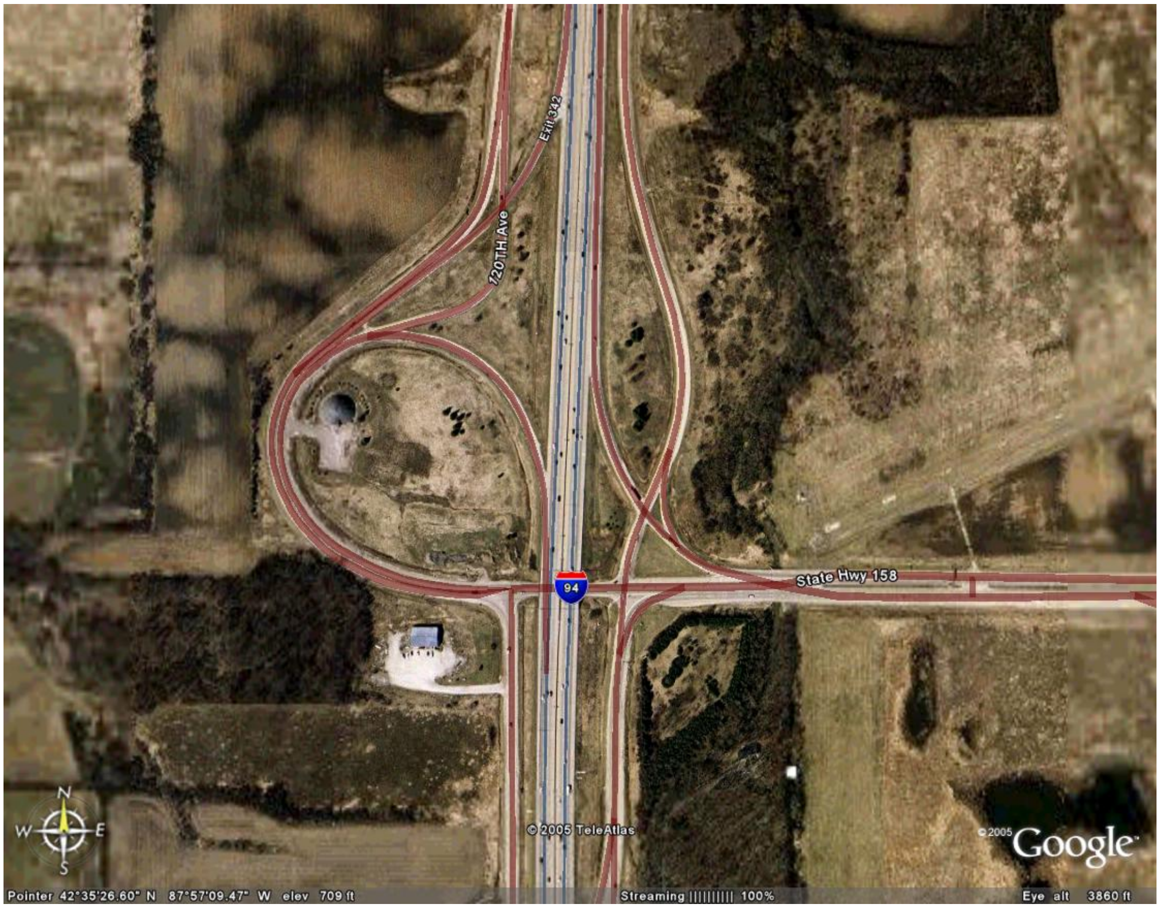


Figure 3-9 Arial view of STH 158

Application of Traffic Criteria

The criteria identified above are applied at a more detailed level.

Traffic Volumes

The threshold is at least 1200 vehicles per hour per lane (vphpl). The volumes at this location are shown in two different formats. The first are 2004 counts which are from WisDOT maps provided on the WisDOT website. The ramp volumes have not been adjusted for trucks, as have the freeway volumes. This minor discrepancy is ignored for this exercise. By adding and subtracting ramp volumes in the direction of travel, the mainline volumes are determined. For this analysis, the mainline volumes are calculated at the merge point. This is typically lower than other volumes because the exiting traffic for the off ramp at that interchange has already been removed from the volumes, and the merging traffic has not yet joined from the on ramp. I-94 is three lanes in each direction in this section. An assumption is made that travel is equally distributed among the three lanes. This determines the daily volume per lane. As discussed in Chapter 2, from the Highway Capacity Manual, the peak hour factor that is most appropriate is .09 (9% of the traffic occurs in the peak hour). When combined, the results are shown in the following Table 3-6. The second method is through 2004 direct calculation of peak hour volumes. The first values are from average annual total volumes, the second from average weekday volumes. There is a significant discrepancy between the two numbers.

Table 3-6. I-94 Mainline Volumes at STH 158

Section	2004 AADT	VPL (3 lanes)	VPLPH (.09)	2004 Peak Hour Volume	2004 VPHPL
WB I-94	**34,900**	**11,633**	**1047**	**2790**	**930**
EB I-94	**34,100**	**11,367**	**1023**	**2140**	**713**

These volumes do not meet the criteria. However, the projected future volumes as part of the SE freeway study are not yet available. When they are available, the same analysis will be applied to them to determine if project volumes warrant ramp metering.

Ramp Volumes
The threshold is at least 240 vehicles per hour (vph) with an assumed one lane ramp. Again, the volumes at this location are provided in two formats. The first is from 2004 average annual counts. As discussed previously, the ramp volumes have not been adjusted for trucks. As discussed in Chapter 2, from the Highway Capacity Manual, the peak hour factor that is most appropriate is .09 (9% of the traffic occurs in the peak hour). When combined, the results are shown in the following Table 3-7. The second is directly calculated average weekday peak hour volumes. Again there is some discrepancy between the two values.

Table 3-7. I-94 at STH 158 Ramp Volumes

Section	2004 AADT	VPH (.09)	2004 VPH
WB I-94 entrance ramp	**3,400**	**306**	**320**
EB I-94 entrance ramp	**2,300**	**207**	**270**

Using the 2004 values, both ramps meet the criteria.

Freeway Speeds
The threshold is less than 30 mph. Similar to the analysis at STH 20, this section of I-94 has surveillance detectors with speed traps and therefore direct availability of data. Again, in discussions with the staff at MONITOR, a spreadsheet was created with average weekday speeds by 15 minute periods for July 2005. A similar approach was used as described above.

The data matching this simplified request shows average 15 minute speeds routinely staying above 50 mph, and never falling below 45 mph. These speeds do not meet the criteria.

Safety Criteria
As discussed previously, there is no guidance from other locations on thresholds or metrics used in determining safety. Without sufficient investigation beyond this project, no solid analysis can be provided at this moment. However, in the interest of providing a starting point for Wisconsin, a simple analysis was completed to develop an initial threshold of 80 accidents per 100 mvm.

The accident rates calculated in Chapter 2 are 95 EB and 49 WB for the section from STH 50 to STH 142 (CTH S). One direction is above the threshold.

Corridor Criteria
At the time of this report, WisDOT had made no decision on whether ramp metering was applicable throughout the SE corridor. These criteria cannot be applied currently.

Ramp Geometry
Full determinations of exact lengths are best properly addressed during the formal design process. Not all geometric detail is available. Still, minimum values for many of the geometric requirements were discussed above. The following are determined as best as possible from available data.

The three main requirements are storage length, acceleration length, and stopping length. Charts with values per various conditions were discussed above. Based on values common to Wisconsin, minimum values for each can be calculated: Using basic assumptions such as 60 mph speed, the minimum values for each are as follows:

- 550 feet for a minimum storage length from Figure 3-6
- 440 feet for acceleration length for 3% grade at 45 mph from Figure 3-7
- 330 feet for a stop bar distance from the formula with the stop bar sight distance criteria discussed previously in this chapter

This combines for a total of 1320 feet from the arterial edge of pavement to the merge point on the freeway. From available data, the current westbound on ramp is 1240 feet long, and the eastbound on ramp is 1110 feet long. Neither provide adequate minimal distances. Additionally, the current ramps will be shortened in the near term due to an additional lane being constructed. Neither meets the criteria and both are significantly short in the current design.

For the ramp metering system itself, there currently exists a fiber optic backbone along the I-94 ROW. This ties into the existing ramp metering system at MONITOR. Therefore, the system level requirements are minimal.

The WisDOT ITS Design Manual does not specify a total footprint for the off pavement components of a ramp metering system. There is great detail on the requirements and specifications, but no summary. Assuming on pavement portions do not take additional ROW, and cable runs and signs do not take additional ROW, the largest components are the cabinet and the enforcement area. The cabinet is assumed to be a large 4'x6' base for 24 square feet. The enforcement area is variable per type of ramp, but is calculated at 2850 square feet. The aerial photo shows this interchange to have sufficient room for this equipment.

As determined above, these design requirements appear to have been met with minimal additional cost or effort.

Alternate Route

The requirement described above was relatively ambiguous as to exactly what defined an alternate route. In this case, frontage roads are available on either side of the freeway within several hundred feet. These frontage roads are continuous to the interchanges on either side of STH 158. The frontage roads are two lanes and paved. No determination of truck loading limits is available.

In general, this design requirement appears to be met.

Funding Requirement

Again, full costing of the system requires a detailed design approach under the separate SE corridor project. The analysis above has illustrated that the cost should be on the minimal side. The interchange is large and open with plenty of ROW. There are existing communications nearby and an operating system in which the ramp meters would be included. No anticipated rerouting of roads or new retaining walls is expected.

From the section following Table 3-2, an estimated impact cost of $75,000 is used. This is expected to be minimal compared to the mainline reconstruction work.

Summary

The base level traffic criteria are met EB and not met WB with the available 2004 data. However, the other thresholds are relatively close to the low end of the criteria, and it is expected that design year modeling numbers WB will meet the criteria. The remainder of the criteria do appear to be met, so that there are no impediments to installation of the ramp metering if the future numbers show they are warranted.

Chapter 4 Criteria Thresholds and Implementation Plan

Spreadsheet Ramp Metering Modeling Process

This application was developed from some earlier work for the Long Island Freeway[25]. The application determines the impact on a section from ramp metering and takes into account the actual operations of ramp metering. The model assumes certain operational procedures and goals as explained below (e.g., assumes operations want to minimize delays on ramps). The operations appear to be consistent with current WisDOT operations. If WisDOT changes their operations, the model can be easily modified to reflect these new operations. The following section details the development of the spreadsheet.

Wisconsin Ramp Analysis Tool — Wilbur Smith Associates

Meter Override Criteria (Qualitative): Potential violations that might occur with lower rates and desire to minimize local road impacts, VS. desire to maintain free flow and higher level of service on mainline freeway.			
	Assumed Mainline Capacity	2200 vphpl	
	Average Vehicle Length	18 feet	Maximum ramp volume threshold for metering: 1200 vph
	Maximum Metering Rate	800 vph	Maximum remaining mainline capacity below which ramp metering is activated: 500 vph per lane
User Input Cells	Minimum Metering Rate	300 vph	
Calculated Cells	TIME PERIOD		Minimum remaining mainline capacity to maintain using automated ramp meter rates: 100 vph per lane

	ENTER RAMP INFORMATION		ENTER MAINLINE INFORMATION			ENTER SERVICE ROAD INFORMATION	BASIC METER RATE CALCULATION	ENTER LOCAL RATE OVERRIDE DATA		ADJUSTED METER RATE CALCULATION	RAMP DEMAND AND DIVERSION CALCULATION							MAINLINE PERFORMANCE SUMMARY	
Location	Ramp Demand (vph) (2004)	Ramp Storage Length (ft)	Mainline Volume (vph) (2004)	Number of Mainline Lanes (direction)	Mainline Capacity (Direction)	(Y or N) Downstream access by Service Road?	Automatic Metering Rate	(Y or N) Desire Rate Override?	Manual Override Rate	Actual Meter Rate (Automatic or Override if Override	Excess Ramp Demand (vph)	Queue Storage Capacity (veh)	Diversion to Service Road	Added Ramp Volumes Due to Diversions from Upstream Ramp	Cumulative Diversions Due to Ramp Capacity Constraints	Adjusted Mainline Volumes	If No Service Road Capacity, Time to Reach Queue Capacity (min)	Non-Metered V/C Ratio	Metered V/C Ratio
I-94 EB from Minnesota													0						
STH 35	189	300	2412	3	6600	Y	800	N		800	0	16	0	X	0	2412	N/A	0.37	0.37
Carmichael Road	747	300	1719	3	6600	Y	800	N		800	0	16	0	0	0	1719	N/A	0.26	0.26
STH 35	126	300	2214	3	6600	Y	800	N		800	0	16	0	0	0	2214	N/A	0.34	0.34
US 12	171	300	1863	3	6600	Y	800	N		800	0	16	0	0	0	1863	N/A	0.28	0.28
STH 65	153	300	1629	2	4400	Y	800	N		800	0	16	0	0	0	1629	N/A	0.37	0.37
County Road T	99	300	1782	2	4400	Y	800	N		800	0	16	0	0	0	1782	N/A	0.41	0.41
STH 63	252	300	1260	2	4400	Y	800	N		800	0	16	0	0	0	1260	N/A	0.29	0.29
County Road B	43	300	1359	2	4400	Y	800	N		800	0	16	0	0	0	1359	N/A	0.31	0.31
STH 128	180	300	1224	2	4400	Y	800	N		800	0	16	0	0	0	1224	N/A	0.28	0.28
I-94 WB to Minnesota													0						
STH 128	261	300	981	2	4400	Y	800	N		800	0	16	0	X	0	981	N/A	0.22	0.22
County Road B	87	300	1357	2	4400	Y	800	N		800	0	16	0	0	0	1357	N/A	0.31	0.31
STH 63	315	300	1233	2	4400	Y	800	N		800	0	16	0	0	0	1233	N/A	0.28	0.28
County Road T	189	300	1557	2	4400	Y	800	N		800	0	16	0	0	0	1557	N/A	0.35	0.35
STH 65	396	300	1620	2	4400	Y	800	N		800	0	16	0	0	0	1620	N/A	0.37	0.37
US 12	540	300	1485	2	4400	Y	800	N		800	0	16	0	0	0	1485	N/A	0.34	0.34
STH 35	585	300	1881	3	6600	Y	800	N		800	0	16	0	0	0	1881	N/A	0.29	0.29
Carmichael Road	882	300	1683	3	6600	Y	800	N		800	82	16	66	0	66	1617	N/A	0.26	0.25
11th Street	918	300	2484	3	6600	Y	800	N		800	118	16	102	66	168	2316	N/A	0.38	0.35
STH 35	495	300	2745	3	6600	N	800	N		800	0	16	0	168	0	2745	0.0	0.42	0.42

Figure 4-1. Sample main worksheet from WRAT

System Wide Parameters

Several parameters apply universally throughout the system or a corridor. These are either thresholds or parameter values. Each is discussed below.

MAXIMUM METERING RATE – during the operation of ramp meters, the rate at which vehicles on the ramp are released (in terms of vehicles per hour) is referred to as the "metering rate." The higher the rate, the less each individual vehicle is delayed. The metering rate reaches a maximum value where the system is releasing vehicles almost as quickly as they reach the signal. To increase the ramp flow any further, the ramp metering must be shut off so the ramp can resume free flow operations. Thus, this rate represents the cut off point at which ramp metering is no longer an effective operational tool. For this project, the maximum metering rate has been set at 800 vehicles per hour or one vehicle every 4 seconds.

MINIMUM METERING RATE – similar to the maximum metering rate, there is a minimum value at which ramp metering can be operated without losing its effectiveness as an operational tool. When the metering rate reaches a minimum value where the system is releasing vehicles almost as slowly as tolerated by the motorists, any further reduction in the metering rate will result in motorists no longer respecting the signal and violations will increase reducing the effectiveness. When the motorist starts violating the signal, the operations have lost the ability to control the flow on the ramp. Thus, this rate represents the cut off point at which ramp metering is no longer an effective operational tool. For this project, the minimum metering rate has been set at 300 vehicles per hour or one vehicle every 12 seconds.

MAXIMUM RAMP VOLUME FOR METERING – ramp metering operations assume that the traffic conditions are appropriate for this tool to be effective. Similar to the maximum metering rate, if the total ramp volumes are too high, then metering is not the correct tool. Likely, geometric improvements or some other policy option are better solutions. At this threshold, the volume of traffic going through the ramp meter would be sufficiently high that either the backup would take too long to dissipate or the diverted traffic would place an undue burden on the other sections of the transportation network. This number is initially set at 1200 vehicles per hour.

EXCESS MAINLINE CAPACITY THRESHOLD FOR TURN ON– the assumption with ramp metering is that by reducing and separating the incoming traffic, the operations of the mainline are smoother and can operate at higher operational speeds. When a section of freeway is operating well beyond its capacity, the value of ramp metering is less. To best implement ramp metering, it is best to turn it on before congestion has occurred to delay the start of congested periods. This value represents a threshold at which ramp metering should be turned on. This value is initially set at 500 vehicles per hour per lane (i.e., ramp metering should be turned on when the hourly volumes reach a point 500 vehicles per hour per lane less than capacity).

MINIMUM EXCESS MAINLINE CAPACITY THRESHOLD TO MAINTAIN – similar to the previous threshold, after congestion occurs on a freeway, metering is less directly effective. At some point near congestion, ramp metering rates should shift from a congestion focus to a safety focus. To best utilize ramp metering, it can be run at the optimal rate up to just before the start of the congested periods. This value represents a threshold at which ramp metering rates should be switched. This value is initially set at 100 vehicles per hour per lane (i.e., ramp metering should be maintained until the hourly volumes reach a point 100 vehicles per hour per lane less than capacity).

MAINLINE CAPACITY – this value has been updated in the Highway Capacity Manual over the years. The current expected value is 2200 vehicles per hour per lane for a limited access high volume facility.[20]

AVERAGE VEHICLE LENGTH – this value is used in the computation of the number of vehicles that can be stored on a ramp. The model is not capable of addressing the excess vehicles other than assuming they will all reroute to the next ramp if an alternate route is available. Based on the length of the ramp, the number of cars that can physically fit on the ramp can be calculated. This is used in the computation of the total ramp storage value.

Corridor Specific Values

As discussed in the previous documents, ramp metering needs to be implemented over a corridor to be truly effective. As such, specific corridors are identified and analyzed as a group. The following values must be input into the spreadsheet for analysis:

LOCATION – through the identified corridor, the individual entrance ramps need to be identified in the direction of traffic flow.

RAMP DEMAND – the number of vehicles per hour per lane using the entrance ramp. These can be based on counts or modeled values.

MAINLINE VOLUME – the number of vehicles per hour on the mainline just prior to the entrance ramp merge. The system wide value for number of lanes is used to calculate a per lane value. If the numbers are from AADT, then a peak hour factor of 0.09[20] should be used to reduce the value to the peak hour. Again, the numbers can be based on counts or modeled results, so long as they are consistent with the ramp demand values.

DESIRED RATE OVERRIDE – this represents an operational decision to use a specific ramp metering rate on a ramp regardless of traffic conditions. There can be many reasons for this decision, none of which are relevant to this initial application. For the purposes of this initial analysis, it is assumed that none of the ramps will be on manual control.

MANUAL OVERRIDE RATE – this represents the ramp metering rate used if a manual control is desired. Similar to the ramp metering rates discussed previously, it represents the number of vehicles per hour to be released on the ramp.

DOWNSTREAM ACCESS BY SERVICE ROAD – this value is a yes or no based on whether a reasonable route exists for excess ramp traffic to bypass this interchange and attempt access to the freeway at the next interchange. This value is relatively easy to determine in more urban locations where frontage roads or parallel arterials exist. In the rural areas, where an arterial may be miles away, it is less valuable. Other problems exist at river crossings and other natural barriers where the freeway has a bridge but the lower types of roadways do not. This value is used in calculating whether diverted traffic is added at downstream ramps, or assumed to take alternate routes.

RAMP STORAGE LENGTH – this represents the centerline length from the ramp meter signal to the cross street feeding the ramp. This information needs to be determined from design records or field observations.

The Model

The first step in the model is to calculate the ramp metering rate to be used. The Highway Capacity Manual is used to determine the automatic metering rate. This rate is then checked to see if it falls within the minimum and maximums and adjusted accordingly. A manual override check is also made to determine if this is being applied. The end result of these checks is a value for the actual metering rate.

Next, the storage capacity of the ramp is checked. The equation takes the ramp length divided by an average vehicle length and is then rounded down to a whole number. This value represents the number of vehicles that can be stored on the ramp prior to the meter. This value is added to the metering rate to determine the number of vehicles that will use the ramp during the model hour. Also determined from this is the time required to reach capacity for storage. It is assumed that the distribution of entering vehicles is constant throughout the hour, so the excess ramp demand is divided by 60 to determine the number arriving per minute. The storage capacity is then divided by this rate to determine the number of minutes before the ramp reaches its storage capacity.

This value can be used with an optional flushing rate, that is, a rate that is used when a ramp reaches storage capacity to flush some of the vehicles off the ramp to prevent accidents on the serving arterial.

Next calculated is the amount of traffic that is diverted to the service road. This is the excess ramp demand minus the storage capacity. If the optional flushing is used, this extra volume handled by the flushing is reflected in a lower number for the diversion traffic. This diversion traffic is used in the calculations for the following ramp and in later adjustments to the mainline volumes. Extra traffic diverted on the service road is added to the ramp demand traffic for the next downstream ramp to determine if that ramp can handle the additional traffic. The model assumes that the excess demand will be met until the maximum metering rate is reached. The difference in the diverted traffic and those handled by the ramps is determined as a cumulative excess demand.

The model assumptions are that the excess demand represents a reduction in freeway volumes from diverted or delayed traffic. The capacity of the facility is used to determine the "historic" V/C ratio (that determined from AADT) and the "adjusted" V/C ratio (determined from reducing AADT values by the excess demand). The result can be used to determine the benefits to the mainline freeway traffic with reduced congestion.

Model Limitations

As discussed at the October 18, 2005, ramp metering meeting, the model used in this analysis is fairly simple and has a specific role within the overall ramp metering decision process. The previous research efforts on this project have illustrated that the decision to implement ramp metering is less straightforward than other decision processes. Many other ITS projects have a less direct impact on traffic. DMS and HAR messages affect travel, but they are not on the travel way, are not regulatory (like a signal), or physical (like a gate). Implementing DMS or HAR is relatively uncontested once the initial system is in place. Other efforts such as lane control signs, automatic de-icing systems, etc., are very specific and require individual study/design efforts to properly design, construct and operate. The decisions to use these technologies or other operational treatments are made carefully through a longer, more technical, analysis. Ramp metering tends to fall in between.

The desire is to treat ramp metering as another type of signal – identify specific warrants that any traffic engineer could apply in the design process to determine where, when, and how to implement. The analysis has shown those warrants do not, and possibly cannot, exist. Therefore, the model developed in this project is not meant as a formal and final decision tool to determine if ramp metering is warranted. That can only come from more detailed analysis of the local traffic and geometry, as they will vary considerably from location to location. This model is a good tool to provide a relatively quick and cost effective way to determine which ramps require the more detailed analysis. So at the highest level, the limitation of the tool is it is meant as a first cut at determining which ramps are likely candidates.

As the model is examined in more detail, there are other limitations. The application of the service road makes a couple of assumptions. First of all, the assumption is that the service road is a viable alternative. There is no definition of how far the service road can be from the expressway. Also, if it has stop signs at every intersection until the next ramp, its usefulness is diminished. Again, the model requires the user to determine whether or not the service road is viable. Second, the model assumes only one entrance ramp per interchange. Multiple service ramps can easily be added, but the application of the diversion to the next ramp via the service road assumes one ramp per interchange. The model can be manually manipulated to reflect multiple entrance ramps, but this requires thorough review of the revisions and thorough noting of the system to ensure the model is not incorrectly applied in another location.

Additionally, the model assumes a specific operations strategy in relation to the ramp metering rate. In this particular application, the model assumes that the operational strategy is to minimize the ramp delay, while providing mainline relief. Other operational strategies include minimizing freeway impact (use minimum metering rate) or more dynamic use of metering rates (minimize rate until ramp queue develops or mainline reaches a specific threshold).

In terms of diversions, the model assumes all traffic will eventually enter the expressway. There is no mode or time shift of the traffic. This assumption is likely very valid, but this is one area that a more detailed modeling approach will have improved analysis of actual traffic changes relative to the ramp metering.

Initial Statewide Ramp Metering Plan

Implementation Criteria and Thresholds

Also included in the spreadsheet analysis is an application of the previously determined criteria. These are shown in spreadsheet "criteria." The model makes the assumption that ramp metering is already in place, and determines how it can best be implemented. For much of Wisconsin, the values are well below the minimums, so the fictional ramp metering operates at a minimal rate that still does not create any diversions.

Two of the values for traffic related criteria are used as input to the model, and therefore readily available. The speed data is more questionable and will have to be input in. As accident metrics have not yet been determined, a placeholder has been put into the spreadsheet. Until such time as a metric and threshold are determined, this value remains unavailable.

The service road criteria are also used as an input to the model. Any policy and financial decisions determined outside of this process must be weighed against the results of this model to determine their relative value. Most of the geometric values for the ramps are not directly used in the model, with the exception of the storage length.

						Wisconsin Ramp Analysis Tool		Wilbur Smith Associates					
							Mainline demand criteria						
	Freeway Ramp Evaluation Database						Minimum	1200	vphpl				
			Maximum Metering Rate	800	vph		Ramp Demand criteria				User Input Cells		
							Minimum	240	vphpl		Calculated Cells		
			Minimum Metering Rate	300	vph						Model Results		
							Mainline speeds criteria						
							Less than	30	mph				
							Safety criteria						
								???					

Location	Ramp Demand (vph) (2004)	Mainline Volume (vph) (2004)	Mainline Speeds	Future Accident Rate Metric	(Y or N) Downstream access by Service Road?	Mainline volumes vphpl	Mainline Criteria Met?	Ramp Criteria Met?	Speed Criteria Met?	Safety Criteria Met?	Overall Traffic Criteria Met for this ramp?	Corridor Traffic Warrant Met?	Service Road criteria met?
I-94 EB from Minnesota													
STH 35	189	2412	50		Y	804	no	no	no	no	no	no	yes
Carmichael Road	747	1719	50		Y	573	no	yes	no	no	no	no	yes
STH 35	126	2214	50		Y	738	no	no	no	no	no	no	yes
US 12	171	1863	50		Y	621	no	no	no	no	no	no	yes
STH 65	153	1629	50		Y	815	no	no	no	no	no	no	yes
County Road T	99	1782	50		Y	891	no	no	no	no	no	no	yes
STH 63	252	1260	50		Y	630	no	yes	no	no	no	no	yes
County Road B	43	1359	50		Y	680	no	no	no	no	no	no	yes
STH 128	180	1224	50		Y	612	no	no	no	no	no	no	yes
I-94 WB to Minnesota													
STH 128	261	981	50		Y	491	no	yes	no	no	no	no	yes
County Road B	87	1357	50		Y	679	no	no	no	no	no	no	yes
STH 63	315	1233	50		Y	617	no	yes	no	no	no	no	yes
County Road T	189	1557	50		Y	779	no	no	no	no	no	no	yes
STH 65	396	1620	50		Y	810	no	yes	no	no	no	no	yes
US 12	540	1485	50		Y	743	no	yes	no	no	no	no	yes
STH 35	585	1881	50		Y	627	no	yes	no	no	no	no	yes
Carmichael Road	882	1683	50		Y	561	no	yes	no	no	no	no	yes
11th Street	918	2484	50		Y	828	no	yes	no	no	no	no	yes
STH 35	495	2745	50		N	915	no	yes	no	no	no	no	no

Figure 4-2. Sample Worksheet on Ramp Metering Criteria

The criteria worksheet applies the logic identified in Chapter 3 and shown in Figure 4-3. It specifically examines the four traffic related criteria (although the safety criteria have not yet been determined). In order to satisfy the overall traffic criteria, two of the four have to be met. The corridor criteria then examine if the majority of the ramps have met the traffic criteria. The service road criteria is not critical to implementation recommendations, but is noted whether it is met.

The other criteria that were discussed in earlier chapters do not directly apply to this analysis. Other criteria may be applied as the analysis continues to the more detailed modeling stage.

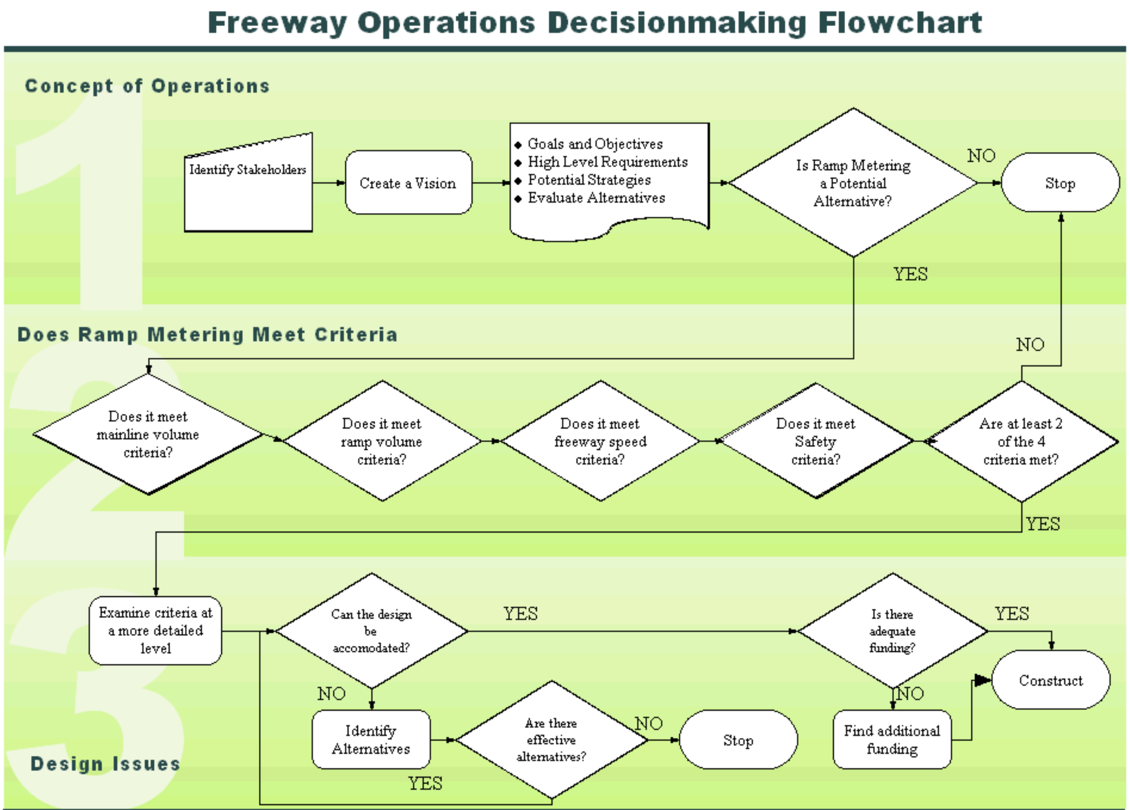


Figure 4-3. Freeway Operations Decision Making Flowchart

Statewide Ramp Control Plan

The criteria for ramp control are based on past road closures within a corridor. Data on where and when full road closures have occurred is difficult to collect outside of the MONITOR area in Southeast Wisconsin. No method has been identified as of yet, and no data has been made available. However, a spreadsheet model was also constructed for analysis of ramp control gates. When the data becomes available, WisDOT should be able to quickly use this tool to identify sections where ramp gates meet the criteria.

The design and application of ramp control gates is much simpler than ramp metering. The one assumption is that the gates will not be operated on a daily or routinely scheduled basis. If a gate was operated this frequently, then a more automated or robust system should be studied. Again, the assumption is that the gate will be manually operated on an infrequent basis.

Another assumption is that the ramp control gate design used in Southeast Wisconsin would be adopted statewide. Alternatives that were previously mentioned included Type III barricades, cones, and barrels. Cones and barrels are not a good candidate for permanent use as the cones are not secure and stable enough to survive intact for long periods, and the barrels, while only slightly more secure and stable, are sometimes difficult to move by passing law enforcement. Horizontal swing gates are a good alternative, but are susceptible to becoming snow packed during plowing. The vertical swing gates are easily used, low maintenance, secure, and less susceptible to operational problems related to snow plowing. Therefore, the assumption is that the current vertical gate design is the best application at other ramps throughout Wisconsin.

Application of Traffic Criteria

The criteria identified in Chapter 2 all related to the number and duration of full closures of the freeway mainline. As discussed in Chapter 2, the criteria are eventually applied to an entire corridor. The assumption is that incidents generally occur randomly, and if incidents occurred on one section of freeway in the study period, they could easily occur in an adjacent section next time.

A corridor can be defined in many ways, but is generally assumed to be between major decision points. In rural areas, this may be between major interstate interchanges over a relatively long distance. In urban areas, it can be between major traffic generators or points where geometry or traffic changes noticeably. The model uses data for any ramps within the corridor that have experienced full mainline closures in the immediate section downstream from the entrance ramp.

The data items entered are the duration of a closure for a specific upstream ramp/interchange by year. The model assumes a three year study period and has room for four closures per ramp per year and four ramps per corridor. Additional closures and ramps can be added if desired. Figure 4-4 below is an illustration of the Wisconsin Ramp Control Worksheet.

Wisconsin Ramp Control Tool Wilbur Smith Associates

Ramp	Identified Section		Year 1	Year 2	Year 3		
			List duration of full closures in hours				
Ramp 1	Immediately downstream of ramp	1					
		2					
		3					
		4				User Input	
Ramp 2	Immediately downstream of ramp	1				Calculations	
		2				Model Results	
		3					
		4					
Ramp 3	Immediately downstream of ramp	1					
		2					
		3					
		4					
Ramp 4	Immediately downstream of ramp	1					
		2					
		3					
		4					
	Total Closures per year		0	0	0		
	Total Short Term Closures per year		0	0	0		
	Total Long Term Closures per year		0	0	0		

Occasional Short Term Criteria		Occasional Long Term Criteria	
Is the Usage Criteria met?	No	Is the criteria met for general usage?	No
Ramp 1	No	Ramp 1	No
Ramp 2	No	Ramp 2	No
Ramp 3	No	Ramp 3	No
Ramp 4	No	Ramp 4	No
Is the Heavy Usage Criteria met?	No	Is the criteria met for heavy usage?	No
Ramp 1	No	Ramp 1	No
Ramp 2	No	Ramp 2	No
Ramp 3	No	Ramp 3	No
Ramp 4	No	Ramp 4	No
Is the Corridor Criteria met?	No	Is the Corridor Criteria met?	No

Figure 4-4. Ramp Control Worksheet - Blank

Test data were used in order to validate the workings of the model. The short term criteria look for frequency of closures less than 8 hours. The long term criteria look for any closures greater than 8 hours, but less than 2 weeks (the assumed length requiring more permanent solutions).

Statewide Policy Considerations

The cost of a ramp closure gate as typically installed in Wisconsin is estimated at a conservative $5000 per gate. This represents the design already used in Southeast Wisconsin with a manually operated arm that can be lowered vertically across the ramp by personnel that then move on to other activities (e.g., closing more gates or assisting with incident operations). There are approximately 200 entrance ramps throughout Wisconsin without any ramp control. By simply applying the assumed cost to the number of ramps, a program of installing control gates at all entrance ramps would cost the state of Wisconsin an estimated $1,000,000. It is likely that a formal contract will realize economies of scale and reduce the unit cost significantly. However, applications in urban and dense suburban areas may require a more positive control device due to their higher volumes and enhanced geometric design. It should be noted that many interchanges are designed to handle significant amounts of traffic and many of the barriers used to help close the ramp have been removed. A simple crossing arm will not be sufficient. For planning purposes, we can assume there are 50 ramps across Wisconsin that need more than the standard closure gate. For a system of more formal and visible gates, that fit within a wider geometry, are manually operated, and accompanied by simple flashers and manually changeable signs, the installation cost for this safe but low tech system would likely be in the range of $30,000. Therefore the "Urban Gate System" would cost an estimated $1,500,000. A good starting point for

Wisconsin to have statewide manual ramp control based on these high level assumptions would be an estimated $2.5 million.

$2,500,000 is a significant value with respect to the various other operational concerns of the Department. However, with respect to current homeland security efforts addressing evacuations, and considering the financial impact of a single severe accident (which do occur on an infrequent basis), the operational benefit of these gates can be justified. Additionally, if Wisconsin examined those ramps in the vicinity of the large urban areas within Wisconsin, and homeland security dollars become available, the majority of the ramp system could be addressed as part of evacuation preparedness.

The cost benefit of ramp control gates was initially discussed in Chapter 1. At $5000 per gate, a person and a vehicle can be assumed to be valued at $150 per hour (the rental cost of a vehicle and a fully loaded staff person to occupy the vehicle). It would take 27 hours of operation to make the ramp control gate cost effective. This analysis assumed that the staff would be available for a single ramp and that direct costs were the only costs. When evacuation efforts are involved, the number of ramps involved increases dramatically. While a single staff person is relatively easy to allocate, tens of staff people and vehicles are not. At this point, the analysis is less about the alternative cost of using other personnel, and more about the time value of both the emergency responders and those people entering the freeway without control. The time value of travelers can vary widely, but with hundreds or thousands of vehicles delayed for several hours, their value can quickly exceed the costs of the gates.

Assuming that no statewide program becomes available to address ramp closures, the one big issue with the traffic criteria for ramp control is that the criteria are reactive instead of proactive. That is, they apply only after an incident has occurred. Considering the relatively small cost of a ramp closure gate with respect to the high cost of managing incidents in general, a proactive approach to adding ramp control either under major reconstruction projects or as a single statewide deployment effort could be operationally beneficial to Wisconsin.

Final Analysis

Three test sections were identified in October, 2005 by WisDOT for testing the WRAT spreadsheet. They are as follows:

- I-94 in St. Croix County,
- US 41 in the Oshkosh/Appleton/Green Bay area,
- I-94 in Eastern Waukesha County

The results of the analysis are included in Appendix C. In general, the analysis indicated that ramp metering was a likely candidate in a few areas. It should be noted that only 2004 data was available – no projected volumes. The thresholds were very close in many cases. This would seem to indicate that when projected volumes are used that many additional areas will then meet the criteria. Additionally, while an initial safety criteria was calculated, it has not yet been fully applied. Significant additional analysis is warranted before the safety criteria becomes more relevant. These and other factors are likely to change which sections do meet the criteria in the future. By providing the Excel spreadsheets for the models to WisDOT, staff should be able to quickly modify and use these models in additional applications.

Use of the model also indicated many of its shortcomings and capabilities. The natural desire on the reviewers was to improve the model. However, many of the suggestions are beyond the capabilities of MS Excel. Additionally, it was noted that the value of the tool to provide a relatively quick and cost effective initial screening. This tool should be used to help WisDOT make cost effective decisions on where to use more complicated and expensive simulation models while determining the applicability of ramp metering.

Following this section are two simple guide sheets for use in reviewing candidate locations. These can be used to help input data into the WRAT spreadsheets or as a quick analysis of a particular interchange.

GUIDES

Guide for Ramp Meters

Traffic Criteria	Check Box
1. Mainline volumes of at least 1200 vehicles per hour per lane	
2. Ramp volumes of at least 240 vehicles per hour for a one lane ramp, and 400 vehicles per hour for a two lane ramp	
3. Mainline speeds of less than 30 mph in the peak hour	
4. Accident rate in the vicinity of the ramp in excess of 80 per hundred million vehicle miles	
Corridor Criteria	
5. Are two of the four traffic criteria met for at least 50% of the corridor	
Minimal Design Requirements	
6. Storage length of at least 450 feet (Use formula or graph for individual ramp calculations.) 450 feet is for 240 vehicles per hour on a one lane ramp	
7. Acceleration distance of at least 1000 feet (Use formula or graph for inidividual ramp calculations.) 1000 feet is for 55mph merge speed on level grade.	
8. Stop bar distance of at least 245 feet (Use formula for individual ramp calculations.) 245 feet is minimum recommended by AASHTO	
9. Foot print for ramp metering equipment is minimal (less than 100 square feet)	
10. Frontage road/alternate route must be somewhat available in the corridor	

Guide for Ramp Control Gates

Incident Criteria	Check Box
1. Previous ramp closure of less than 8 hours at least once per year for three consecutive years	
2. Previous ramp closure of less than 8 hours more than three times in any given year	
3. Previous ramp closure of more than 8 hours once within last three years	
Corridor Criteria	
4. If any ramp within the corridor has met any criteria in the past three years	

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Appendix A

Additional Ramp Metering and Ramp Control Reference Material

Additional Ramp Metering Reference Material

The following is a list of ramp metering reference material collected as part of Chapter 1 – Ramp Metering Literature Review. The references listed in this appendix were not used as part of Chapter 1, they have been recorded for possible use in subsequent WisDOT effortst.

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19. K. Ozbay, I. Yasar, P. Kachroo, "Comprehensive Evaluation of Feedback-Based Freeway Ramp-Metering Strategy by Using Microscopic Simulation: Taking Ramp Queues Into Account," Transportation Research Board, December 2004.
20. A. O'Brien, "Adaptive Ramp Metering to Avoid Flow Breakdown at On-Ramps and Bottlenecks," Transportation Research Board, December 2004.
21. Cynthia Taylor, Deirdre Meldrum, "Evaluation of a Fuzzy Logic Ramp Metering Algorithm: A Comparative Study Between Three Ramp Metering Algorithms Used in the Greater Seattle Area," Transportation Research Board, December 2004.

Appendix B

Case Studies

The case studies provided below are taken from Gary Piotrowicz and James Robinson's *Ramp Metering Status in North America 1995 Update*[2] and are provided for the reader's convenience.

The abbreviated case studies presented here are just a few examples of effective ramp metering operations. The benefit statistics presented are not consistent from city to city as there are no uniform evaluation criteria. Additionally, the measures of effectiveness (MOEs) vary depending on the objectives of the system. Complicating the matter, many ramp metering installations are implemented at the same time as other freeway improvements such as increased capacity, high occupancy vehicle (HOV) lanes, surveillance systems, traffic information systems, and incident management programs. In these cases, it is not always possible to evaluate the 3 individual components of the larger projects. The conditions of the evaluations of these case studies are noted for each discussion.

Portland, Oregon

The first ramp meters in the Pacific Northwest were installed along a 6 mile section of I-5 in Portland in January 1981. The meters are operated by the Oregon Department of Transportation. I-5 is the major north/south link, and is an important commuter route through the metropolitan area. This initial system consisted of 16 metered ramps between downtown Portland and the Washington state line. Nine of the meters operated in the northbound direction during the PM peak and seven controlled southbound entrances during the AM peak. The meters operate in a fixed time mode. There are currently 58 ramp meters operating on five different freeways. Prior to metering, it was common along this section of I-5 for platoons of vehicles to merge onto the freeway and aggravate the already congested traffic. The northbound PM peak hour average speed was 16 mph. Fourteen months after installation, the average speed for the same time period was 41 mph. Travel time was reduced from 23 minutes (but highly variable) to about 9 minutes. Pre-metered conditions in the southbound AM peak were much less severe and hence the improvements were smaller. Average speeds increased from 40 to 43 mph resulting in only slight reductions in southbound travel times.

Additional benefits that were evaluated for the PM peak period included fuel savings and a before and after accident study. It was estimated that fuel consumption, including the additional consumption caused by ramp delay, was reduced by 540 gallons of gasoline per weekday. There was also a reduction in rear end and side swipe accidents. Overall, there was a 43% reduction in peak period traffic accidents.

Minneapolis/St. Paul, Minnesota

The Twin Cities Metropolitan Area Freeway Management System is composed of several systems and subsystems that have been implemented over a 25 year period by the Minnesota Department of Transportation. The first two fixed time meters were installed in 1970 on southbound I-35E north of downtown St. Paul. In November 1971, these were upgraded to operate on a local traffic responsive basis and 4 additional meters were activated. This 5 mile section of I-35E has been evaluated periodically since the meters were installed. The most recent study shows, that after 14 years of operation, average peak hour speeds remain 16% higher, from 37 to 43 mph, than before metering. At the same time, peak period volumes increased 25% due to increased demand. The average number of peak period accidents decreased 24% and the peak period accident rate decreased 38%.

In 1974, a freeway management project was activated on a 16 mile section of I-35W from downtown Minneapolis to the southern suburbs. In addition to 39 ramp meters, the system included 16 closed circuit television (CCTV) cameras, 5 variable message signs (VMS), a 1.2 mile zone of highway advisory radio (HAR), 380 vehicle detectors, and a computer control monitor located at the MnDOT Traffic Management Center in Minneapolis. This project also included extensive "freeway flyer" (express bus) service and eleven ramp meter bypass ramps for HOVs. An evaluation of this project after 10 years of operation shows that average peak period freeway speeds increased from 34 to 46 mph or 35%. Over the same 10 year span, peak period volumes increased 32%, the average number of peak period accidents declined 27%, and the peak period accident rate declined 38%. Over one million dollars a year in road user benefits are attributed to reduced accidents and congestion.

This system also has positive environmental impacts. Peak period air pollutant emissions, which include carbon monoxide, hydrocarbons, and nitrogen oxides, were reduced by just under 4.4 million pounds per year. Over 300 additional ramp meters have been implemented from 1988 to 1995, and there are currently 368 meters in operation. Further projects are now in the design and construction phases. Over the next five years, the plans are to complete the ramp metering system that will cover the entire Twin Cities freeway network. The success of the Twin Cities system has shown that the staged implementation of a comprehensive freeway management system on a segment by segment, freeway by freeway basis, over a long period of time, is an effective way of implementing an area wide program.

Seattle, Washington

In September 1981, the Washington State Department of Transportation (WSDOT) implemented metering on I-5 north of the Seattle Central Business District. Initially the system, which is named FLOW (not an acronym), included 17 southbound ramps that were metered during the AM peak and 5 northbound ramps that were metered during the PM peak. Currently, the ramp metering system includes 54 meters on I-5, I-90, and SR 520. These meters are all operated under centralized computer control.
Future expansion plans include additional ramp meters on SR 520 east of Lake Washington, all of I-405, and I-5 south of Seattle.

One evaluation of the initial 22 meter system showed that between 1981 and 1987, mainline volumes during the peak traffic periods increased 86% northbound and 62% southbound. Before the installation of metering, the travel time on a specific 6.8 mile course was measured at 22 minutes. In 1987, the travel time for the same course was measured at 11.5 minutes. Over the same six year time period, the accident rate decreased by 39%.
A somewhat unique application of metering was implemented in Seattle on SR-520 in 1986. While diversion caused by metering is often controversial, one of the 5 objectives of metering SR-520 was to reduce commuter diversion through a residential

neighborhood. The meters were installed on the two eastbound ramps on SR-520 between I-5 and Lake Washington. One of these ramps, the Lake Washington Blvd. on ramp, is the last entry onto SR-520 before the Evergreen Point Floating Bridge. Because there were no bottlenecks downstream of this ramp, traffic would normally flow freely on the bridge and beyond. Motorists, especially commuters from downtown Seattle, were using residential streets to reach the Lake Washington Boulevard on ramp to avoid congestion on SR-520. This on ramp, however, was a major contributor to congestion on SR-520 because of the high entering volumes. By metering the ramp, it was anticipated that traffic diverting through the adjacent neighborhood from downtown would be discouraged by the delay caused by the meter. Motorists would instead use the Montlake Boulevard on ramp that was also metered at the same time. A HOV bypass lane was also installed at the Montlake Boulevard on ramp. Two other objectives of this project were to improve flow on SR- 520 and to encourage increased transit use and carpooling.

An evaluation of this two ramp meter "system" after four months of operation showed there was a 6.5% increase in mainline peak period volume, a 43% decrease in the volume on the Lake Washington Boulevard on ramp, an 18% increase in the volume on the Montlake Boulevard on ramp, and a 44% increase in HOVs using the Montlake Boulevard on ramp.7 Another indication of the effectiveness of the combination of the HOV bypass and the improved SR-520 flow is a decrease of 3 minutes in METRO (King County Department of Metropolitan Services) transit travel times for buses traveling from downtown to the east and a 4 minute decrease for buses traveling from University District to the east. The reliability of the bus travel times also improved and METRO adjusted the schedules for these routes accordingly.

In 1993, the WSDOT implemented weekend ramp metering for the first time. Three ramps north of Seattle on southbound I-5 have been metered several hours due to heavy weekend volumes. Because of this success, in March of 1995, weekend metering was expanded to include four additional southbound ramps. In April of 1995, WSDOT began operating seven southbound I-5 meters during the evening commute. This is WSDOTs first implementation of metering both directions of a corridor during the same peak period. The motivation behind this operational change is that the traditional reverse commute direction has become increasingly congested. Prior to this, metering along this section had operated southbound (inbound toward Seattle) during the morning commute and northbound (outbound) during the evening commute.

Denver, Colorado

The Colorado Department of Transportation activated a pilot project to demonstrate the effectiveness of ramp metering on a section of northbound I-25 in March 1981. The initial system consisted of five local traffic responsive metered ramps operated during the AM peak on a 3 mile section of I-25 south of the city. Periodic after evaluations revealed significant benefits. An 18 month after study showed that average peak period driving speeds increased 57% and average travel times decreased 37%. In addition, incidences of rear end and sideswipe accidents declined 5% due to the elimination of stop and go conditions.

The success of the pilot project led to expansion of the system. In 1984, a central computer was installed and a System Coordination Plan implemented which permits central monitoring and control of all meters. Since 1984, additional ramp meters have been added until reaching the current number of 28. In late 1988 and early 1989, a comprehensive evaluation of the original metered section was conducted. A number of changes occurred between 1981 and 1989. The most significant change was the completion of a new freeway, C-470, which permitted more direct access to I-25 from the southwest area and generated higher demand for I-25. Volumes during the 2 hour AM peak period increased from 6,200 vph in 1981 to 7,350 vph in 1989 (on 3 lanes). Speeds measured in late 1988 decreased from the original evaluation, but remained higher than the speeds before metering was implemented: 43 mph before, 53 mph after in 1981, and 50 mph in late 1988. The frequency of accidents during the AM peak period did not increase between the original evaluation and 1989, as a result, the accident rate decreased significantly because of the increased volumes. Rear end and sideswipe type accidents decreased by 50% during metered periods.

An interesting unplanned "evaluation" of the system occurred in the Spring of 1987. To accommodate daylight savings time, all of the individual ramp controllers were adjusted one hour ahead. Unfortunately, the central computer clock was overlooked. The central computer overrode the local controllers and metering began an hour late. Traffic was the worst it had been in years. This oversight did have a bright side for the Department of Transportation, since this incident, the media has been even more supportive of ramp metering. In 1988, the Colorado Department of Transportation conducted a study to evaluate different levels of ramp metering control. The study compared ramp meters operating in local traffic responsive mode versus meters operating under centralized computer control. The results showed that if local traffic responsive metering could maintain freeway speeds above 56 mph, centralized control had little or no additional benefit. However, if local traffic responsive metering was unable to maintain speeds near the posted speed limit of 56 mph, centralized control was very effective. Data showed speeds increased 35.5%, from 31 to 42 mph and vehicle hours of travel were reduced by 13.1%. This evaluation shows the importance of implementing operating strategies that correspond to the needs of the freeway network.

Detroit, Michigan

Ramp metering is an important aspect of the Michigan Department of Transportation's (MDOT) Surveillance Control and Driver Information (SCANDI) System in Detroit. The SCANDI metering operation began in November 1982 with six ramps on the eastbound Ford Freeway (I-94). Nineteen more ramps were added on I-94 in January 1984 and three more in November 1985. An evaluation performed by Michigan State University for MDOT determined that ramp metering increased speeds on I-94 by about 8%. At the same time, the typical peak hour volume on the three eastbound lanes increased to 6,400 vehicles per hour from an average of 5,600 vehicles per hour before metering. In addition, the total number of accidents was reduced nearly 50% and injury accidents were down 71%. The evaluation done by Michigan State also showed that significant additional benefits could be achieved by metering the three freeway to freeway connectors on this section of I-94.

Austin, Texas

In the late 1970's, in Austin, the Texas Department of Transportation implemented traffic responsive meters at 3 ramps along a 2.6 mile segment of northbound I- 35 for operation during the AM peak period. This section of freeway had two bottleneck locations that were reducing the quality of travel. One was a reduction from 3 to 2 lanes and the other was a high volume entrance ramp just downstream of a lane drop. Metering resulted in an increased vehicle throughout of 7.9% and an increase in average peak period mainline speeds of 60% through the section. The meters were removed after the reconstruction of I-35 eliminated the lane drop in this section. This situation shows the versatility of ramp metering in that it can also be used effectively as a temporary solution. Austin is currently in the preliminary design stages and is expected to begin ramp metering again in about 3 years.

Long Island, New York

At the other end of the spectrum from Austin is the INFORM (Information For Motorists) project on Long Island. The INFORM project covers a 40 mile long by 5 mile wide corridor at the center of which is the Long Island Expressway (LIE). Also included in the system is an east-west parkway, an east-west arterial and several crossing arterials and parkways, which is a total of 129 miles of roadways. System elements include 70 metered ramps on the LIE and the Northern State/Grand Central Parkway.

In 1989, an analysis of the initial metered segment was conducted after 2 months of operation. In the peak period, the study showed a 20% decrease in mainline travel time (from 26 to 21 minutes) and a 16% increase in average speed (from 29 to 35 mph). Motorists entering at metered ramps also experienced an overall travel time reduction of 13.1% and an increase in average speed from 23 to 28 mph. The MOE for this project included vehicle emissions. For this initial segment, the analysis indicates there was a 6.7% reduction in fuel consumption, 17.4% reduction in carbon monoxide emissions, 13.1% reduction in hydrocarbons, and 2.4% increase in nitrous oxide emissions. The latter is associated with the higher speeds. Initial observations of the effect of metering the four lane parkway on the INFORM project indicate the benefits may be even greater than those achieved on wider freeways. Intuitively, this makes sense because the impact of an unrestricted merge on only two lanes (in one direction) can be severe. A more extensive evaluation of the INFORM project was completed in 1991. Data from this study showed much more conservative results. It is believed that this study is more representative of the true traffic conditions. The main reason for this is related to the "queuing off" (shut down of the meter due to excessive queuing) of the ramp meters. The original study did not include areas where metering was usually shut off due to heavy ramp volumes, while this study accounted for all ramps. This evaluation showed that while throughout had only increased about 2%, the average mainline speeds had increased from 40 to 44 mph, or about 9%.

However, at two separate bottleneck locations, data showed increases of 33 to 52 and 33 to 55 mph, or gains of about 36% and 40% respectively. This evaluation also included calculation of a "congestion index." This index is the proportion of detector zones for which speeds were less than 30 mph. While no benefit was shown in the evening peak period, the morning peak period showed an improvement of 25% in the congestion index. The accident frequency also showed encouraging improvement with a 15% reduction compared to the control section.

San Diego, California

In San Diego, ramp metering was initiated in 1968. That system, installed and operated by the California Department of Transportation (Caltrans), now includes 134 metered ramps on 68 plus miles of freeway. No detailed evaluations of metering have been conducted on the San Diego system since the early installations, but sustained volumes of 2200 vph to 2400 vph, and occasionally even higher, are common on San Diego metered freeways. A noteworthy aspect of the program is the metering of eight freeway to freeway connector ramps. Metering freeway to freeway connectors requires careful attention to storage space, advanced warning, and sight distance. If conditions allow, freeway connector metering can be just as safe and effective as other ramp meters.

Appendix C

Sample Model Applications

Calculations for I-94 in St. Croix County

Wisconsin Ramp Analysis Tool — **Wilbur Smith Associates**

Meter Override Criteria (Qualitative): Potential violations that might occur with lower rates and desire to minimize local road impacts, VS. desire to maintain free flow and higher level of service on mainline freeway.	Assumed Mainline Capacity	2200	vphpl
	Average Vehicle Length	18	feet
User Input Cells	Maximum Metering Rate	800	vph
Calculated Cells	Minimum Metering Rate	300	vph
	TIME PERIOD		

- Maximum ramp volume threshold for metering: 1200 vph
- Maximum remaining mainline capacity below which ramp metering is activated: 500 vph per lane
- Minimum remaining mainline capacity to maintain using automated ramp meter rates: 100 vph per lane

	ENTER RAMP INFORMATION		ENTER MAINLINE INFORMATION			ENTER SERVICE ROAD INFORMATION	BASIC METER RATE CALCULATION	ENTER LOCAL RATE OVERRIDE DATA		ADJUSTED METER RATE CALCULATION	RAMP DEMAND AND DIVERSION CALCULATION							MAINLINE PERFORMANCE SUMMARY	
Location	Ramp Demand (vph) (2004)	Ramp Storage Length (ft)	Mainline Volume (vph) (2004)	Number of Mainline Lanes (direction)	Mainline Capacity (Direction)	(Y or N) Downstream access by Service Road?	Automatic Metering Rate	(Y or N) Desire Rate Override?	Manual Override Rate	Actual Meter Rate (Automatic or Override if Override	Excess Ramp Demand (vph)	Queue Storage Capacity (veh)	Diversion to Service Road	Added Ramp Volumes Due to Diversions from Upstream Ramp	Cumulative Diversions Due to Ramp Capacity Constraints	Adjusted Mainline Volumes	If No Service Road Capacity, Time to Reach Queue Capacity (min)	Non-Metered V/C Ratio	Metered V/C Ratio
I-94 EB from Minnesota													0						
STH 35	189	300	2412	3	6600	Y	800	N		800	0	16	0	X	0	2412	N/A	0.37	0.37
Carmichael Road	747	300	1719	3	6600	Y	800	N		800	0	16	0	0	0	1719	N/A	0.26	0.26
STH 35	126	300	2214	3	6600	Y	800	N		800	0	16	0	0	0	2214	N/A	0.34	0.34
US 12	171	300	1863	3	6600	Y	800	N		800	0	16	0	0	0	1863	N/A	0.28	0.28
STH 65	153	300	1629	2	4400	Y	800	N		800	0	16	0	0	0	1629	N/A	0.37	0.37
County Road T	99	300	1782	2	4400	Y	800	N		800	0	16	0	0	0	1782	N/A	0.41	0.41
STH 63	252	300	1260	2	4400	Y	800	N		800	0	16	0	0	0	1260	N/A	0.29	0.29
County Road B	43	300	1359	2	4400	Y	800	N		800	0	16	0	0	0	1359	N/A	0.31	0.31
STH 128	180	300	1224	2	4400	Y	800	N		800	0	16	0	0	0	1224	N/A	0.28	0.28
I-94 WB to Minnesota													0						
STH 128	261	300	981	2	4400	Y	800	N		800	0	16	0	X	0	981	N/A	0.22	0.22
County Road B	87	300	1357	2	4400	Y	800	N		800	0	16	0	0	0	1357	N/A	0.31	0.31
STH 63	315	300	1233	2	4400	Y	800	N		800	0	16	0	0	0	1233	N/A	0.28	0.28
County Road T	189	300	1557	2	4400	Y	800	N		800	0	16	0	0	0	1557	N/A	0.35	0.35
STH 65	396	300	1620	2	4400	Y	800	N		800	0	16	0	0	0	1620	N/A	0.37	0.37
US 12	540	300	1485	2	4400	Y	800	N		800	0	16	0	0	0	1485	N/A	0.34	0.34
STH 35	585	300	1881	3	6600	Y	800	N		800	0	16	0	0	0	1881	N/A	0.29	0.29
Carmichael Road	882	300	1683	3	6600	Y	800	N		800	82	16	66	0	66	1617	N/A	0.26	0.25
11th Street	918	300	2484	3	6600	Y	800	N		800	118	16	102	66	168	2316	N/A	0.38	0.35
STH 35	495	300	2745	3	6600	N	800	N		800	0	16	0	168	0	2745	0.0	0.42	0.42

Criteria analysis for I-94 in St. Croix County

Wisconsin Ramp Analysis Tool Wilbur Smith Associates

Freeway Ramp Evaluation Database

Maximum Metering Rate	800	vph
Minimum Metering Rate	300	vph

Mainline demand criteria

Minimum	1200	vphpl

Ramp Demand criteria

Minimum	240	vphpl

Mainline speeds criteria

Less than	30	mph

Safety criteria

	80	a100mvm

User Input Cells	
Calculated Cells	
Model Results	

Location	Ramp Demand (vph) (2004)	Mainline Volume (vph) (2004)	Mainline Speeds	Accident Rate Metric	(Y or N) Downstream access by Service Road?	Mainline volumes vphpl	Mainline Criteria Met?	Ramp Criteria Met?	Speed Criteria Met?	Safety Criteria Met?	Overall Traffic Criteria Met for this ramp?	Corridor Traffic Warrant Met?	Service Road criteria met?
I-94 EB from Minnesota													
STH 35	189	2412	50		Y	804	no	no	no	no	no	no	yes
Carmichael Road	747	1719	50		Y	573	no	yes	no	no	no	no	yes
STH 35	126	2214	50		Y	738	no	no	no	no	no	no	yes
US 12	171	1863	50		Y	621	no	no	no	no	no	no	yes
STH 65	153	1629	50		Y	815	no	no	no	no	no	no	yes
County Road T	99	1782	50		Y	891	no	no	no	no	no	no	yes
STH 63	252	1260	50		Y	630	no	yes	no	no	no	no	yes
County Road B	43	1359	50		Y	680	no	no	no	no	no	no	yes
STH 128	180	1224	50		Y	612	no	no	no	no	no	no	yes
I-94 WB to Minnesota													
STH 128	261	981	50		Y	491	no	yes	no	no	no	no	yes
County Road B	87	1357	50		Y	679	no	no	no	no	no	no	yes
STH 63	315	1233	50		Y	617	no	yes	no	no	no	no	yes
County Road T	189	1557	50		Y	779	no	no	no	no	no	no	yes
STH 65	396	1620	50		Y	810	no	yes	no	no	no	no	yes
US 12	540	1485	50		Y	743	no	yes	no	no	no	no	yes
STH 35	585	1881	50		Y	627	no	yes	no	no	no	no	yes
Carmichael Road	882	1683	50		Y	561	no	yes	no	no	no	no	yes
11th Street	918	2484	50		Y	828	no	yes	no	no	no	no	yes
STH 35	495	2745	50		N	915	no	yes	no	no	no	no	no

Calculations for I-94 in Eastern Waukesha County

Wisconsin Ramp Analysis Tool

Wilbur Smith Associates

Assumed Mainline Capacity: 2200 vphpl

Meter Override Criteria (Qualitative): Potential violations that might occur with lower rates and desire to minimize local road impacts, VS. desire to maintain free flow and higher level of service on mainline freeway.

Average Vehicle Length: 18 feet

Maximum Metering Rate: 800 vph

Minimum Metering Rate: 300 vph

TIME PERIOD

User Input Cells (blue)

Calculated Cells (pink)

Maximum ramp volume threshold for metering: 1200 vph

Maximum remaining mainline capacity below which ramp metering is activated: 500 vph per lane

Minimum remaining mainline capacity to maintain using automated ramp meter rates: 100 vph per lane

	ENTER RAMP INFORMATION		ENTER MAINLINE INFORMATION			ENTER SERVICE ROAD INFORMATION	BASIC METER RATE CALCULATION	ENTER LOCAL RATE OVERRIDE DATA		ADJUSTED METER RATE CALCULATION	RAMP DEMAND AND DIVERSION CALCULATION							MAINLINE PERFORMANCE SUMMARY	
Location	Ramp Demand (vph) (2004)	Ramp Storage Length (ft)	Mainline Volume (vph) (2004)	Number of Mainline Lanes (direction)	Mainline Capacity (Direction)	(Y or N) Downstream access by Service Road?	Automatic Metering Rate	(Y or N) Desire Rate Override?	Manual Override Rate	Actual Meter Rate (Automatic or Override if Override	Excess Ramp Demand (vph)	Queue Storage Capacity (veh)	Diversion to Service Road	Added Ramp Volumes Due to Diversions from Upstream Ramp	Cumulative Diversions Due to Ramp Capacity Constraints	Adjusted Mainline Volumes	If No Service Road Capacity, Time to Reach Queue Capacity (min)	Non-Metered V/C Ratio	Metered V/C Ratio
I-94 WB in Eastern Waukesha													0						
Moorland Road	1062	300	5094	2	4400	Y	300	N		300	762	16	746	X	746	4348	N/A	1.16	0.99
USH 18	270	300	5139	2	4400	Y	300	N		300	0	16	0	746	716	4423	N/A	1.17	1.01
CTH JJ	819	300	4590	2	4400	Y	300	N		300	519	16	503	716	1219	3371	N/A	1.04	0.77
STH 164	846	300	4329	2	4400	Y	300	N		300	546	16	530	1219	1749	2580	N/A	0.98	0.59
CTH J	648	300	4410	2	4400	Y	300	N		300	348	16	332	1749	2081	2329	N/A	1.00	0.53
STH 16		300		2	4400	Y	800	N		800	0	16	0	2081	1281	-1281	N/A	0.00	-0.29
CTH T	288	300	3060	2	4400	Y	800	N		800	0	16	0	2081	1569	1491	N/A	0.70	0.34
CTH G	270	300	2961	2	4400	Y	800	N		800	0	16	0	1569	1039	1922	N/A	0.67	0.44
CTH SS	57	300	2904	2	4400	Y	800	N		800	0	16	0	1039	296	2609	N/A	0.66	0.59
I-94 EB in Eastern Waukesha													0						
CTH SS	261	300	2895	2	4400	Y	800	N		800	0	16	0	X	0	2895	N/A	0.66	0.66
CTH G	405	300	2931	2	4400	Y	800	N		800	0	16	0	0	0	2931	N/A	0.67	0.67
CTH T	774	300	3048	2	4400	Y	578	N		578	196	16	180	0	180	2868	N/A	0.69	0.65
STH 16		300		2	4400	Y	800	N		800	0	16	0	180	0	0	N/A	0.00	0.00
CTH J	756	300	4410	2	4400	Y	300	N		300	456	16	440	180	620	3790	N/A	1.00	0.86
STH 164	972	300	4428	2	4400	Y	300	N		300	672	16	656	620	1276	3152	N/A	1.01	0.72
Barker/US 18	1854	300	4338	2	4400	Y	300	N		300	1554	16	1538	1276	2814	1524	N/A	0.99	0.35
Moorland Road	1674	300	4995	2	4400	Y	300	N		300	1374	16	1358	2814	4172	823	N/A	1.14	0.19

Criteria analysis for I-94 in Eastern Waukesha County

Wisconsin Ramp Analysis Tool Wilbur Smith Associates

Freeway Ramp Evaluation Database

Maximum Metering Rate 800 vph

Minimum Metering Rate 300 vph

Mainline demand criteria
Minium 1200 vphpl

Ramp Demand criteria
Minium 240 vphpl

Mainline speeds criteria
Less than 30 mph

Safety criteria
80 a100mvm

User Input Cells
Calculated Cells
Results

Location	Ramp Demand (vph) (2004)	Mainline Volume (vph) (2004)	Mainline Speeds	Accident Rate Metric	(Y or N) Downstream access by Service Road?	Mainline volumes vphpl	Mainline Criteria Met?	Ramp Criteria Met?	Speed Criteria Met?	Safety Criteria Met?	Overall Traffic Criteria Met for this ramp?	Corridor Traffic Warrant Met?	Service Road criteria met?
I-94 WB in Eastern Waukesha													
Moorland Road	1062	5094	50		Y	2547	yes	yes	no	no	yes	yes	yes
USH 18	270	5139	50		Y	2570	yes	yes	no	no	yes	yes	yes
CTH JJ	819	4590	50		Y	2295	yes	yes	no	no	yes	yes	yes
STH 164	846	4329	50		Y	2165	yes	yes	no	no	yes	yes	yes
CTH J	648	4410	50		Y	2205	yes	yes	no	no	yes	yes	yes
STH 16	0	0	50		Y	0	no	no	no	no	no	yes	yes
CTH T	288	3060	50		Y	1530	yes	yes	no	no	yes	yes	yes
CTH G	270	2961	50		Y	1481	yes	yes	no	no	yes	yes	yes
CTH SS	57	2904	50		Y	1452	yes	no	no	no	no	yes	yes
I-94 EB in Eastern Waukesha													
CTH SS	261	2895	50		Y	1448	yes	yes	no	no	yes	yes	yes
CTH G	405	2931	50		Y	1466	yes	yes	no	no	yes	yes	yes
CTH T	774	3048	50		Y	1524	yes	yes	no	no	yes	yes	yes
STH 16	0	0	50		Y	0	no	no	no	no	no	yes	yes
CTH J	756	4410	50		Y	2205	yes	yes	no	no	yes	yes	yes
STH 164	972	4428	50		Y	2214	yes	yes	no	no	yes	yes	yes
Barker/US 18	1854	4338	50		Y	2169	yes	yes	no	no	yes	yes	yes
Moorland Road	1674	4995	50		Y	2498	yes	yes	no	no	yes	yes	yes

Calculations for US 41 in the Oshkosh – Appleton – Green Bay area

Wisconsin Ramp Analysis Tool **Wilbur Smith Associates**

Assumed Mainline Capacity 2200 vphpl

Meter Override Criteria (Qualitative): Potential violations that might occur with lower rates and desire to minimize local road impacts, VS. desire to maintain free flow and higher level of service on mainline freeway.

Average Vehicle Length 18 feet

Maximum ramp volume threshold for metering 1200 vph

Maximum Metering Rate 800 vph

Maximum remaining mainline capacity below which ramp metering is activated 500 vph per lane

User Input Cells

Calculated Cells

Minimum Metering Rate 300 vph

Minimum remaining mainline capacity to maintain using automated ramp meter rates 100 vph per lane

TIME PERIOD

	ENTER RAMP INFORMATION		ENTER MAINLINE INFORMATION			ENTER SERVICE ROAD INFORMATION	BASIC METER RATE CALCULATION	ENTER LOCAL RATE OVERRIDE DATA		ADJUSTED METER RATE CALCULATION	RAMP DEMAND AND DIVERSION CALCULATION							MAINLINE PERFORMANCE SUMMARY	
Location	Ramp Demand (vph)	Ramp Storage Length (ft)	Mainline Volume (vph)	Number of Mainline Lanes (direction)	Mainline Capacity (Direction)	(Y or N) Downstream access by Service Road?	Automatic Metering Rate	(Y or N) Desire Rate Override?	Manual Override Rate	Actual Meter Rate (Automatic or Override if Override	Excess Ramp Demand (vph)	Queue Storage Capacity (veh)	Diversion to Service Road	Added Ramp Volumes Due to Diversions from Upstream Ramp	Cumulative Diversions Due to Ramp Capacity Constraints	Adjusted Mainline Volumes	If No Service Road Capacity, Time to Reach Queue Capacity (min)	Non-Metered V/C Ratio	Metered V/C Ratio
US41 NB from Oshkosh to GB													0						
CTH N - WN	657	300	1350	2	4400	Y	800	N		800	0	16	0	X	0	1350	N/A	0.31	0.31
STH 44 - WN	684	300	1773	2	4400	Y	800	N		800	0	16	0	0	0	1773	N/A	0.40	0.40
9th Avenue	792	300	2232	2	4400	Y	800	N		800	0	16	0	0	0	2232	N/A	0.51	0.51
STH 21 - WN	828	300	2394	2	4400	N	800	N		800	28	16	0	0	0	2394	34.3	0.54	0.54
US 45 - WN	180	300	2025	2	4400	Y	800	N		800	0	16	0	0	0	2025	N/A	0.46	0.46
STH 76 - WN	738	300	1917	2	4400	N	800	N		800	0	16	0	0	0	1917	0.0	0.44	0.44
Breezewood	999	300	2475	3	6600	Y	800	N		800	199	16	183	0	183	2292	N/A	0.38	0.35
CTH JJ - WN	882	300	2853	3	6600	Y	800	N		800	82	16	66	183	249	2604	N/A	0.43	0.39
CTH II+A62 - WN	873	300	2952	3	6600	Y	800	N		800	73	16	57	249	306	2646	N/A	0.45	0.40
US 10 - WN	882	300	2754	3	6600	Y	800	N		800	82	16	66	306	372	2382	N/A	0.42	0.36
CTH BB - WN	558	300	2790	3	6600	Y	800	N		800	0	16	0	372	130	2660	N/A	0.42	0.40
CTH CA - OU	567	300	2025	3	6600	Y	800	N		800	0	16	0	130	0	2025	N/A	0.31	0.31
STH 96 - OU	576	300	2304	3	6600	Y	800	N		800	0	16	0	0	0	2304	N/A	0.35	0.35
STH 15 - OU	720	300	1692	3	6600	Y	800	N		800	0	16	0	0	0	1692	N/A	0.26	0.26
STH 47 - OU	594	300	2178	2	4400	Y	800	N		800	0	16	0	0	0	2178	N/A	0.50	0.50
CTH E - OU	513	300	1908	2	4400	Y	800	N		800	0	16	0	0	0	1908	N/A	0.43	0.43
STH 441 - OU	738	300	1251	2	4400	Y	800	N		800	0	16	0	0	0	1251	N/A	0.28	0.28
CTH N - OU	243	300	1890	2	4400	Y	800	N		800	0	16	0	0	0	1890	N/A	0.43	0.43
STH 55? - OU	135	300	1683	2	4400	Y	800	N		800	0	16	0	0	0	1683	N/A	0.38	0.38
CTH J - OU	189	300	1548	2	4400	Y	800	N		800	0	16	0	0	0	1548	N/A	0.35	0.35
CTH U - OU	117	300	1602	2	4400	N	800	N		800	0	16	0	0	0	1602	0.0	0.36	0.36
CTH S - BR	243	300	1668	2	4400	Y	800	N		800	0	16	0	0	0	1668	N/A	0.38	0.38
CTH F - BR	783	300	1620	2	4400	Y	800	N		800	0	16	0	0	0	1620	N/A	0.37	0.37
CTH G - BR	855	300	1782	2	4400	Y	800	N		800	55	16	39	0	39	1743	N/A	0.41	0.40
CTH AAA - BR	936	300	2187	2	4400	Y	800	N		800	136	16	120	39	159	2028	N/A	0.50	0.46
STH 172A - BR	1224	300	1854	2	4400	Y	800	N		800	424	16	408	159	567	1287	N/A	0.42	0.29
STH 172B - BR	216	300	1701	2	4400	Y	800	N		800	0	16	0	567	0	1701	N/A	0.39	0.39
CTH VK - BR	594	300	2457	2	4400	Y	800	N		800	0	16	0	0	361	2096	N/A	0.56	0.48
STH 54 - BR	693	300	2250	2	4400	Y	800	N		800	0	16	0	361	254	1996	N/A	0.51	0.45
STH 29 - BR	783	300	1800	2	4400	Y	800	N		800	0	16	0	254	237	1563	N/A	0.41	0.36
US 141 - BR	369	300	1890	2	4400	Y	800	N		800	0	16	0	237	0	1890	N/A	0.43	0.43
INT 43	657	300	2187	2	4400	Y	800	N		800	0	16	0	0	0	2187	N/A	0.50	0.50
CTH J	162	300	1269	2	4400	Y	800	N		800	0	16	0	0	0	1269	N/A	0.29	0.29
CTH M - BR	144	300	1530	2	4400	N	800	N		800	0	16	0	0	0	1530	0.0	0.35	0.35
CTH B - BR	86	300	1215	2	4400	N	800	N		800	0	16	0	0	0	1215	0.0	0.28	0.28
US 41 SB From GB to Oshkosh													0		0				
CTH B - BR	486	300	1702	2	4400	N	800	N		800	0	16	0	0	0	1702	0.0	0.39	0.39
CTH M - BR	576	300	1575	2	4400	N	800	N		800	0	16	0	0	0	1575	0.0	0.36	0.36
CTH J	315	300	1233	2	4400	Y	800	N		800	0	16	0	0	0	1233	N/A	0.28	0.28
INT 43	1080	300	1557	2	4400	N	800	N		800	280	16	0	0	0	1557	3.4	0.35	0.35
US 141 - BR	684	300	2043	2	4400	Y	800	N		800	0	16	0	0	0	2043	N/A	0.46	0.46
STH 29 - BR	1188	300	1791	2	4400	Y	800	N		800	388	16	372	0	372	1419	N/A	0.41	0.32
STH 54 - BR	1008	300	2268	2	4400	Y	752	N		752	256	16	240	372	612	1656	N/A	0.52	0.38
CTH VK - BR	585	300	2556	2	4400	Y	800	N		800	0	16	0	612	397	2159	N/A	0.58	0.49
STH 172B - BR	963	300	1701	2	4400	Y	800	N		800	163	16	147	397	544	1157	N/A	0.39	0.26
STH 172A - BR	297	300	2538	2	4400	Y	800	N		800	0	16	0	544	41	2497	N/A	0.58	0.57
CTH AAA - BR	459	300	1953	2	4400	Y	800	N		800	0	16	0	41	0	1953	N/A	0.44	0.44
CTH G - BR	549	300	1719	2	4400	Y	800	N		800	0	16	0	0	0	1719	N/A	0.39	0.39
CTH F - BR	243	300	1728	2	4400	Y	800	N		800	0	16	0	0	0	1728	N/A	0.39	0.39
CTH S - BR	67	300	1773	2	4400	Y	800	N		800	0	16	0	0	0	1773	N/A	0.40	0.40
CTH U - OU	117	300	1611	2	4400	Y	800	N		800	0	16	0	0	0	1611	N/A	0.37	0.37
CTH J - OU	270	300	1755	2	4400	Y	800	N		800	0	16	0	0	0	1755	N/A	0.40	0.40
STH 55? - OU	414	300	1701	2	4400	Y	800	N		800	0	16	0	0	0	1701	N/A	0.39	0.39
CTH N - OU	495	300	1926	2	4400	Y	800	N		800	0	16	0	0	0	1926	N/A	0.44	0.44
STH 441 - OU	864	300	1260	2	4400	Y	800	N		800	64	16	48	0	48	1212	N/A	0.29	0.28
CTH E - OU	612	300	1638	2	4400	Y	800	N		800	0	16	0	48	0	1638	N/A	0.37	0.37
STH 47 - OU	531	300	2133	2	4400	Y	800	N		800	0	16	0	0	0	2133	N/A	0.48	0.48
STH 15 - OU	846	300	2250	3	6600	Y	800	N		800	46	16	30	0	30	2220	N/A	0.34	0.34
STH 96 - OU	738	300	2187	3	6600	Y	800	N		800	0	16	0	30	0	2187	N/A	0.33	0.33
CTH CA - OU	1251	300	2664	3	6600	Y	800	N		800	451	16	435	0	435	2229	N/A	0.40	0.34
CTH BB - WN	594	300	3051	3	6600	Y	800	N		800	0	16	0	435	229	2822	N/A	0.46	0.43
US 10 - WN	495	300	2745	3	6600	Y	800	N		800	0	16	0	229	0	2745	N/A	0.42	0.42
CTH II - WN	270	300	3663	3	6600	Y	800	N		800	0	16	0	0	0	3663	N/A	0.56	0.56
CTH JJ - WN	369	300	2763	3	6600	Y	800	N		800	0	16	0	0	0	2763	N/A	0.42	0.42
Beezelwood	342	300	2151	3	6600	N	800	N		800	0	16	0	0	0	2151	0.0	0.33	0.33
STH 76 - WN	477	300	2232	2	4400	Y	800	N		800	0	16	0	0	0	2232	N/A	0.51	0.51
US 45 - WN	990	300	2133	2	4400	Y	800	N		800	190	16	174	0	174	1959	N/A	0.48	0.45
STH 21 - WN	612	300	2151	2	4400	Y	800	N		800	0	16	0	174	0	2151	N/A	0.49	0.49
9th Avenue	315	300	1998	2	4400	Y	800	N		800	0	16	0	0	0	1998	N/A	0.45	0.45
STH 44 - WN	324	300	2187	2	4400	Y	800	N		800	0	16	0	0	0	2187	N/A	0.50	0.50
CTH N - WN	144	300	1260	2	4400	Y	800	N		800	0	16	0	0	0	1260	N/A	0.29	0.29

Criteria Analysis for US 41 in the Oshkosh – Appleton – Green Bay area

Wisconsin Ramp Analysis Tool Wilbur Smith Associates

Freeway Ramp Evaluation Database

Maximum Metering Rate 800 vph

Minimum Metering Rate 300 vph

Mainline demand criteria
Minium 1200 vphpl

Ramp Demand criteria
Minium 240 vphpl

Mainline speeds criteria
Less than 30 mph

Safety criteria
80 a100mvm

User Input Cells
Calculated Cells
Results

Location	Ramp Demand (vph)	Mainline Volume (vph)	Mainline Speeds	Accident Rate Metric	(Y or N) Downstream access by Service Road?	Mainline volumes vphpl	Mainline Criteria Met?	Ramp Criteria Met?	Speed Criteria Met?	Safety Criteria Met?	Overall Traffic Criteria Met for this ramp?	Corridor Traffic Warrant Met?	Service Road criteria met?
US41 NB from Oshkosh to GB													
CTH N - WN	657	1350	50		Y	675	no	yes	no	no	no	no	yes
STH 44 - WN	684	1773	50		Y	887	no	yes	no	no	no	no	yes
9th Avenue	792	2232	50		Y	1116	no	yes	no	no	no	no	yes
STH 21 - WN	828	2394	50		N	1197	no	yes	no	no	no	no	no
US 45 - WN	180	2025	50		Y	1013	no	no	no	no	no	no	yes
STH 76 - WN	738	1917	50		N	959	no	yes	no	no	no	no	no
Breezewood	999	2475	50		Y	825	no	yes	no	no	no	no	yes
CTH JJ - WN	882	2853	50		Y	951	no	yes	no	no	no	no	yes
CTH II+A62 - WN	873	2952	50		Y	984	no	yes	no	no	no	no	yes
US 10 - WN	882	2754	50		Y	918	no	yes	no	no	no	no	yes
CTH BB - WN	558	2790	50		Y	930	no	yes	no	no	no	no	yes
CTH CA - OU	567	2025	50		Y	675	no	yes	no	no	no	no	yes
STH 96 - OU	576	2304	50		Y	768	no	yes	no	no	no	no	yes
STH 15 - OU	720	1692	50		Y	564	no	yes	no	no	no	no	yes
STH 47 - OU	594	2178	50		Y	1089	no	yes	no	no	no	no	yes
CTH E - OU	513	1908	50		Y	954	no	yes	no	no	no	no	yes
STH 441 - OU	738	1251	50		Y	626	no	yes	no	no	no	no	yes
CTH N - OU	243	1890	50		Y	945	no	yes	no	no	no	no	yes
STH 55? - OU	135	1683	50		Y	842	no	no	no	no	no	no	yes
CTH J - OU	189	1548	50		Y	774	no	no	no	no	no	no	yes
CTH U - OU	117	1602	50		N	801	no	no	no	no	no	no	no
CTH S - BR	243	1668	50		Y	834	no	yes	no	no	no	no	yes
CTH F - BR	783	1620	50		Y	810	no	yes	no	no	no	no	yes
CTH G - BR	855	1782	50		Y	891	no	yes	no	no	no	no	yes
CTH AAA - BR	936	2187	50		Y	1094	no	yes	no	no	no	no	yes
STH 172A - BR	1224	1854	50		Y	927	no	yes	no	no	no	no	yes
STH 172B - BR	216	1701	50		Y	851	no	no	no	no	no	no	yes
CTH VK - BR	594	2457	50		Y	1229	yes	yes	no	no	yes	no	yes
STH 54 - BR	693	2250	50		Y	1125	no	yes	no	no	no	no	yes
STH 29 - BR	783	1800	50		Y	900	no	yes	no	no	no	no	yes
US 141 - BR	369	1890	50		Y	945	no	yes	no	no	no	no	yes
INT 43	657	2187	50		Y	1094	no	yes	no	no	no	no	yes
CTH J	162	1269	50		Y	635	no	no	no	no	no	no	yes
CTH M - BR	144	1530	50		N	765	no	no	no	no	no	no	no
US 41 SB From GB to Oshkosh													
CTH B - BR	486	1702	50		N	851	no	yes	no	no	no	no	no
CTH M - BR	576	1575	50		N	788	no	yes	no	no	no	no	no
CTH J	315	1233	50		Y	617	no	yes	no	no	no	no	yes
INT 43	1080	1557	50		N	779	no	yes	no	no	no	no	no
US 141 - BR	684	2043	50		Y	1022	no	yes	no	no	no	no	yes
STH 29 - BR	1188	1791	50		Y	896	no	yes	no	no	no	no	yes
STH 54 - BR	1008	2268	50		Y	1134	no	yes	no	no	no	no	yes
CTH VK - BR	585	2556	50		Y	1278	yes	yes	no	no	yes	no	yes
STH 172B - BR	963	1701	50		Y	851	no	yes	no	no	no	no	yes
STH 172A - BR	297	2538	50		Y	1269	yes	yes	no	no	yes	no	yes
CTH AAA - BR	459	1953	50		Y	977	no	yes	no	no	no	no	yes
CTH G - BR	549	1719	50		Y	860	no	yes	no	no	no	no	yes
CTH F - BR	243	1728	50		Y	864	no	yes	no	no	no	no	yes
CTH S - BR	67	1773	50		Y	887	no	no	no	no	no	no	yes
CTH U - OU	117	1611	50		Y	806	no	no	no	no	no	no	yes
CTH J - OU	270	1755	50		Y	878	no	yes	no	no	no	no	yes
STH 55? - OU	414	1701	50		Y	851	no	yes	no	no	no	no	yes
CTH N - OU	495	1926	50		Y	963	no	yes	no	no	no	no	yes
STH 441 - OU	864	1260	50		Y	630	no	yes	no	no	no	no	yes
CTH E - OU	612	1638	50		Y	819	no	yes	no	no	no	no	yes
STH 47 - OU	531	2133	50		Y	1067	no	yes	no	no	no	no	yes
STH 15 - OU	846	2250	50		Y	750	no	yes	no	no	no	no	yes
STH 96 - OU	738	2187	50		Y	729	no	yes	no	no	no	no	yes
CTH CA - OU	1251	2664	50		Y	888	no	yes	no	no	no	no	yes
CTH BB - WN	594	3051	50		Y	1017	no	yes	no	no	no	no	yes
US 10 - WN	495	2745	50		Y	915	no	yes	no	no	no	no	yes
CTH II - WN	270	3663	50		Y	1221	yes	yes	no	no	yes	no	yes
CTH JJ - WN	369	2763	50		Y	921	no	yes	no	no	no	no	yes
Beezelwood	342	2151	50		N	717	no	yes	no	no	no	no	no
STH 76 - WN	477	2232	50		Y	1116	no	yes	no	no	no	no	yes
US 45 - WN	990	2133	50		Y	1067	no	yes	no	no	no	no	yes
STH 21 - WN	612	2151	50		Y	1076	no	yes	no	no	no	no	yes
9th Avenue	315	1998	50		Y	999	no	yes	no	no	no	no	yes
STH 44 - WN	324	2187	50		Y	1094	no	yes	no	no	no	no	yes
CTH N - WN	144	1260	50		Y	630	no	no	no	no	no	no	yes