Ramp Metering

Print

INTRODUCTION

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 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 are often used for more effective results. See our Telecommunications Diagram on Ramp Meters for more information.

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.

The Rationale for Ramp Metering

Principal causes of freeway congestion are: (1) incidents/accidents; (2) queues from exiting vehicles that spill over onto the mainline; (3) bottlenecks; (4) entering demand that exceeds exiting demand; and (5) mainline flow disrupted by platooned entering demand. By regulating ramp access to the mainline, on-ramp metering aims to eliminate, or at least reduce operational problems resulting from (3), (4), and (5). The predominant goal of most, if not all, ramp metering applications is to prevent, alleviate, or reduce congestion.

SYSTEM DESCRIPTION

Physical Components

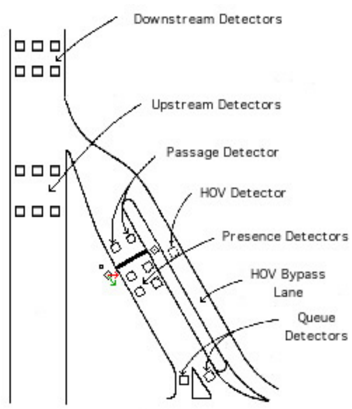
A ramp metering system consists of various components. Often these components are elements within a larger freeway management architecture. These components are:

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

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

- **Check-In Detector-** The check-in, or demand detector is located upstream of the ramp metering cordon line. The check-in detector notifies the controller that a vehicle is approaching and to activate the green interval. It is common to use two or more demand detectors per lane to avoid situations where a vehicle stopped just upstream of the detector is not recognized by the controller and the ramp meter fails to switch to green.

- **Check-Out Detector-**The check-out, or passage detector is located downstream of the ramp metering cordon line. The check-out detector notifies the controller that a vehicle has passed through the ramp meter and that the signal should be returned to red. In this manner, one vehicle passes per green interval.



Metered Freeway Ramp

- **Merge Detector-**The merge detector is an optional component which senses the presence of vehicles in the primary merging area of the ramp. To prevent queuing in the primary merging area, the controller holds a red indication if the merge detector indicates a vehicle within this area. This prevents vehicles having to merge onto the freeway from a stopped position, requiring additional acceleration distance on the mainline and disrupting mainline vehicle speeds. This typically occurs when a timid motorist hesitates, impacting subsequent vehicles. In the case of single-entry metering, subsequent green intervals are preempted until the vehicle merges.

- **Queue Detector-** The queue detector is located on the ramp, upstream of the check-in detector. The queue detector prevents spillover onto the surface street network. Continued actuation of the queue detector with no actuation of the check-in detector indicates that the first queued vehicle has stopped in advance of the check-in detector, and the ramp metering signal should be turned to green to allow this vehicle to proceed. Once ramp queues reach the queue detector and queues begin to spill onto the surface street, the metering rate is reduced or metering is terminated. This is also prevented with multiple check-in detectors, as already discussed.

- **Mainline Detectors-** Mainline detectors are located on the freeway upstream, and downstream of the on-ramp. For isolated ramp metering applications, only the occupancy/flow registered from upstream detectors influences the ramp metering rate if the metering is adaptive (not preset), responding to traffic conditions. For ramp metering *systems*, data from both upstream and downstream detectors influence the metering rate.

Ramps themselves must possess characteristics suitable for metering, namely the availability of vehicle storage space on the ramp, and adequate acceleration and merge distance downstream of the meter cordon line. Storage requirements to prevent queues from backing up onto the arterial network, can be estimated from the projected metering rate and ramp demand.

Metering Systems

The sophistication and size of a ramp metering system should reflect the amount of desired improvement and existing conditions. Ramp metering strategies can be based on fixed metering rates (historical), real-time data, or predicted traffic demand. Strategies can be implemented to optimize conditions locally or system-wide. Each control mode has an associated hardware configuration. Distinguished by their responsiveness to prevailing traffic conditions, metering systems fall into three categories:

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

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

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

Metering Rates and Control Strategies

The performance of a metering system depends largely on the metering rate and ramp control strategy. The rate at which on-ramp traffic is metered is dependent on the goal of the ramp metering system. If the system is intended to eliminate or reduce mainline congestion, the metering rate is based on the upstream mainline demand, the downstream capacity, and the on-ramp demand. If the combination of upstream mainline and ramp flows exceed the capacity of the freeway, metering rates are set to reduce the ramp flow so that downstream capacity is not exceeded. If the aim of the metering system is to facilitate a smooth ramp merging operation, metering rates are imposed to separate platooned vehicles. A freeway, when operating close to capacity, generally can accommodate one or two vehicles at a time. Platoons attempting to force their way into dense traffic can create "turbulence" and contribute to flow disruption. By breaking up these platoons, metering can smooth the merging process.

Practical threshold metering rates range from four to fifteen seconds per vehicle, or 900 to 240 vph for single lane applications. Metering rates less than four seconds tend to confuse drivers since a typical move up time at the cordon line is two seconds for a typical driver. After fifteen seconds meter violations increase significantly due to impatient drivers. To prevent overflow, demand should not exceed the ramps finite storage and release capabilities. Theoretical and empirical results indicate that the metering strategy and control algorithm can dramatically affect the level of benefits achieved. Some results [11, 12] suggest that metering has to be extremely precise to be beneficial. In practice, most properly controlled metering seems to be beneficial.

Sophisticated ramp metering systems that do not operate with preset metering rates utilize data fed into an algorithm that selects the appropriate metering rate. Data is typically obtained from mainline loop detectors. Occupancy data is the most commonly used parameter in ramp metering since it is measured directly by the detectors and is directly related to density. Furthermore, occupancy readings have unambiguous interpretations, whereas flow (count data) does not distinguish between congested or uncongested conditions. For these reasons, occupancy, not flow, is the commonly used indicator of the level of service on the freeway.

The basic principle behind traffic responsive metering is that real-time data is used to set the metering rate. The term "real-time" actually refers to data retrieved in the previous minute, and not at that instant. Variations of the basic principle of traffic responsive metering are demand-capacity control and occupancy control. Under demand-capacity control, metering rates are the difference between the upstream flow measured in the previous period, usually 1 minute earlier, and the downstream capacity. The upstream flow is measured by the loop detector. Occupancy control sets metering rates based on occupancy measurements taken upstream of the ramp during the previous period, usually 1 minute prior.

The control interval over which the selected metering rate is in effect is much shorter for traffic responsive than for preset metering strategies. Traffic responsive intervals are typically 1 minute whereas preset intervals can range from 30 minutes to the entire peak period of demand. Therefore, traffic responsive strategies are more appropriate when demand is not predictable.

Outlined below are commonly employed meter control algorithms.

Demand-Capacity Control Strategy

Demand-capacity control was introduced with the earliest field implementations of responsive ramp control. Under demand-capacity control, metering rates are the difference between the upstream flow (or occupancy) measured in the previous period, usually 1 minute earlier, and the downstream capacity (or desired occupancy). Metering is initiated when: (1) the mainline or ramp flows (or occupancy) exceed pre-specified locally calibrated thresholds or, (2) downstream flow (occupancy) drop below a preset value. The algorithm determines the metering rate locally from input-output capacity considerations as follows (for rates based on flow data):

$R(t) = C - I(t-1)$

where: R - number of vehicles allowed to enter in period t
C - Capacity of freeway section

I(t-1) - Upstream flow in period t-1

The upstream flow, I(t-1), is measured by the loop detector, and the downstream capacity, C, is a predetermined value.

Local Predictive Algorithms

Traffic-predictive algorithms use "feedback" to determine the ramp metering rate for subsequent periods, and attempt to anticipate operational problems before they occur. The basic principle behind traffic responsive metering is that real-time data is used to set the metering rate.

One example of such an algorithm is ALINEA (Asservissement LINeaire d'Entree Autroutiere), developed by engineers at the Technical University of Munich [14]. ALINEA is a local-feedback control algorithm that adjusts the metering rate to keep the occupancy downstream of the on-ramp at a prespecified level, called the occupancy set-point. ALINEA incorporates a continuum of metering rates rather than the discrete threshold approach used in other strategies. The feedback control algorithm determines the ramp metering rate as a function of : the desired downstream occupancy; the current downstream occupancy; the downstream occupancy recorded previously; and the ramp metering rate from the previous period. [14]

Similar to the demand-capacity algorithm, metering is initiated when: (1) the mainline or ramp flows exceed pre-specified locally calibrated thresholds or, (2) downstream speeds drop below a preset value. The number of vehicles allowed to enter the motorway is based on the mainline occupancy downstream of the ramp, and is given by:

$$R(k) = R(k-1) + K[Os - O(k-1)]$$

where:

R(k) - number vehicles allowed to enter in time period k

K - current time period
Os - occupancy set-point
O(k-1) downstream occupancy in previous time interval

Fuzzy Logic

Fuzzy Logic algorithms appear to be well suited to ramp metering because they can utilize inaccurate or imprecise information and they allow a smooth transition between metering rates. Inputs and outputs are descriptive (e.g., "no congestion", "light congestion", and "medium congestion") to allow for imprecise data. Fuzzy Logic systems use rule-based logic to incorporate human expertise; in this way, it can balance several performance objectives simultaneously and consider many types of information, such as traffic conditions downstream. These capabilities allow Fuzzy Logic to anticipate a problem and take temperate, corrective action before congestion occurs [16].

While it is difficult to compare algorithms evaluated under heterogeneous circumstances, comparative results on the same motorway are available. Recent results suggest that the Fuzzy Logic algorithms potentially offer the best performance. See the case study below on Seattle, Washington for more information.

Advanced Control Features
Responsive metering systems present the opportunity to implement advanced meter control techniques. One common feature is a queue over-ride, where once ramp queues threaten to spillback onto arterials the metering rate is increased until the queue dissipates. Sophisticated centralized strategies can also be developed, such as those implemented by Seattle and Denver.

In the Denver global system, if a ramp is metered at the most restricted rate or is in queue override for an extended duration, the ramp is defined as critical and system coordination is initiated. Upstream ramp rates gradually become more restrictive until the critical condition improves.

Advanced features in Seattle include a volume reduction strategy based on downstream bottlenecks and an advanced queue override. Once a downstream, congestion-prone section surpasses a preset capacity and begins to store vehicles (i.e. more vehicles enter than leave), a volume reduction strategy is distributed over upstream ramps. A weighting factor determines the fractional reduction at each ramp. Seattle also uses a second queue override, which occurs when loop occupancy near an arterial ramp feeder exceeds a threshold for a specified duration.

Gap Acceptance Control
Gap acceptance (or merge) control strategies seek to smooth flow without necessarily providing capacity operation. Gap-acceptance control, sets metering rates based on occupancy measurements taken upstream of the ramp during the previous period, usually 1 minute prior. In gap acceptance control, the ramp signals turn green in response to the detection of an available gap in the merging lane on the freeway such that the ramp vehicle has adequate time to accelerate and merge into the gap. In doing so, the strategy must determine the time for the gap to arrive at the ramp and the time it will take the motorist on the ramp to accelerate to freeway speed. Gap acceptance control is intended to enable a maximum number of entrance ramp vehicles to merge safely without causing significant disruption to freeway traffic by inserting vehicles onto the freeway upon detection of an "acceptable" gap.

Gap acceptance control methods assume constant driver aggressiveness (i.e. each driver will accept the same size gap and will accelerate and merge similarly) and that lane changing does not occur between the upstream detector and the ramp. As such, these methods have been plagued with difficulties resulting from the instability of measured gaps (both size of the gap and the time to arrival at the ramp), the unreliability of acceleration behavior of vehicles, and lane changing effectively closing gaps.

A study undertaken at the Texas Transportation Institute [13] identified the common problems of ramp meter applications using gap acceptance control strategies to be: (1) more restrictive metering when compared to demand-capacity control; (2) a higher violation rate; and (3) lower travel times from the ramp meter to the merge area, indicating a smoother merging operation. Although a smoother merging operation is achieved, gap acceptance control may result in overrestricvtive metering where the bottleneck is "starved" at times. Furthermore, motorist safety is compromised when the controller places ramp vehicles into perceived gaps which have disappeared due to lane changing.

ASSESSMENT

Key Results

In practice, ramp metering systems have been extremely successful in reducing congestion and increasing safety. Most result in higher mainline throughput with lower congestion, significant travel time savings, and higher travel time reliability. However, effects on fuel consumption and emissions have been mixed. The reduced congestion on the freeway allows for greater fuel efficiency and reduced emissions once on the mainline, but vehicles queued at ramp meters have increased rates of fuel consumption and emissions.

Ramp metering algorithms have some limitations, which researchers are working to eliminate. One problem is that existing algorithms react to rather than prevent bottlenecks. This causes oscillatory behavior, as a result of the time lag between detection and corrective action. If an initial reaction to congestion leads to overly restrictive metering, excessive queue buildup may ensue. When a queue override is activated, freeway congestion will again increase, and the process starts over. Once the system starts oscillating between restrictive and high metering rates, the algorithm may have trouble escaping such oscillation until congestion dissipates. A proposed solution involves integrating traffic predictive capabilities into the metering logic. Several such algorithms employ neural networks and Fuzzy Logic techniques, and can potentially delay or prevent bottleneck formation.

Benefits

Metering shortens the duration of congestion and improves overall traffic conditions. There is evidence that metering increases throughput, as many metered highways sustain peak volumes well in excess of 2,100 vph (flows up to 2450 vph have been achieved). 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.

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 1,160 tons of emissions

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 [17].

While travel time savings is often cited as the primary benefit of metering, as described in the table below, numerous other potential benefits exist. Benefits are phrased as "potential" because results will vary with regional traffic and geometric conditions, and with the size and efficiency of the metering system.

Table 4 Potential Benefits of Ramp Metering

Benefit	Description
Efficient Use of Capacity	If there is excess capacity on surface streets, it may be worthwhile to divert traffic from congested freeways to surface streets, and discourage trip paths with high societal costs. A driver with a simple inexpensive alternative to a congested freeway should be encouraged to take it. If insufficient capacity exists, metering can have adverse effects. Ramp metering can also result in temporal diversion, where drivers shift ramp arrival time. Empirical results show these shifts can results in up to 15% reductions in premetering volumes. Flow peaks are thus spread out over a longer period resulting in better freeway capacity utilization.
Improved Safety	Reduced turbulence in merge zones can lead to reduced sideswipe and rear-end type accidents which are associated with unmetered areas. Such turbulence is generated by platoons of entering vehicles which disrupt mainline flow. Similarly, if metering prevents a bottleneck, one can also expect safer conditions through the reduced variance in speed distributions.
Public Education	Although benefits can be demonstrated empirically, the benefits may not be recognized by individual motorists. The most successful metering projects involved a proactive public relations campaign. Many failures to date seem to be attributed to public rejection arising from a "business as usual" attitude by the implementing agency. The effectiveness of the metering system is also dependent on compliance by drivers. The public should be informed that ramp meters are traffic control devices which must be obeyed. Experience has shown that advance notice to the public results in lower violation rates, and that police enforcement is also needed.
Reduced Vehicle Emissions	Smoother traffic flow resulting in less speed variation on a metered freeway can lead to substantial reduction in emissions and fuel savings.
Travel Time Savings	If properly implemented metering can significantly increase peak speeds and reduce travel times. While ramp delays increase, system wide delay reductions can be large and positive.

Costs

Ramp metering is not without its costs. Careful consideration of potential costs is required, since many are subtle and not easily measurable.

Table 5 Potential Costs of Ramp Metering

Potential	Description

Cost	
Diversion	Diversion involves the diversion of trips from the freeway to alternate surface network routes. Factors which influence diversion include O-D patterns, trip length, ramp delays, and the quality of alternate routes. Conceptually, freeways were not designed for short trips, so diversion may be desirable if surface streets are under utilized. Even if alternate routes do not exist, experiences in Virginia, Chicago, and Denver indicate that metering can still be effective.
Equity	Because ramp metering favors through traffic, metering benefits longer trips at the expense of "local" motorists. Trips may be diverted to local surface streets, and residents close to the CBD may be deprived of access given to suburban dwellers. In Milwaukee, where equity proved to be a delicate subject, metering rates were adjusted so that delay to the average motorist was the same on close-in ramps and on outlying ramps.
Installation and Maintenance Costs	Depending on existing ramp configuration and the size of the system, capital and maintenance costs can be sizable. Ramp metering systems typically have high costs associated with the communication medium connecting the ramps to the control center.
On-Ramp Emissions	Local emissions near the ramp may increase from stop-and-go conditions and vehicle queuing on the ramp.
Promotes Longer Trips	There is evidence that metering results in longer trips replacing shorter trips, as those trips taking up critical bottleneck capacity are also likely to use the long uncongested upstream or downstream freeway sections. Such catering to longer trips can have negative feedback effects, encouraging rather than discouraging commutes from further out.
Ramp Delay and Spill Back	Queues which back up onto adjacent arterial streets can adversely affect the surface network. Those vehicles which use the ramp are delayed as they pass through the meter.
Public Opposition	In addition to physical requirements of the ramp, the feasibility of implementing ramp metering control is dependent on public acceptance of ramp metering. The issue of public acceptance is critical, as the public is bound to be critical of a new installation.
Transfer of Land Values	Users who have been accustomed to ready freeway access may be rerouted in favor of new users, which can cause land values to change.

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 systemwide 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 mainline capacity has already been filled by drivers entering 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 accomodate the small portion of traffic that is diverted.

Theoretical Evaluation

New ramp control 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.

In a recent simulation study for the Minnesota Department of Transportation, a simluation of ramp metering showed the striking effects of ramp metering. Total travel time in the mainline decreased by 46 percent when control was introduced under normal congestion. In heavy congestion, the total system travel time decreased by 24 percent and total delay by 39 percent. Total ramp delays increased substantially as expected, but overall system total travel time was reduced by 35 percent and delays, by 62 percent. Similar improvements were also realized in the remaining measures of effectiveness. Generally, in both cases with control, higher speeds were achieved and flow was smoother throughout the freeway. [18]

WHERE IS RAMP METERING IMPLEMENTED?

Ramp metering is implemented across the United States and Europe. Locations where ramp metering has been implemented are noted below, along with brief evaluations of each system's results. There is no uniform or standard evaluation criteria and the measures of effectiveness vary with the system objectives. Nevertheless most systems achieved substantial system wide benefits. While it is reasonable to assume that difficulties and significant costs were also involved, they were not highlighted in the evaluations. It has been argued that many evaluations fail to fully analyze disbenefits, such as the impacts of diversion onto surface networks. Most U.S. evaluations are almost a decade or more old. Continuous traffic growth suggests that modern evaluations are needed to conclusively assess ramp meter performance.

Note that an inventory of deployed ramp metering systems is not provided, only results from published evaluations. For an inventory of existing systems the reader is referred to the Intelligent Transportation Infrastructure Deployment Site.

Table 6 Evaluations of Deployed Ramp Metering Systems

Location	Implementing Agency	System & Site Description	Results
Austin, Texas	Department of Highways	Three meters were installed on ramps along a northbound section of I-35 for operation during the AM peak. The section had two bottlenecks, a lane drop and a high volume ramp.	Metering increased throughput by 7.9% and increased speeds by 60%. The meters were later removed when the section was geometrically improved.
Houston, Texas	Texas Department of Transportation	Ramp meters along the I-10 Katy Freeway were installed in late 1996, and evaluated in early 1997 vs. the premetered conditions.	The total daily estimated travel time savings (before metering vs. metering) was 2,875 vehicle-hours. For an estimated value of time of $12.88 per vehicle hour, these time savings result in benefits of $37,030 per day. TXDOT estimate these time savings will be realized 150 days of the year.[15]
Denver, Colorado	Colorado Department of Highways	Initiated in the late 1970s, the Denver metering system started with five ramps on northbound I-25. Geometric improvements to bring acceleration lanes to standard length and improve interchange design were required.	An early evaluation was performed during 1981 and 1982 with promising results. Speeds increased dramatically by 58%, vehicle hours of travel decreased by 37%, vehicle emissions dropped by 24%, and accidents dropped by 5%. With metering, mainline flows exceeded 2450 vphpl on several occasions. Because it eliminated stop and go traffic on the freeway, the system was an immediate public relations success and received accolades from the media. Motorists shifted their arrival times to avoid ramp delays, and flows on area arterials increased from 100 to 400 vph, resulting in virtually no degradation of surface street conditions.
		The Denver system was subsequently expanded to a centralized system with additional meters.	A later evaluation suggested that central coordination was only beneficial when congested conditions (speeds less than 55 mph) existed. However, when speeds were near 55 mph, central coordination was of little benefit.
Detroit, Michigan	Michigan Department of Transportation	Metering has been an important part of the Michigan DOT's Surveillance and Driver Information System (SCANDI). Metering was initiated in 1982 with six ramps on east-bound I-94, with many more ramps added later.	Ramp metering increased speeds by about 8%, even though volumes increased from 5600 vph to 6400 vph. The total number of accidents was reduced by nearly 50% and the number of injury accidents dropped by 71%. The evaluation also showed that significant additional benefits could be achieved by metering inter-freeway connectors to I-94.

Great Britain	Department of Transport	In response to periods of long congestion on the M6 motorway, an isolated, fixed time ramp meter and VMS were implemented. The system was connected to a central computer for monitoring purposes. The initial system released platoons of up to 8 or 9 vehicles. Results of the study led to the expansion of metering to other sites.	Although congestion continued to occur after installation, significant benefits were achieved. Bottleneck capacity increased by 172 vph (3.2%), which resulted in an estimated 20 minute reduction in the peak period. This resulted in a daily savings of 107 vehicle hours, worth 110,000 pounds (1986 value) per year. The total capital outlay was 225,000 pounds (1986 value). Assuming an annual maintenance cost of 10,000 pounds, journey time savings represented a first year rate of return of 40%. Less than 5% of drivers were diverted to surface streets, although there was a shift towards earlier arrivals. Ramp delays added 1.5 minutes to the average travel time. The system enjoyed the support of the police and motoring organizations, with no adverse public reaction. Metering was less effective during winter months, when lower speeds made it difficult to prevent flow breakdown. With higher speeds during the Summer the system was more effective.
Long Island, New York	New York Department of Transportation	Sixty ramp meters were installed on the eastbound Long Island Expressway as part of the Information for Motorists project (INFORMS). The evaluation was performed between 1987 and 1990.	After the meter installation mainline travel times decreased from 26 to 22 minutes, and the averaged motorist using a metered ramp saved 13% in travel time, Average speeds increased from 29 to 35 mph. Maximum throughput showed no conclusive results, with a 7% increase in some areas and none elsewhere. For the AM peak the number of detectors showing a speed less than 30 mph decreased by 50%. The average queue lengths at ramp meters ranged from 1.2 to 3.4 vehicles, representing 0.1% of vehicle hours traveled. As part of a public perception survey 40% of respondents viewed the meters favorably while 40% did not think the meters were a good idea.
Minneapolis / St. Paul, Minnesota	Minnesota Department of Transportation		Meters were installed in the 1970s as part of the Twin Cities Metropolitan Area Freeway Management System. The first installation, along a section of I-35 E, included several meters initially operated on a fixed time metering scheme, but later

		upgraded to isolated traffic responsive operation.	
		In 1974 along I-35 W an extensive freeway management system was initiated which included 39 ramp meters (some with HOV bypass), CCTVs, VMS, and Highway Advisory Radio.	After ten years of operation evaluation showed that average peak period speeds increased from 34 to 46 mph while average peak throughput increased by 32%. The number of peak-period accidents declined 27% (from 421 to 308 per year) and the peak period accident rate declined 38%. These results were for the entire management system.
Portland, Oregon	Oregon Department of Transportation	In 1981 meters were installed along I-5, a major north-south link and important commuter route. Sixteen meters in fixed cycle operation were evaluated.	With metering, average northbound speeds increased from 16 to 41 mph. As pre-metered conditions were less severe in the southbound direction, average speeds increased from 40 to 43 mph. It was estimated that fuel consumption, including that caused by ramp delay, was reduced by 540 gallons per weekday. Improved traffic flow also led to a reduction in rear-end and side-swipe accidents. Overall there was approximately a 43% reduction in peak period accidents.
Seattle, Washington	Washington Department of Transportation	Beginning in 1981, as part of the FLOW program, WDOT implemented metering on I-5 north of the Seattle CBD. A six year evaluation consisted of seventeen southbound ramps during the AM peak and five northbound during the PM peak along a 6.9 mile test corridor.	Over the study period travel time dropped from 22 minutes before metering to 11.5 minutes after, despite higher volumes (mainline volumes increased over 86% northbound and 62% southbound). The accident rate dropped about 39%, and average metering delays at each ramp remained at or below three minutes.
Zoetemeer, Netherlands	Dutch Ministry of Transport	Initiated in 1989, nine ramp meters were in place by 1995. This evaluation focused on the A12 motorway between Utrecht and Hague. The road carried more than 110,000 vpd on weekdays, but became congested near Zoetemeer due to lane drops and weaving sections.	For the 11 km study area, the ramp metering system increased bottleneck capacity by 3%. Other positive effects included higher speeds during congested periods (from 46 to 53 kph), and 13% shorter travel times (from 13.8 to 12.0 minutes). Although ramp travel time increased by about 20 seconds, total system wide effects were positive.

Source: FHWA Traffic Control handbook. June 1996.

CASE STUDIES

Twin Cities Metropolitan Area, Minnesota

The Minnesota Department of Transportation (Mn/DOT) uses ramp meters to manage freeway access on approximately 210 miles of freeways in the Twin Cities metropolitan area. Since the first testing in 1969, approximately 430 ramp meters have been installed and used to help merge traffic onto freeways and to manage the flow of traffic through bottlenecks.

In recent years, some members of the public have questioned the effectiveness of the ramp metering system. In response to these concerns, a bill was passed by the Minnesota Legislature, requiring Mn/DOT to study the effectiveness of the Twin Cities ramp metering system by conducting a shutdown study. Two five week studies were conducted in the fall of 2000, one with the ramp meters in operation, the other without. Through comparison of statistics from these two studies, ramp metering was found to provide striking benefits. A summary of those benefits and their associated values is provided below.

Table 7 Annual Benefits of the 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

On the other hand, before the shutdown travelers at some ramps experienced very long delays (up to 17 minutes). When ramp metering was resumed, metering rates at these ramps were increased.

(Excerpted from [17])

Seattle, Washington

In an ongoing effort to smooth traffic flow, the Washington State Department of Transportation (WSDOT) has sponsored research since 1994 to improve its ramp metering algorithm. After lengthy development and testing, a new algorithm has proved so successful that WSDOT is using it in the greater Seattle area to meter more than 100 ramps on Interstates 5, 405, and 90, and on State Route 520.

The successful algorithm uses Fuzzy Logic control, as described in the Metering Rates and Control Strategies section. The Fuzzy Logic algorithm (FLA) control strategy was tested along I-405 and I-90 for a 4-month period beginning March 1999. The FLA's performance was compared with that of two previous WSDOT algorithms, dubbed "bottleneck" and "local".

At the I-90 study site, the FLA produced an 8.2% decrease in congestion, prevented significant regular bottlenecks and produced a 4.9% increase in throughput. Overall, it controlled the mainline more efficiently than the local algorithm. On the other hand, ramp queue results were mixed. Some queues decreased while others increased slightly. However, all the ramps had sufficient storage capacity, so given the mainline benfits, slightly longer ramp queues were acceptable.

The I-405 site, which was significantly more congested, posed a more difficult challenge. The FLA produced a 0.8% increase in vehicle throughput, but a 1.2% increase in mainline congestion over bottleneck metering. However, the FLA trimmed the ramp queues significantly, reducing the time each ramp was congested by an average of 26.5 minutes. The shorter ramp queues made the FLA the politically preferable choice, even with minimal results on the mainline, because no acceptable level of metering would have reduced mainline congestion significantly.[16]

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