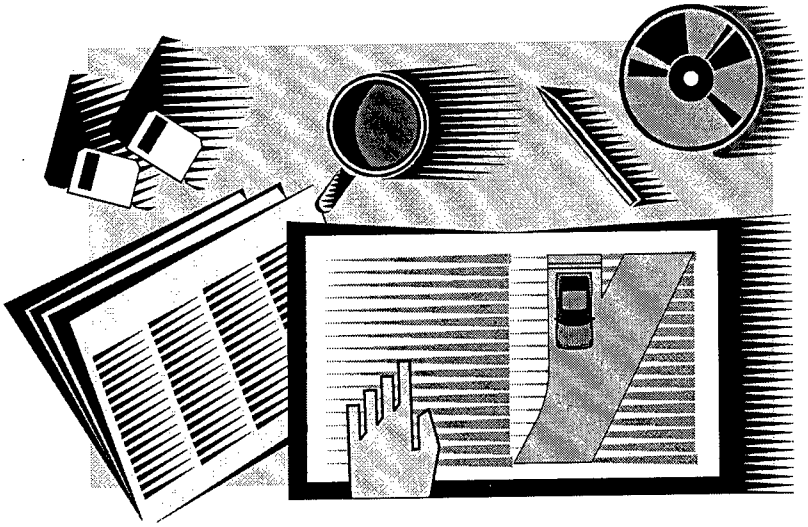
TECHNICAL
ASSISTANCE REPORT

PB99-123077

RAMP METERING: A REVIEW OF THE LITERATURE



E. D. ARNOLD, Jr.
Senior Research Scientist

REPRODUCED BY:
U.S. Department of Commerce
National Technical Information Service
Springfield, Virginia 22161

V · I · R · G · I · N · I · A
VTRC
TRANSPORTATION RESEARCH COUNCIL

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

PB99-123077

Standard Title Page - Report on State Project

Report No.	Report Date	No. Pages	Type Report:	Project No.:
			Technical Assistance	00021535-6940
VTRC 99-TAR5	December 1998	21	Period Covered: Dec. 1997 – Dec. 1998	Contract No.

Title and Subtitle:
RAMP METERING: A REVIEW OF THE LITERATURE

Key Words:
Ramp metering
Freeway traffic management
ATMS
Ramp metering guidelines

Authors:
E. D. Arnold, Jr.

Performing Organization Name and Address:

Virginia Transportation Research Council
530 Edgemont Road
Charlottesville, VA 22903

Sponsoring Agencies' Name and Address

Virginia Department of Transportation
1401 E. Broad Street
Richmond, VA 23219

Supplementary Notes

Abstract

Ramp metering is an effective, viable, and practical strategy used to manage freeway traffic. It is a proven freeway management technique as various forms of ramp control have been in place since the 1960s in the Chicago, Detroit, and Los Angeles areas. Due in part to the success of these early applications, ramp metering has received increased emphasis in recent years under the umbrella of advanced traffic management systems (ATMS), a component of intelligent transportation systems (ITS). ITS America reports that there are currently more than 40 ATMS deployed, under construction, or in the planning stage in the U.S. by state transportation agencies. The future of ramp metering is also in this ITS context. Integration and interface with local street system control and other advanced ITS traffic control systems such as advanced vehicle control systems, dynamic route guidance, and advanced traveler information systems are the latest in ramp metering applications.

Ramp meters are in place and working effectively on segments of I-395 and I-66 in Northern Virginia. The Virginia Department of Transportation is very much interested in the feasibility of implementing ramp metering on other segments of freeways throughout the state. Accordingly, the purpose of this study was to review and synthesize the existing literature on ramp metering. Specific topics included in the review were:

- impacts of ramp metering, including its advantages/benefits and disadvantages/disbenefits
- warrants, criteria, and guidelines for ramp metering
- metering rates.

Detailed information on these topics is included in the report as well as general conclusions regarding ramp metering.

PROTECTED UNDER INTERNATIONAL COPYRIGHT
ALL RIGHTS RESERVED.
NATIONAL TECHNICAL INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE

TECHNICAL ASSISTANCE REPORT

RAMP METERING: A REVIEW OF THE LITERATURE

E. D. Arnold, Jr.
Senior Research Scientist

(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agency.)

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

Charlottesville, Virginia

December 1998
VTRC 99-TAR5

Copyright 1998, Virginia Department of Transportation.

ABSTRACT

Ramp metering is an effective, viable, and practical strategy used to manage freeway traffic. It is a proven freeway management technique as various forms of ramp control have been in place since the 1960s in the Chicago, Detroit, and Los Angeles areas. Due in part to the success of these early applications, ramp metering has received increased emphasis in recent years under the umbrella of advanced traffic management systems (ATMS), a component of intelligent transportation systems (ITS). ITS America reports that there are currently more than 40 ATMS deployed, under construction, or in the planning stage in the U.S. by state transportation agencies. The future of ramp metering is also in this ITS context. Integration and interface with local street system control and other advanced ITS traffic control systems such as advanced vehicle control systems, dynamic route guidance, and advanced traveler information systems are the latest in ramp metering applications.

Ramp meters are in place and working effectively on segments of I-395 and I-66 in Northern Virginia. The Virginia Department of Transportation is very much interested in the feasibility of implementing ramp metering on other segments of freeways throughout the state. Accordingly, the purpose of this study was to review and synthesize the existing literature on ramp metering. Specific topics included in the review were:

- impacts of ramp metering, including its advantages/benefits and disadvantages/disbenefits
- warrants, criteria, and guidelines for ramp metering
- metering rates.

Detailed information on these topics is included in the report as well as general conclusions regarding ramp metering.

TECHNICAL ASSISTANCE REPORT

RAMP METERING: A REVIEW OF THE LITERATURE

E. D. Arnold, Jr.
Senior Research Scientist

INTRODUCTION

Ramp metering is an effective, viable, and practical strategy used to manage freeway traffic. It is a proven freeway management technique as various forms of ramp control have been in place since the 1960s in the Chicago, Detroit, and Los Angeles areas. As of the early 1990s, ramp metering systems existed in 20 metropolitan areas in the United States, in addition to numerous cities around the world.[1] Due in part to the success of these early applications, ramp metering has received increased emphasis in recent years under the umbrella of advanced traffic management systems (ATMS), a component of intelligent transportation systems (ITS). ITS America reports that there are currently more than 40 ATMS deployed, under construction, or in the planning stage in the U.S. by state transportation agencies. These systems use a variety of detection, control, and information technologies to manage the flow of traffic. There are over 3,800 miles of roadways that have ramp meters, changeable message signs, and closed-circuit TV (CCTV) cameras.[2] The future of ramp metering is also in this ITS context. Integration and interface with local street system control and other advanced ITS traffic control systems such as advanced vehicle control systems, dynamic route guidance, and advanced traveler information systems are the latest in ramp metering applications.

A ramp meter is a traffic signal on a freeway on-ramp that is used to regulate the flow of vehicles onto the freeway. In theory, a vehicle is given a green light and is allowed to smoothly enter the flow of traffic on the freeway by taking advantage of existing gaps in the mainline traffic. Thus, the bottleneck, turbulence, and delay resulting from a platoon of vehicles vying for the existing gaps are avoided. In actuality, the bottleneck and delay are moved onto the on-ramp; however, freeway flow is optimized and overall corridor flow is improved. Metering may be pre-timed, allowing vehicles to enter every few seconds, or traffic-responsive, where freeway traffic is monitored for available gaps and ramp traffic is monitored for queues.

Ramp metering has frequently been used in combination with high-occupancy vehicle (HOV) bypass lanes that bypass the ramp meter in order to encourage use of vans and car pools. Ramp meters are generally designed to allow emergency vehicles to bypass the signals.

IMPACTS OF RAMP METERING

A number of advantages/benefits and disadvantages/disbenefits (costs) are associated with ramp metering. The following reports the findings from various documents and reports that have summarized these impacts from case studies. The reader is referred to the Appendix for more detailed information on a number of these case studies. (Note that there is redundancy in the numbers reported as they were excerpted from a number of different documents.)

Advantages and Benefits

Benefits attributed to ramp metering in the literature include increased freeway speeds, decreased travel times, reduced delays, increased freeway capacity/throughput, reduction in accidents/improved safety, congestion reduction, cost-effectiveness, reduction in emissions/improved air quality, reduction in fuel consumption/improved fuel economy, and efficient use of capacity. These benefits are quantified for a freeway management system in Table 1 and then by individual benefit following the table.

Table 1
Summary of Freeway Management System Benefits
(Source: Reference 3)

MEASURE	IMPACT OF FREEWAY MANAGEMENT
Travel Time	decrease 20% - 48%
Travel Speed	increase 16% - 62%
Freeway Capacity	increase 17% - 25%
Accident Rate	decrease 15% - 50%
Fuel Consumption	decrease fuel used in congestion 41%
Emissions (Detroit Study)	decrease CO emissions 122,000 tons annually
	decrease HC emissions 1,400 tons annually
	decrease NOx emissions 1,200 tons annually

Increased Freeway Speeds, Decreased Travel Times, and Reduced Delays

Improved flow on the freeway, as evidenced by an increase in speeds, a decrease in travel time, or a reduction in delay, is the most often cited benefit of ramp metering. Following are a number of examples that quantify this benefit.

A survey made for the FHWA of seven ramp metering systems in the U.S. and Canada revealed that average highway speeds increased 29% after ramp metering was installed. Even when delays on ramps were included, speeds still increased 20% and travel times decreased 16.5%.[4]

Most of these studies were carried out in the mid-eighties or before. A more recent study in Minneapolis found freeway speeds up 35%.[5]

Based on information from five cities in the U.S. shown in Table 2, speeds increased by an average of 12.5 mph and travel times decreased by an average of 41.5% after implementation of ramp metering.[4]

Table 2
Before and After Travel Comparisons for Five U.S. Ramp Metering Projects
(Source: Reference 4)

				CHANGE	**IN:**	
	Before Speed	After Speed	Speeds	Travel Time	Accidents	Volumes
Portland	16 mph	41 mph	+25 mph	-61%	-43%	NA
Minneapolis	34 mph	46 mph	+12 mph	NA	-27%	+32%
Seattle	NA	NA	NA	-48%	-39%	+62%
Denver	43 mph	50 mph	+7 mph	-37%	-5%	+19%
Long Island	29 mph	35 mph	+6 mph	-20%	NA	0

In Detroit, speeds at two specific merge areas increased from 27 to 60 mph and 35 to 58 mph after the on-ramps were metered.[4] Another study of Detroit's SCANDI System estimated an 8% increase in speeds on I-94.[6]

In 1981, prior to ramp metering, the average travel time along a 15-mile stretch of I-5 in Seattle was 22 minutes. In 1983, after 2 years of ramp metering, the average travel time was reduced to 12.5 minutes. In 1987, the average travel time was 11.5 minutes.[7]

Traffic-responsive metering often produces results 5% to 10% better than pre-timed metering.[4]

Increased Freeway Capacity/Throughput

Ramp metering controls traffic demand so that freeway capacity is not exceeded and forced flow conditions do not develop. Metering increases the throughput of a freeway as the following examples show.

The data from Minneapolis, San Diego, Seattle, Detroit, and Denver showed mainline volumes well in excess of 2,100 vph per lane on metered sections, and sustained volumes in the range of 5% to 6% greater than pre-metered conditions.[6]

Likewise, Minnesota reported that ramp metering allows more vehicles to use the freeway. Typically, metering allows 2,200 vph per lane on the freeway, which is 400 more than the average 1,800 vehicles on the freeway without metering.[8]

In Seattle, highway volumes increased 12% to 40% after metering was installed.[5]

A 60% increase in volumes was obtained in Seattle's FLOW system after metering.[4]

Referring to Seattle's I-5 example, during the same 1981 to 1987 period, mainline traffic volumes increased 62%, showing that ramp metering helped improve and maintain mobility during a period of high traffic growth.[7]

Referring to Table 2, volumes increased by an average of 38% after metering for the three cases cited.[4]

Reduction in Accidents/Improved Safety

Another major benefit attributable to ramp metering is an improvement in safety, primarily through a reduction in accidents in merging areas. Another benefit of improved safety results from the fact that traffic flow is not disrupted as frequently by accidents. Studies indicate that an accident blocking one of three lanes reduces capacity by 50%. Thus, a 20-minute blockage of a three-lane freeway carrying 6,000 vph would cause 2,100 vehicle-hours of delay and a queue over 3 kilometers long and take 2.5 hours to return to normal assuming there were no secondary accidents or incidents.[6] A final safety benefit is a reduction in response time to incidents, reported as being decreased by 20 minutes in Minneapolis.[5] The following examples illustrate the reduction in accident experiences.

The case studies presented in this report consistently showed a reduction in accident rates of 24% to 50%.[6]

Nationally, areas that implemented ramp metering realized reductions in accident rates ranging from 25% to 50%. In the Seattle area, the 1989 WSDOT report entitled *Six Year FLOW Evaluation* concluded that the Northwest Region ramp metering system resulted in a 39% reduction in the accident rate on I-5.[7]

In Seattle, accident reductions of 20% to 58% were reported after ramps were metered. A more recent study in Minneapolis found accidents down by 25%.[5]

Minnesota reports that the accident rate decreased 40% with metering.[8]

A study of Detroit's SCANDI System estimated a 50% reduction in total accidents and a 71% reduction in injury accidents.[6]

Referring to Table 2, accidents decreased by an average of 29% for the four cases cited.[4]

Congestion Reduction

Ramp metering reduces congestion by managing traffic demand, improving the efficiency of merging, and reducing accidents. That is, metering results in some of the freeway demand being shifted to less congested routes and/or time periods. Efficient merging maintains smooth traffic flow and avoids the congestion caused by multiple vehicles trying to merge into the mainline flow. Efficient merging also results in fewer accidents (see earlier discussion), which typically cause major traffic congestion. An example of the congestion reduction benefits of ramp metering was seen in the PM peak period on

southbound I-5 in Seattle. Ramp metering was initiated on seven ramps over a 5-mile section in April 1995 with the following observed benefits:[7]

- The average duration of congestion on non-Fridays and Fridays was reduced from 3.5 to 2.0 hours and 5.7 to 2.8 hours, respectively.

- The average extent of mainline queuing on non-Fridays and Fridays was reduced from 4.9 to 2.8 miles and 4.0 to 2.8 miles, respectively.

Cost-Effectiveness

Given the tremendous cost of accidents, in terms of property damage, medical and legal costs, and lost productivity due to congestion, continued operation and expansion of the ramp metering system will remain one of WSDOT's most beneficial products.[7]

Reduction In Emissions/Improved Air Quality

Improved traffic flow, particularly the reduction in stop-and-go conditions, decreases certain vehicle emissions as described in the following examples:

An evaluation of I-35 south of Minneapolis estimated that peak period emissions (including carbon monoxide, hydrocarbons, and nitrogen oxides) were reduced by just under 2 million kg per year.[6]

A 1989 evaluation of the INFORM system in Long Island indicated that there was a 17.4% reduction in carbon monoxide emissions, 13.1 % reduction in hydrocarbons, and 2.4% increase in nitrous oxide emissions. (This latter increase is associated with the higher speeds.)[6]

Reduction in Fuel Consumption/Improved Fuel Economy

Likewise, improved traffic flow, particularly the reduction in stop-and-go conditions, decreases fuel consumption as suggested by the following examples.

Results from an evaluation of the Portland system indicated that fuel consumption, including the additional consumption caused by ramp delay, was reduced by 2,040 liters of gasoline per weekday after the implementation of metering.[6]

A 1989 evaluation of the INFORM system on Long Island indicated that there was a 6.7% reduction in fuel consumption.[6]

Efficient Use of Capacity

Ramp metering encourages more efficient use of existing highway capacity. If there is excess capacity on nearby local streets, it may be worthwhile to divert traffic from congested freeways to these local streets and thus discourage trip paths with high societal costs. A driver with a simple and inexpensive alternative to a congested freeway should be encouraged to take it.[1]

Disadvantages and Disbenefits (Costs)

Disbenefits attributed to ramp metering in the literature include diversion; increased ramp delays and spill back; equity issues; costs of installation, maintenance, enforcement, and public relations; on-ramp emissions and fuel consumption; and mode choice issues. Specific information on these disbenefits follows; however, most of it is intuitive with minimal quantitative support. In fact, it has been suggested that many evaluations, most which are 10 or more years old, fail to fully analyze disbenefits. Due to the continuous traffic growth over the last 10 years, new evaluations are needed to conclusively assess ramp meter performance.[1]

Diversion

Diversions to local streets and the resulting disruption of arterial street operations are the most serious disbenefits of ramp metering. This issue certainly raises the most concerns and opposition from the public. As queues form on metered ramps and delays increase, motorists may switch to alternate routes, particularly for short trips where non-congested parallel routes are available. The additional "through" traffic on the local street network has the potential to cause problems, especially on streets that are already operating near capacity. Traffic-responsive and new "network-optimizing" systems, however, are designed to minimize the reasons for diversions.[5] Further, empirical results suggest that no more than 5% to 10% of vehicles will be diverted and, in most evaluations, no adverse effects on the surface networks were found.[1] 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.[6]

It has also been suggested that diversion has positive impacts. That is, ramp metering can cause temporal diversion whereby drivers shift ramp arrival times. Empirical results show that these shifts can result in up to 15% reductions in pre-metering volumes. Thus, freeway capacity is better utilized because peak flows are spread out over a longer period.[1] Also, diverting short trips to underutilized local streets while reserving the freeway for longer trips is considered a desirable use of existing resources. Finally, diverting traffic from high-volume, substandard, or other problem ramps to more efficient ramps is desirable.[6]

Increased Ramp Delay and Spill Back

Motorists on metered ramps can typically expect to experience an increase in delay. It is generally agreed, however, that this additional delay is more than compensated for by the improved flow on the freeway, thus resulting in a net reduction in delay over the length of the trip.

Queues often form on metered on-ramps and may "spill over" onto the adjacent local street network, especially if the ramp was designed with a minimum storage area. This spillback may have negative impacts on adjacent street operations.

Equity

Equity is another issue that is often at the heart of public opposition to ramp metering. Simply stated, ramp metering provides the most benefits (travel time savings) to the long-distance, often suburban, traveler who is passing through the metered area. Close-in, city residents, especially in the metered areas, feel they are bearing the expense of the benefits to the long-distance traveler by having limited access to and increased delay at the metered ramps.

Many areas have implemented strategies to mitigate the equity issue. In Detroit, metering was initiated only in the outbound direction to minimize the city-suburb equity concerns. Once the effectiveness of the metering was established, the system was expanded with fewer objections. In Seattle, the system was designed to allow more restrictive metering rates (i.e., less vehicles allowed to enter) farther away from downtown. In Milwaukee, it was proposed to meter each ramp that contributes traffic to congested freeway segments. The metering rates were designed to reduce volumes on all ramps by an equal percentage and would be adjusted to the extent possible in order to ensure that average delays were about the same at close-in and outlying ramps.[6]

Costs of Installation, Maintenance, Enforcement, and Public Relations

Capital and maintenance costs for ramp meters can be significant. The amount depends on the existing ramp geometry and the extent of the ramp metering/freeway management system being implemented.

Enforcement of ramp metering is critical for successful operation. Violation rates of 10% have been found to be acceptable, but higher numbers may significantly reduce ramp metering benefits.[5] Traditional enforcement methods are difficult to use in high-accident merge areas and can be quite expensive.

Public acceptance and the resulting compliance by the motoring public are important for ramp metering to be successful. Accordingly, a well-designed, comprehensive, and costly public relations campaign is an important part of implementing a ramp metering/freeway management system.

On-Ramp Emissions and Fuel Consumption

Vehicle delay and stop-and-go conditions increase at the on-ramp once it is metered. This increases emissions in the vicinity of the ramp as well as fuel consumption.

Mode Choice

As noted earlier, ramp metering results in improved flow and increased throughput on the freeway. It has been surmised that the resulting improved flow may discourage the use of potential transit and HOVs and that part of the increased throughput may be derived from travelers who switched from transit or other high-occupancy modes to single-occupancy vehicles. The latest studies of I-405 and I-90 in Seattle indicate, however, a 10% to 15% increase in HOV lane usage.[9] It has been suggested, however, that implementation of ramp metering be accompanied by the promotion of corridor TDM strategies to discourage this potential switch.[4]

WARRANTS, CRITERIA, AND GUIDELINES FOR RAMP METERING

The reviewed literature and documentation provide few examples of warrants, criteria, or guidelines that can be used to determine if ramp metering is a justifiable traffic control measure at a given location.

There have been a number of attempts to develop "warrants" for ramp metering; however, this has proven difficult because of the many factors involved. Some have suggested ramp metering can improve the operation of any, if not all, freeways that experience congestion. Freeway operation, however, is only one of several factors that must be considered in evaluating the appropriateness of metering. Generally, all the disbenefits discussed earlier should be considered (and possibly mitigated) to evaluate whether ramp metering is warranted. A number of sources suggested that ramp metering should be an element of an overall freeway management program and, as was discussed previously, ramp metering is currently under the umbrella of ATMS. Ramp metering, however, has proven to be successful as a stand-alone strategy, especially in the vicinity of the metered ramp.[6]

The *Manual on Uniform Traffic Control Devices*[10] notes in Section 4E-23 that there are too many variables that influence freeway capacity to permit the development of numerical volume warrants that are applicable to the wide variety of conditions found in practice. General guidelines for the successful application of ramp control, however, are identified as follows:

- The installation of ramp control signals should be preceded by an engineering analysis of the physical and traffic conditions on the highway facilities likely to be affected. This should include the determination of capacities and demand/capacity relationships for each freeway section, thus enabling the identification of potential problems and mitigating strategies.

- Consideration should be given to public acceptance potential and enforcement requirements, as well as alternate means of increasing capacity, reducing demand, or improving characteristics of the freeway.

- Generally, the installation of ramp meters 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 with ramp control signals and when at least one of the following instances occurs:

  - There is recurring congestion on the freeway due to traffic demand exceeding capacity or there is recurring congestion or a severe accident hazard at the freeway entrance because of an inadequate merging area. It is suggested that operating speeds less than 50 mph and occurring for a period of half an hour is an indication of developing congestion problems. Speeds less than 30 mph for a half-hour period are an indication of severe congestion.

  - Signals are needed to accomplish transportation system management objectives identified locally for freeway traffic flow. Examples would include the maintenance of a specified level of service or the provision of higher levels of service for transit and other HOVs.

  - Signals are needed to reduce sporadic congestion on isolated sections of freeway caused by short-period peak traffic loads from special events or from severe peak loads of recreational traffic.

The following general guidelines for identifying candidate locations for ramp metering are derived simply by reviewing the measure's positive and negative impacts.

Consider the installation of ramp metering at locations where:

- The freeway is usually plagued with poor traffic flow conditions in the peak periods, such as speeds less than 30 mph, low volumes per lane, levels of service of E or F, and stop-and-go traffic.

- There are numerous accidents on the freeway, especially in on-ramp weaving areas.

- There are obvious merging problems occurring at freeway on-ramps.

- Heavy traffic volumes occur at closely spaced on-ramps.

- Metering will accommodate the ramp demand volumes from both a maximum and minimum standpoint. (See discussion below on metering rates.)

- There is adequate vehicle storage on the ramp.

- A freeway management system is being planned.

Do not consider the installation of ramp metering (unless appropriate mitigating measures can also be implemented) at locations where:

- Adjacent local street network will be negatively impacted either from motorist diversion or ramp spill back because it is geometrically deficient or already operating at or close to capacity.

Metering Rates

The capacity and traffic flow at metered on-ramps are governed by very practical considerations of the upper and lower limits of acceptable metering rates. There is a minimum reasonable cycle length of 4.0 seconds (2.5 seconds of red, or red plus yellow, and 1.5 of green). Accordingly, the maximum volume of a single metered lane is about 900 vph (3,600 seconds/hour divided by 4). If two vehicles per green are allowed, the minimum cycle length should be increased to about 6.0 or 6.5 seconds and the maximum volume becomes 1,100 to 1,200 vph. Another technique used at high-volume ramps is to widen the ramp to two or more lanes at the meter and permit one or two vehicles per lane per green. These ramps are then transitioned back to one lane before merging with the freeway. Accordingly, the maximum volume on a ramp with two lanes and one vehicle being released per lane is about 1,800 vph; however, this can be increased by adding more lanes and releasing more than one vehicle per green.[6]

Experience has shown that a wait (or cycle length) of about 15 seconds is the maximum that motorists will tolerate before significant violations occur. Accordingly, the minimum volume for which ramp metering is appropriate is about 240 vph.[6]

SUMMARY OF FINDINGS

1. Ramp metering is an effective, viable, and practical control strategy to manage freeway traffic.

2. While it is most effective when employed as an element of a freeway management system, e.g., in conjunction with CCTV, VMS, and HAR, ramp metering is also effective when used as a stand-alone measure. Many of the current "systems" were initiated with ramp metering, and evaluations of the early operations show significant benefits.

3. Most ramp metering today is being considered in the context of intelligent transportation systems and one of its major components: advanced traffic management systems.

4. Generally, ramp metering has significant positive impacts on traffic flow on the freeway and potentially significant negative impacts on traffic flow on the ramp and adjacent local street network.

5. Benefits of ramp metering include the following:

   - Increase in speeds on the freeway mainline
   - Decrease in travel times on the freeway mainline and for the overall trip
   - Reduction of delays on the freeway mainline and for the overall trip
   - Increase in freeway capacity and throughput
   - Reduction in accidents/improvement in safety
   - Reduction in congestion
   - Cost-effectiveness
   - Reduction in emissions/improvements in air quality
   - Reduction in fuel consumption/improvements in fuel economy
   - Efficient use of capacity.

6. Disbenefits of ramp metering include the following:

   - Diversion
   - Increase in delays on the ramps
   - Spill back onto the local street network
   - Equity issues
   - Costs of installation, maintenance, enforcement, and public relations
   - Increase of emissions and fuel consumption on the ramps
   - Negative impact on mode choice.

7. Although some attempts have been made to develop warrants, criteria, or guidelines for the implementation of ramp metering, few have been successful due to the many factors involved with ramp metering.

8. The *Manual on Uniform Traffic Control Devices* [10] notes that the installation of ramp meters 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, and when *at least one* of the following instances occurs:

   - There is recurring congestion on the freeway or there is recurring congestion or a severe accident hazard at the freeway entrance. (The manual suggests that operating speeds less than 50 mph and occurring for a period of half an hour is an indication of developing congestion problems. Speeds less than 30 mph for a half-hour period is an indication of severe congestion.)

   - Signals are needed to accomplish transportation system management objectives that have been identified locally for freeway traffic flow.

   - Signals are needed to reduce sporadic congestion on isolated sections of freeway caused by short-period peak traffic loads from special events or from severe peak loads of recreational traffic.

CONCLUSIONS

Based on the review of existing reports and documents on ramp metering, the following conclusions can be made:

1. Ramp metering is a freeway traffic management strategy that increases speeds (thus decreasing travel times and delays), improves safety, improves air quality and fuel economy, reduces congestion, and generally results in a more efficient use of the existing highway infrastructure. These benefits apply mostly to the freeway mainline.

2. Ramp metering increases delays (thus increasing vehicle emissions and fuel consumption) on the ramps, may result in vehicle spillback and diversion onto the local street network, and raises issues of equity regarding access and use of the freeway system.

3. Many of the negative impacts of ramp metering are intuitive and not supported by field evaluations. In fact, some of the potential negative impacts are refuted by the results of field evaluations. Many of the negative impacts can be mitigated with proper planning, design, and promotion.

4. Most of the ramp metering evaluations are dated (≥10 years old), and it has been suggested that significant increases in traffic have rendered ramp metering much less effective than currently documented in the literature. In this regard, it has also been suggested that new and comprehensive evaluations be undertaken.

5. In lieu of specific guidelines, the positive and negative impacts of ramp metering can be useful in identifying candidate locations, that is:

    - Consider the installation of ramp metering at locations where:

        - The freeway is usually plagued with poor traffic flow conditions in the peak periods, such as speeds less than 30 mph, low volumes per lane, levels of service of E or F, and stop-and-go traffic.

        - There are numerous accidents on the freeway, especially in on-ramp weaving areas.

        - There are obvious merging problems at freeway on-ramps.

        - Heavy traffic volumes occur at closely spaced on-ramps.

        - Metering will accommodate the ramp demand volumes from both a maximum and minimum standpoint. (See discussion in text on metering rates.)

        - There is adequate vehicle storage on the ramp.

        - A freeway management system is being planned.

- Do not consider the installation of ramp metering (unless appropriate mitigating measures can also be implemented) at locations where:

  - The adjacent local street network will be negatively impacted either from motorist diversion or ramp spillback because streets are geometrically deficient or already operating at or close to capacity.

6. There are a number of other issues that should be considered and planned for when considering the implementation of ramp metering, most of which were at least mentioned in the text. These include:

   - Public acceptance
   - Equity
   - Public relations efforts
   - Enforcement
   - Funding
   - System design (fixed-time vs. traffic responsive, metering rates, ramp geometry, hardware, etc.)
   - System maintenance.

REFERENCES

1. LEAP, "Ramp Metering," downloaded from www.path.berkeley.edu/~leap/ramp/rampmeter.html, December 19, 1997.

2. ITSA, Fact Sheets, "Deployment of Advanced Traffic Management Systems in the U.S. by State Agencies," September 24, 1998.

3. Operation TimeSaver, "Intelligent Transportation Infrastructure Benefits: Expected and Experienced," U.S. DOT, January 1996.

4. ITE, "A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility," prepared by Michael D. Myers, Ph.D., P.E., Georgia Institute of Technology, 1997.

5. Boston MPO, "Ramp Metering," downloaded from www.magnet.state.ma.us/bostonmpo/glossary/ramp.htm, December 19, 1997.

6. FHWA, "Ramp Metering Status in North America, 1995 Update," prepared by Gary Piotrowicz and James Robinson, DOT-T-95-17, June 1995.

7. WSDOT Northwest Region Ramp Metering System, e-mail received from Arefi Mahrokh on February 23, 1998.

8. MnDOT "Ramp Metering," downloaded from www.dot.state.mn.us/tmc/program/ramp.fhtml, December 19, 1997.

9. WSDOT, "Summary of AM Ramp Metering Impacts on SB I-405; Part II, summarized by Mahrokh Arefi, P.E.

10. *Manual on Uniform Traffic Control Devices*, 1988 edition.

APPENDIX

CASE STUDIES OF RAMP METERING APPLICATIONS

Portland, Oregon

(Source: Reference 6)

System Description

The first 16 ramp meters were installed on I-5 between downtown Portland and the Washington state line, in January 1981. 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 freeways.

Results from Evaluations

Northbound PM:

Before metering, the peak hour average speed was 26 kph; 14 months after installation, the average speed was 66 kph. Travel time was reduced from 23 minutes (but highly variable) to about 9 minutes. It was estimated that fuel consumption, including the additional consumption caused by ramp delay, was reduced by 2,040 liters of gasoline per weekday. There was also a reduction in rear-end and sideswipe accidents. Overall, there was a 43% reduction in peak period traffic accidents.

Southbound AM:

Pre-metered conditions in the southbound AM peak were much less severe, and hence the improvements were smaller. Average speeds increased from 64 to 69 kph, which resulted in only slight reductions in southbound travel times.

Minneapolis/St. Paul, Minnesota

(Source: Reference 6)

System Description

The Twin Cities Metropolitan Area Freeway Management System is composed of several systems and sub-systems that have been implemented over a 25-year period. 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 four additional meters were activated.

In 1974, a freeway management project was activated on I-35W from downtown Minneapolis to the southern suburbs. In addition to 39 ramp meters, the system included 16 CCTV cameras, 5 VMS, a zone of HAR, 380 vehicle detectors, and a computer control monitor located at the MNDOT Traffic Management Center in Minneapolis. This project also included extensive express bus service and 11 ramp meter bypass lanes for HOVs.

Over 300 additional ramp meters were activated between 1988 to 1995. Further projects are now in the design and construction phases, and the plans are to complete a ramp metering system that will cover the entire Twin Cities freeway network.

Results from Evaluations

I-35E North of St. Paul:

This section of I-35E has been evaluated periodically over the years. The most recent study showed that after 14 years of operation, average peak hour speeds remain 16% higher (60 to 69 kph) while peak period volumes have increased 25%. The average number of peak period accidents decreased 24%, and the peak period accident rate decreased 38%.

I-35W South of Minneapolis:

An evaluation of this project after 10 years of operation showed that average peak period freeway speeds increased 35% (55 to 74 kph), peak period volumes increased 32%, the average number of peak period accidents decreased 27%, and the peak period accident rate decreased 38%. Over $1 million a year in road user benefits were attributed to reduced accidents and congestion, and peak period emissions (including carbon monoxide, hydrocarbons, and nitrogen oxides) were reduced by just under 2 million kilograms per year.

Seattle, Washington

(Source: Reference 6)

System Description

The FLOW system was first implemented in September 1981 on I-5 north of the CBD and included 17 southbound ramps metered during the AM peak and 5 northbound ramps metered during the PM peak. Currently, the ramp metering system, which operates under centralized computer control, includes 54 meters on I-5, I-90, and SR 520. Future expansion plans include additional ramp meters on SR 520 east of Lake Washington, all of I-405, and I-5 south of Seattle.

In 1993, **weekend** metering was introduced at three ramps north of Seattle on southbound I-5 due to heavy volumes. This proved successful and was expanded to include four additional southbound ramps in March 1995. A month later, metering was activated on the southbound lanes during the PM peak period, the first use of metering in the **reverse commuting direction**.

Results from Evaluations

A 1981 to 1987 evaluation of the initial 22-meter system showed that mainline volumes during the peak traffic periods increased 86% northbound and 62% southbound; however, travel time on a specific 11-km section decreased from 22 minutes before metering to 11.5 minutes in 1987. Over the same 6-year period, the accident rate decreased by 39%.

Results from a more recent evaluation of southbound I-405 are not as positive. The study was conducted in the spring of 1997, approximately 1 year after the ramp meters were activated. Metering was in operation during both the AM and PM peak periods to mitigate congestion.

AM Peak Period:

Mainline volumes (including HOVs) increased an average of 5%, with the highest being 14% and the lowest being a 1% decrease. The volume of HOVs increased an average of 16%, and the percentage of HOVs in the mainline through traffic increased an average of 10%. It was speculated that commuters were shifting to HOVs to take advantage of the HOV bypass lanes at the metered ramps. Travel times actually increased, ranging from 3% to 9%. Sideswipe and rear-end accidents dropped by 67%.

PM Peak Period:

Mainline volumes (including HOVs) increased an average of 6%, with the highest being 17%. The volume of HOVs increased an average of 17%, and the percentage of HOVs in the mainline through traffic increased an average of 10%. Travel times data were limited due to insufficient data being obtained; however, there was an 11% increase in one section and about a 19% decrease along another section. Sideswipe and rear-end accidents were reduced by 67%.

Denver, Colorado

(Source: Reference 6)

System Description

A pilot project to demonstrate the effectiveness of ramp metering was implemented on northbound I-25 south of Denver in March 1981. The initial system consisted of five local traffic responsive metered ramps operated during the AM peak. Due to the success of the pilot project, the system has been expanded to include a central computer with a System Coordination Plan and a total of 28 metered ramps.

An unplanned "evaluation" of the system occurred in the spring of 1987. Due to an oversight, the central computer clock was not adjusted for daylight savings time and metering began an hour late. The traffic was reported to be the worst it had been in years. The public relations and media support for ramp metering increased significantly.

Results of Evaluations

Pilot Project Demonstration:

An 18-month after study showed that average peak period speeds increased 57% and average travel times decreased 37%. Incidences of rear-end and sideswipe accidents declined 5% due to the elimination of stop-and-go conditions.

1988-89 Evaluation of Original Metered Section:

Due primarily to the opening of a new freeway, volumes during the 2-hour AM peak period increased from 6,200 vph in 1981 to 7,350 vph in 1989. Speeds, however, increased from 69 km/h before metering to 80 km/h in late 1988. The frequency of accidents remained fairly constant during the AM peak period and, 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.

In 1988, a study was initiated to compare ramp meters operating in local traffic responsive mode with meters operating under centralized computer control. The results showed that if local traffic responsive metering could maintain freeway speeds above 90 km/h, 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 90 km/h, centralized control was very effective. Data showed speeds increased 35.5% (50 to 68 km/h) and vehicle hours of travel were reduced by 13.1%.

Detroit, Michigan

(Source: Reference 6)

System Description

The Surveillance Control and Driver Information (SCANDI) System in Detroit began operation in November 1982 with six ramps on the eastbound I-94. Nineteen more ramps were added in January 1984, and three more in November 1985.

Results of Evaluations

Speeds on the three eastbound lanes increased by about 8% after metering, while typical peak hour traffic volumes increased from an average of 5,600 vph to 6,400 vph. The total number of accidents was reduced nearly 50%, and injury accidents were down 71%.

Austin, Texas

(Source: Reference 6)

System Description

Traffic responsive meters at three ramps along a section of northbound I-35 were activated during the AM peak period in the late 1970s. This section of freeway had two bottleneck locations – a reduction from three to two lanes and a high volume entrance ramp just downstream of a lane drop.

Results of Evaluations

Metering increased vehicle throughput by 7.9% and average peak period mainline speeds by 60% through the section. The meters were removed after the reconstruction of I-35 that eliminated the lane drop. This situation shows the versatility of ramp metering in that it can be used effectively as a temporary solution to a problem at a specific location.

Long Island, New York

(Source: Reference 6)

System Description

The INFORM (Information For Motorists) project on Long Island covers a 64-km long by 8-km wide corridor centered on the Long Island Expressway. An east-west parkway, an east-west arterial, and several crossing arterials and parkways, amounting to about 207 km of roadways, are included in the system. There are a total of 70 metered ramps on the expressway and one of the parkways.

Results of Evaluations

An analysis of the initial metered segment was conducted in 1989 after two months of operation. During the peak period, mainline travel time decreased 20% (26 to 21 minutes) and average speed increased 16% (47 to 56 km/h). Motorists entering at metered ramps experienced an overall travel time reduction of 13.1% and an increase in average speed from 37 to 45 km/h. The analysis indicated that 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. (This latter increase is associated with the higher speeds.)

A more extensive evaluation completed in 1991 showed much more conservative results. It is believed that this study is more representative as it included all ramps, whereas the original study did not include areas where metering was usually shut off due to heavy ramp volumes. Throughput increased only about 2%, and the average mainline speeds increased only about 9% (64 to 71 km/h) The results were better, however, at two bottleneck locations, where speeds increased 36% and 40%. This evaluation also included calculation of a "congestion index," which was defined as the proportion of detector zones for which speeds were less than 48 km/h. While no benefit was seen in the evening peak period, the congestion index improved by 25% in the morning peak period. The accident frequency was reduced by 15% when compared to a control section.