7. RAMP MANAGEMENT AND CONTROL

7.1 INTRODUCTION

The geometric design of a freeway ramp (width, curvature, vertical alignment, etc.) can have a positive or negative influence on the operation of the ramp itself, and on the operation of the freeway at and/or or upstream of, the merge point. Freeway design standards generally address those considerations. Ramp control, on the other hand, seeks to regulate the flow of vehicles at freeway ramps in order to achieve some operational goal such as balancing demand and capacity or enhancing safety. Other than freeway-to-freeway interchanges, freeway ramps represent the only opportunity for motor vehicles to legally enter or leave a freeway facility and, therefore, the only point at which positive control can be exercised. Freeway ramp control systems have been in operation at various locations throughout the country since the early nineteen sixties.

Most ramp control systems have been proven to be successful in terms of reduced delay and travel time (and the concomitant reductions in fuel consumption and vehicle pollutants), and in collision reduction. They are more effective when they are part of an integrated transportation management plan that incorporates other systems as described in other chapters of this Handbook. Deployment of ramp control systems has sometimes been limited due to some public resistance.

Freeway ramp control is the application of control devices such as traffic signals, signing, and gates to regulate the number of vehicles entering or leaving the freeway, in order to achieve operational objectives. Typically, the objectives will be to balance demand and capacity of the freeway in order to maintain optimum freeway operation and prevent operational breakdowns or to reduce collision rates associated with vehicles entering the freeway.

7.1.1 Purpose of Chapter

This chapter on ramp management and control is to provide insights into and guidelines on the issues associated with planning, designing, implementing and operating a ramp management and control subsystem in a freeway management system (FMS). This chapter also gives guidance to planners, designers, managers, and operators in the public relations aspects of freeway ramp control. Specific items discussed include the traffic flow theory behind ramp metering, objectives and benefits of ramp metering, the various ramp metering strategies (e.g., restrictive vs. non-restrictive, local vs. system, algorithms for determining metering rates), design considerations for ramp management, and operational issues. A separate section on examples of ramp metering is not provided as in other chapters; rather, illustrative examples are provided throughout the text.

The scope of this ramp control chapter is intended to include general guidelines as well as serving as a guide to references and other documentation that may be of benefit to freeway management and FMS practitioners. It is not intended to provide detailed design specifications or other construction documents. Typical plans, specifications, and estimates documents can usually be obtained from agencies already operating ramp control systems.

7.1.2 Relation to Other Freeway Management Activities

The Chapter is but one of many in the Freeway Management and Operations Handbook, and has been developed to "stand alone" within its topic area to a great extent. Not lost on this, though, are the relationships and dependencies between ramp control and other elements of the freeway and surface transportation network. There are many freeway management activities and FMS infrastructure elements – discussed in other chapters herein – that are related to ramp control, including:

- **Surveillance:** The surveillance subsystem (discussed in Chapter 15) includes various techniques for determining freeway and ramp operating conditions that may have an influence on metering rates or operational overrides. Examples of the types of surveillance used in conjunction with ramp control include:
  - Vehicle Detection – Vehicle sensors located on the freeway and ramps can serve multiple purposes if located correctly. Detectors located in the freeway lanes generally have the purpose of input to incident detection algorithms and for system monitoring, motorist information and evaluation of mainline operation. Freeway mainline detectors can also be used as input data in determining metering rates in traffic responsive operations. Detectors located on entrance ramps are also used for ramp meter control.
  - Closed-Circuit Television – Closed-circuit television (CCTV) cameras can be used to fine tune and monitor operation of individual metered ramps, precluding the necessity for on-site field observation.
  - Environmental Sensors – Due to grades on ramps, it is often necessary to adjust ramp metering rates or terminate operation during extreme weather conditions such as icy or extremely wet roadway surfaces. Environmental sensors will give early warning when such conditions exist.

- **HOV Treatments:** Preferential treatment of high-occupancy vehicles at metered ramps has been used successfully freeway entrance ramps. These systems have primarily involved a separate lane to bypass the queue of low occupancy vehicles and perhaps the ramp signal.

- **Roadway and Other Improvements:** The implementation of ramp metering may require geometric improvements (e.g., widening, lengthening) along the ramp to increase ramp capacity and/or storage, or to accommodate HOV by-pass lanes. Signage specific to ramp metering operation will also be required. Ramp metering may cost-effectively address some of the same issues that roadway and other improvements address (refer to Chapters 5 and 6). Implementation of ramp metering may negate the necessity of constructing certain geometric improvements.

- **Transportation Management Center:** While ramp control systems generally have the capability to operate in an isolated manner without supervision from a central site, most are interfaced to a traffic management center (refer to Chapter 14) through the communication system. Operators can monitor and actively manage ramps via central control and the communications network.

- **Coordination With Other Management Activities:** Ramp management (e.g., metering, closures) is one of the few positive control tools the practitioner has at his or her disposal for "real time" management of the freeway; and it may be utilized in support of a wide variety of activities. For example, metering may be activated (or the metering rates changed) during traffic incident management (Chapter 10) to reduce the traffic flow upstream of the incident.

Ramps may be closed as part of the overall plan to manage traffic during planned special events (Chapter 11) or evacuations (Chapter 12), particularly when contra-flow operations are implemented. Moreover, ramp management needs to be viewed as just one component of an overall program to manage the overall surface transportation network. Accordingly, ramp metering systems should be coordinated with surface street traffic signals to account for spill back of ramp queues and mainline queuing due to exit ramp congestion.

7.2 CURRENT PRACTICES, METHODS, STRATEGIES & TECHNOLOGIES

7.2.1 Overview

The following types of ramp control may be used:

- **Entrance Ramp Metering:** Metering on entrance ramps involves determination of a metering rate[15] according to some criteria such as measured freeway flow rates, speeds, or occupancies upstream and downstream of the entrance ramp. The rates may be fixed (pre-timed for certain periods, based on historical data), or may be variable (traffic responsive) based on measured traffic parameters. With "real time" traffic responsive operation, the ramp meter rates are calculated every 20 or 60 seconds, depending on the system. The entry of vehicles at that rate is regulated by one or more traffic signals beside the ramp (i.e., post-mounted) at driver's-eye height (Figure 7-1), or mounted above the ramp via mastarms. Sensors may be located on the ramp and/or on adjacent surface streets to measure the length of ramp queues to prevent them from spilling back to an unacceptable location and / or to limit the queue waiting time to an acceptable value. Signage is usually provided at the entrance to the ramp indicating to approaching traffic that the ramp that it is being metered (Figure 7-2).

- **Entrance Ramp Closure:** Typically, lower metering rates (say 2 to 4 vehicles per minute) over a sustained period of time are not acceptable to drivers, and they will tend to disregard the signal. In the extreme case where the metering rates must be sustained at lower levels, it may be necessary to physically close the ramp with automatic gates or manually placed barriers. This may cause negative public reaction and should be applied only after considerable planning and a public information program. Entrance ramp closure is rarely used except during construction, major incidents, emergencies, or special events.

- **Exit Ramp Control:** Exit ramp control may take the form of a closure of the exit ramp; or improvement of traffic flow at exit ramps and on the freeway mainline near exit ramps by improved signal timing at the intersection of the exit ramp and surface streets. (Note – As discussed in Chapter 5, the addition of an auxiliary lane for exiting vehicles may also improve the operation of the freeway mainline)

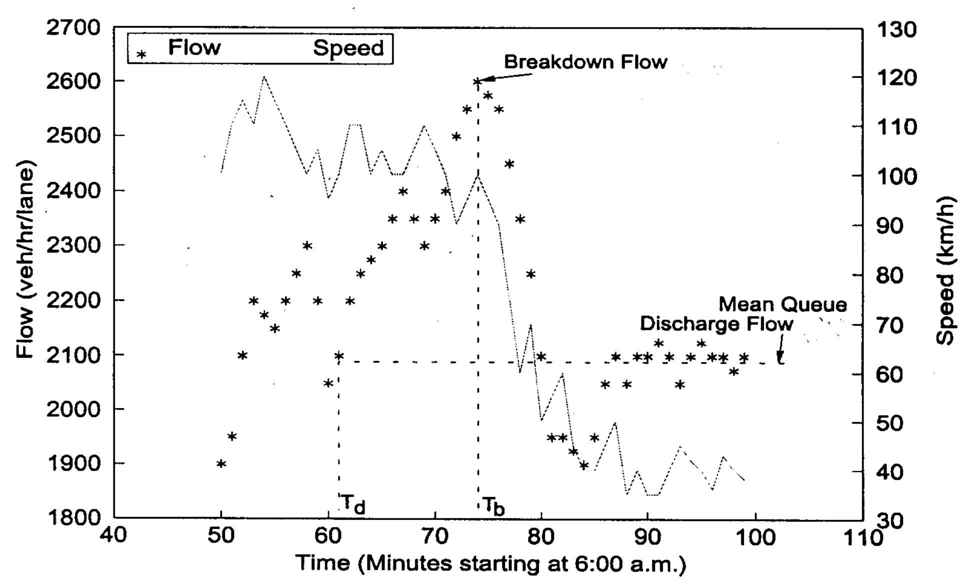
[15] 4 to 15 vehicles per minute are the typical minimum and maximum rates, respectively, for single lane metering.

Figure 7-1: Ramp Metering Signals

Figure 7-2: Advance Ramp Control Warning Sign

7.2.1.1 Background and Control Philosophy

Chapter 1 (Section 1.5.2.1) discusses the general essentials of traffic flow theory. Summarizing, as traffic demand (i.e., flow) increases, density increases with a corresponding decrease in speed. As vehicle demand approaches highway capacity, traffic flow begins to deteriorate. Traffic flow is interrupted by spots of turbulence and shock waves, which disrupt efficiency. Then, traffic flow begins to break down rapidly, followed by further deterioration of operational efficiency. An example of the breakdown in stable flow is shown in Figure 7-3 (2).



Time Trends for Speed and Flow During a Typical Morning Rush Period

Figure 7-4

Figure 7-3: Time Trends for Speed and Flow (Typical Morning Rush)

During the past decade there has been considerable research into identifying the properties of non-congested, stable flow as compared with congested, unstable flow, including the transitions between these conditions (2,3,35). The thrust of this research is described with reference to Figure 7-4.

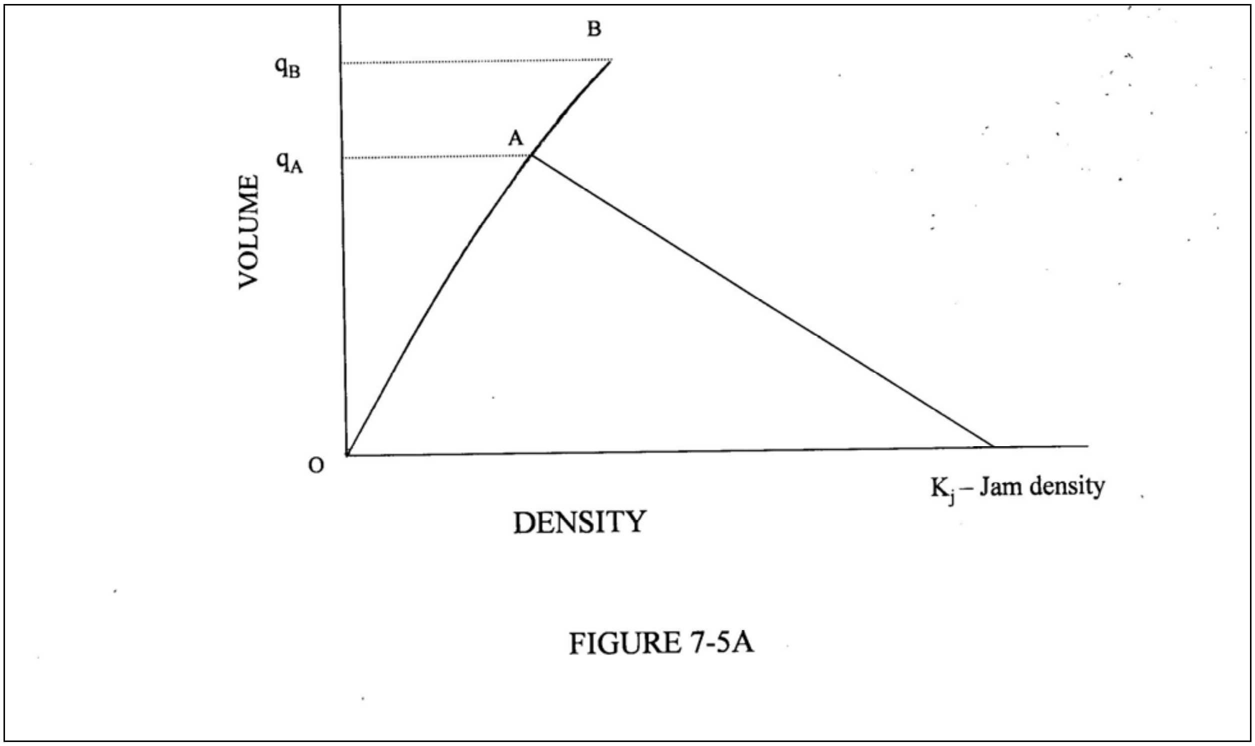
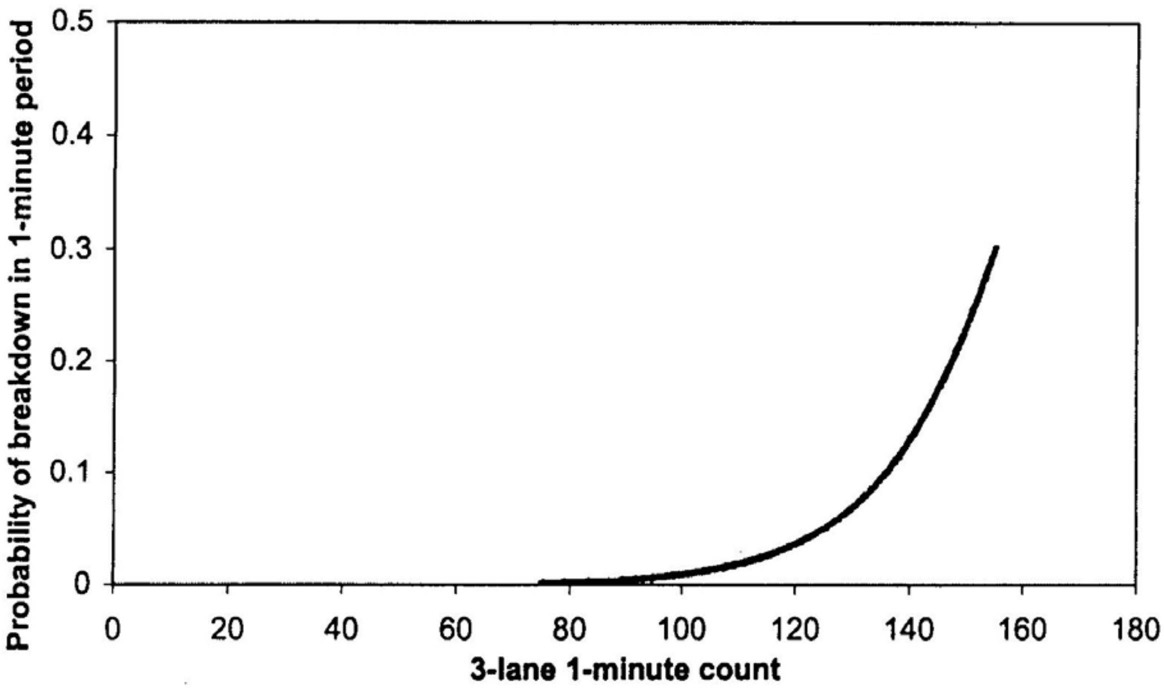


Figure 7-4: Volume – Density Relationships

As volume increases, average density increases in an approximately linear relationship until the volume reaches the level q_A. This near linear relationship implies little speed change. When volume exceeds q_A, a probability arises that the flow will transition to an unstable state, which is generally characterized by lower volume, lower speed and higher density. In Figure 7-4, this transition occurs in the region that is to the right of line AB. If transition has not occurred and if volume continues to increase, operation continues along AB toward point B. Transition will have occurred prior to reaching point B or at that point. After transition, unstable flow conditions may lie to the right of line OB in Figure 7-4. Some researchers represent the average of flow conditions in this area by line AK_j; however, the actual conditions may vary considerably.

One of the goals of ramp metering, then, is to control the amount of traffic entering the freeway such that the mainline flows do not exceed q_A, thereby minimizing the probability of flow breakdown. If flows are allowed to exceed this value, the probability of flow breakdown – that is, transition from a stable state to a congested state – significantly increases as represented in Figure 7-5.



Probability of Flow Breakdown

FIGURE 7-5B

Figure 7-5: Probability of Flow Breakdown

(Reference 2)

7.2.2 Benefits of Ramp Metering

Ramp metering can help satisfy many of the operational objectives associated with freeway management, including:

- **Improved System Operation** – In general, the primary focus of ramp metering (i.e., controlling the number of vehicles entering the freeway) is to reduce congestion and the associated delays on the mainline. It may also be used as part of a broader program to distribute delays on the mainline and ramps to minimize overall delays to freeway users, and to minimize overall delay in a corridor consisting of freeways and a network of surface street arterials. There are potential constraints – such as the maximum acceptable ramp delays, disturbances to surface street traffic resulting from queues spilling back from metered ramps, and congestion on other routes resulting from diverted traffic – that may affect the extent to which ramp metering may be used to improve freeway flow. Even with these constraints, ramp metering can still be a very effective tool. The mainline flow may still breakdown; but the onset of congestion may be delayed and the number of hours a day that these unstable flow conditions exist may be reduced. Moreover, by smoothing out the surges of vehicles that arrive at the entry point of the freeway – that is, breaking up platoons of entering vehicles such that vehicles are accepted into the mainline flow one or two at a time – the associated turbulence caused by these entering vehicles is reduced; and this also improves traffic flow conditions. It also enhances safety as noted below.

- **Safety** – Accidents on freeways tend to cluster at merge areas. One cause of this increased accident frequency is the increased difficulty in merging when large platoons of ramp vehicles arrive in the merge area. By breaking up these platoons of vehicles, which may enter the ramp from discharge at an adjacent intersection or traffic generator, the incidence of vehicle crashes is decreased in the merging area, where multiple vehicles compete for gaps. Vehicle crashes on the freeway are also reduced as the merge becomes smoother, and freeway drivers in the outside (merging) lane are less likely to have to brake abruptly or make lane-change maneuvers. Finally, in system-wide operation, the overall freeway is maintained in a more stable, uniform operational mode and vehicle crashes resulting from stop and go operations are reduced.

- **Reduction in Vehicle Emissions and Fossil Fuel Consumptions** – The direct correlation between improved traffic operations and the reduction of fuel consumption and vehicle emissions is well-known. Reductions in delay and numbers of stops, together with the maintaining of more uniform speeds will, in virtually every situation, result in a similar reduction in fuel consumption and vehicle pollutants. An exception might be where speeds are in higher ranges than is typically experienced during peak periods on metropolitan freeways.

- **Promotion of Multimodal Operation** – By giving preferential treatment to High Occupancy Vehicles at entrance ramps, the ramp control subsystem can promote travel mode shifts and reduction of single occupancy vehicles.

Piotrowics and Robinson (4) report the benefits from a sample of ramp metering installations up to 1995. Table 7-1 summarizes some of the key information reported in that reference.

Table 7-1: Summary of Ramp Metering Benefits

(Reference 4)

Location	Traffic Flow Benefits	Safety Benefits	Approximate Time of Implementation or Evaluation
Portland, Oregon	Northbound – Improvement of 26 Kph to 66 Kph. Southbound – Improvement of 64 Kph to 64 Kph.	43% reduction in peak period accidents	1981
Minneapolis/St. Paul, Minnesota (early data)	Peak hour speeds increased from 64 Kph to 69 Kph with 25% increase in peak period volume.	Decrease in peak period accident rate of 38%.	Initial implementation in 1970. Evaluation in 1989.
Seattle, Washington (early data)	Peak period travel time reduction from 22 minutes to 11.5 minutes during period volumes increased 74%	Accident rate decreased by 34%	1981-1987
Denver, Colorado	A.M. peak period speed increase from 69 Kph to 80 Kph with 18.5% increase in peak period volume	Reduction of 50% in rear end and side swipe accidents	1981-1989
Detroit, Michigan	Speed increase of 8% with volume increase of 14%	Total accidents reduced by 50%, injury accidents by 71%	1984
Long Island, N.Y.	Speed increase of 9% with throughput increase of 2%	Accident rate decrease of 15%	1991

A more recent evaluation occurred in the Minneapolis – St Paul area. To satisfy the requirements of the State legislature, an evaluation of the effectiveness of ramp metering was conducted in the years 2000 and 2001. Performance of the metering, then in effect, was measured and the ramp meters were then turned off for a period of six weeks during which time data was collected. The results of this Phase 1 study are summarized as follows (30):

- Without ramp metering, freeway volume decreased by 9% and peak period throughput decreased by 14% (VMT); freeway travel time increased by 22% with a 7% reduction in freeway speeds;
- Without ramp metering peak period crashes increased 24% on freeways and ramps;

- Without ramp metering vehicle emissions increased by 1,160 tons per year;
- Without ramp metering fuel consumption decreased by 22,246 gallons per year. This was the only category where ramp metering had a negative impact;
- Market research indicated that regional traveler attitudes changed after ramp meters were turned off, and most survey respondents believed that traffic conditions worsened.
- An analysis of ramp meter deployment and congestion management in the Twin Cities showed a benefit to cost ratio of 5:1.

At the conclusion of the Phase I ramp meter shut down experiment in December of 2000, several Phase II interim ramp metering strategies were implemented, including: a number of meters were left turned off; ramp meter operations were reduced to four hours each day; and faster metering rates were used.

The Phase I and Phase II evaluations were conducted in a similar fashion and covered the same corridor study areas. The Phase II evaluation used field observations, focus groups, and telephone surveys to measure system performance and gauge public reaction to modified operations. Despite the resumption of ramp metering at selected locations in each corridor, traffic operations and safety performance remained degraded, and were unable to be restored to pre-shut down (full metering) levels by the end of the interim period. The following results were presented in the Phase II report (31):

- The number of commuters who supported a complete shutdown of metering declined significantly from 21% in 2000 to about 14% in 2001. This change was attributed to ramp meter control strategies that limited commuter wait time (Refer to Section 7.2.5.2).

- The number of crashes recorded for the first seven months of 2001 (interim period with reduced ramp metering capacity) was 15% higher than the average number of crashes measured for the first seven months of 1998, 1999 and 2000 (fully metered period).

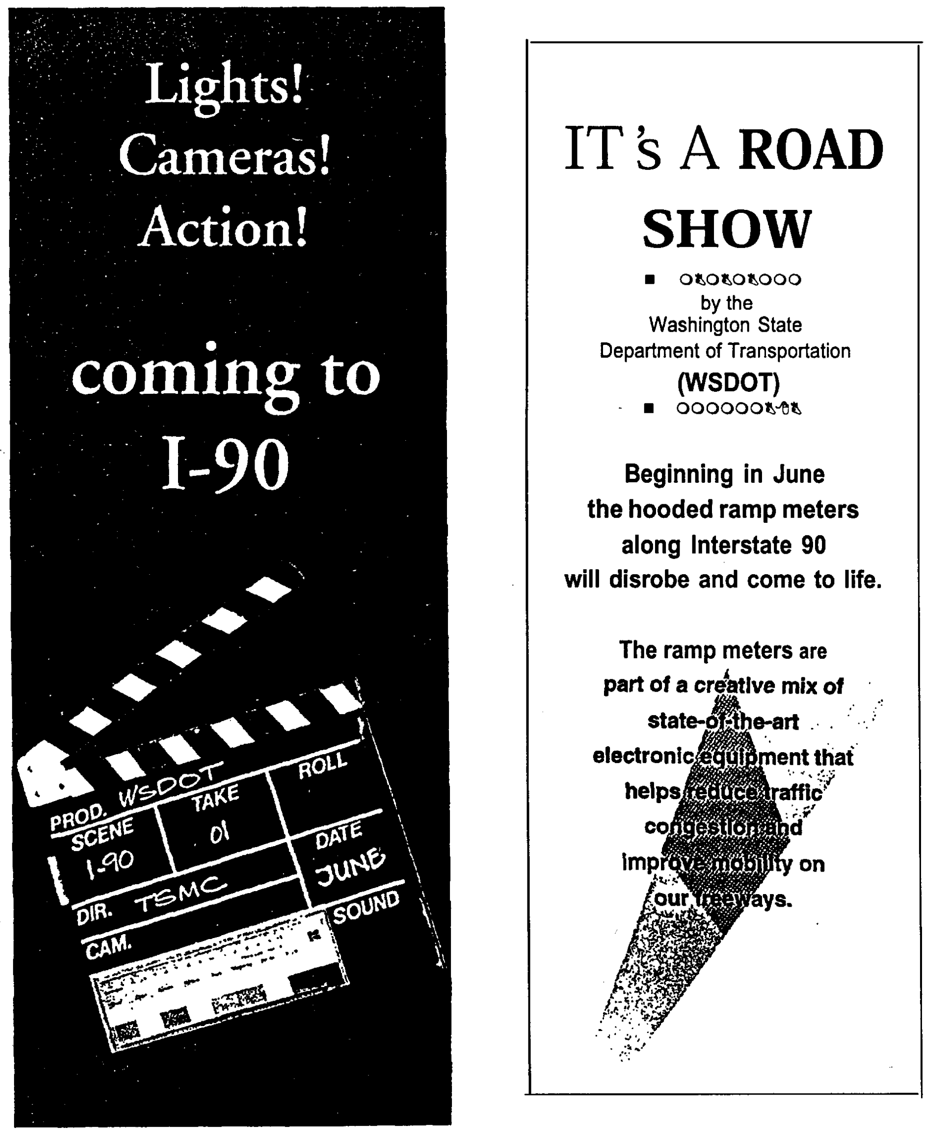
- Overall, freeway travel speeds decreased 5-10% between 2000 and 2001, while freeway travel times increased 5-10% between 2000 and 2001.

7.2.3 Key Considerations During Freeway Management Program Development

Ramp metering represents a form of positive control (i.e., regulating the rate by which vehicles enter the freeway). But the implementation (or expansion) of metering, and the installation of a traffic control device where none existed before, can lead to the perception of a reduction in driving freedom by users. Accordingly, the institutional environment and stakeholders (refer to "funnel" diagram / Figure 3-1) may be the most important considerations when considering ramp metering as part of a freeway management program. The following stakeholders need to be involved when developing and subsequently operating a ramp metering program:

- **The Public** – If ramp metering is new to the user community, a public information program using the media, brochures as shown in Figure 7- 6 (4), and public information meetings is often employed to describe the benefits as well as how to respond to metered signals. Methods for disseminating information about ramp control system include brochures, town meetings, and handouts. If modest additions are made to an existing ramp metering installation, a lower level public information program may be appropriate.

- **Media** – Local news media, both print and electronic, can have a profound effect on the success of ramp control systems. It is important that a media relations plan be developed to help ensure that positive support is secured. As stated previously, it is important that the benefits of ramp control, which are realistic and measurable, be fully explained, and that they not be oversold as adding capacity (as in the case of adding a lane).



Brochure Cover

Figure 7-6

Figure 7-6: Brochure Cover

(Reference 4)

- **Officials/Political Environment** – 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 control 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 (voter) complaints can have an adverse effect on the success of ramp control projects. System planners, designers, and operators must help those in office understand the goals, objectives, and operating characteristics of the system prior to system turn-on.

- **Enforcement / Judicial System** – 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 (5). 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.

- **Managers / Operators of the Arterial Street Network** – 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. Measures to mitigate this potential problem are discussed in subsequent sections herein.

The Concept of Operations is a key document for laying out the ramp metering concept and explaining how metering will work once it is in operation. Specifically, the Concept of Operations should identify the primary reason for implementing meeting (e.g., to reduce mainline congestion, enhance safety, combination), and the metering strategies that will be deployed (e.g., system-wide vs. more local, restrictive vs. non-restrictive). It is also critical that the Concept of Operations address how stakeholder communications and public / media outreach will be addressed during the implementation and initial operation of ramp metering.

Another important consideration is that of performance monitoring and evaluation. Since metering provides benefits in terms of reduced mainline travel times, increased throughput, and reduced collision rates, but provides disbenefits in terms of ramp queues and also possibly longer surface street travel times, performance measures (refer to Chapter 4) are needed to assure that significant total benefits are being achieved and that significant inconveniences such as excessive ramp waiting times are avoided. Moreover, successful ramp metering programs require public acceptance and support. Publicizing the results of performance monitoring may assist in developing public support. Properly designed detector placement and system software can largely automate the process of collecting monitoring data and developing reports on the performance of ramp metering.

7.2.4 Relationship to National ITS Architecture

The National ITS Architecture (6) “Freeway Control” market package includes ramp metering. This market package supports ramp meter controls on the freeway, traffic data flow from the freeway to the traffic management center, the control of ramp meters from the traffic management center, the control of sensor and controller equipment, status and performance monitoring.

7.2.5 Technologies and Strategies

A variety of ramp metering strategies may be used in appropriate combinations, including the following:

- **Restrictive and Non-Restrictive Ramp Metering:** Restrictive ramp metering sets the metering rate below the non-metered ramp volume, while non-restrictive ramp metering sets the metering rate equal to the average ramp arrival volume. This classification primarily determines whether significant queues will build up on the ramps and the extent to which diversion of traffic desiring ramp access will influence mainline congestion.

- **Local and System-Wide Ramp Metering:** Local ramp metering is employed when only the conditions local to the ramp (as compared with other ramps) are used to develop the metering rates. System-wide metering is employed when metering rates are established in a coordinated fashion on the freeway section.

- **Selection of Metering Rates:** metering rates may be selected for implementation in a variety of ways, including:
  - Pretimed Metering – Time of day metering rate schedules are commonly used, either as the primary means of control, as a component in a traffic responsive ramp metering algorithm, or as a backup to traffic responsive ramp metering in the event that traffic responsive ramp metering cannot be used because of equipment failure.

  - Traffic Responsive Metering– This incorporates algorithms to compute or select metering rates for local or system-wide ramp metering, using current data from freeway detectors.

  - Manual – Operator selection of metering rate

These various strategies are discussed in below

7.2.5.1 Restrictive and Non-Restrictive Ramp Metering

Ramp metering may either be restrictive or non-restrictive as discussed below.

- **Restrictive ramp metering** sets the metering rate below the non-metered ramp volume. Restrictive ramp metering results in improvement of mainline congestion in the following ways:
  - Reduction in the number of vehicles admitted by the meter onto the mainline facilitates the service of higher volumes upstream of the metered ramp.
  - By providing a more even distribution of vehicles to the ramp merge with the freeway mainline. Metering enables a higher level of operation on the OAB curve of previous Figure 7-4, and therefore delays the onset of congestion.

  Restrictive metering results in queue buildup on the ramp. A certain percentage of the vehicles that had previously used the ramp may also divert to alternative surface streets.

- **Non-restrictive ramp metering** sets the metering rate equal to the average ramp arrival volume. This may be implemented by setting the programmed metering rate to an equal or higher value than the average ramp arrival volume. As a result, smaller ramp queues are typically experienced than for restrictive metering, and diversion to surface streets is also significantly reduced. By breaking up ramp platoons of entering vehicles such that these vehicles are accepted into the mainline flow one or two vehicles at a time, non-restrictive ramp metering reduces crashes; and a non-restrictive metering strategy is often used for this purpose even where freeway capacity is sufficient to service the demand. Smoothing the merge process can also delay the onset of congested operation (35). Non-restrictive metering may also be used when it is not possible to use restrictive metering because vehicle storage space on the ramp or its approaches is insufficient, traffic diversion to surface streets is unacceptable, or there is lack of community acceptance of significant queue development and ramp delay resulting from restrictive ramp metering.

7.2.5.2 Local and System-Wide Ramp Metering

Local Ramp Metering

Local ramp metering is employed when only the conditions local to the ramp (as compared with other ramps) are used to provide the metering rates. Local ramp metering may be restrictive or non-restrictive. One or more ramps in a section of ramps may be metered. Local ramp metering is typically used when:

- Only non-restrictive metering is required.
- Where the traffic congestion at a location can be reduced by the metering of a single ramp.
- Where several ramps in a freeway section are to be metered but are separated by a number of unmetered entry ramps or several exit ramps that in effect, provide a reduced level of control if they were to be metered on a system-wide basis.
- Where agencies may be resource limited in supporting system-wide metering.

Local ramp metering should not be used when:

- Traffic diverted to surface streets may result in unacceptable congestion.
- The redistributed traffic causes freeway congestion at upstream or downstream ramps, or in the mainline sections associated with those ramps.

Traffic impact studies and analyses (as discussed in Chapter 4) should be used to assure that these conditions will not occur prior to the implementation of local ramp metering.

Restrictive local metering establishes the metering rate at a rate below the rate of vehicle arrivals at the ramp. Depending on the length of the ramp queues and on the capability of the surface streets to accommodate traffic, the metering rate may be set as follows:

- Metering rate + upstream mainline volume <= downstream capacity
  When metered in this way, downstream capacity is greater than or equal to demand and no queue is built.

- Metering rate + upstream mainline volume > downstream capacity
  Queues will build on the mainline under these conditions, but at a lower rate than for an unmetered ramp. Ramp storage limitations, surface street congestion or other issues may limit the ability to meter more aggressively.

System-Wide Ramp Metering

In most cases, it is preferable to meter a series of ramps in a freeway section in a coordinated fashion based on criteria that consider the entire freeway section. The strategy may also consider the freeway corridor consisting of the freeway section as well as the surface streets that will be affected by metered traffic. Situations leading to the selection of system-wide metering include:

- Multiple bottlenecks / locations of recurring congestion on the freeway.
- Optimization of throughput on the freeway or freeway corridor may require the coordinated establishment of rates for several ramp meters.
- The improved ability to address non-recurring congestion problems (traffic incidents, construction, emergencies, special events) with metering.
- Flexibility to address changing conditions over time more rapidly.

Many of the constraints previously noted (e.g., avoidance of unacceptable spillback from the ramps, limiting ramp waiting time to a value that is acceptable to the motoring community, surface street congestion resulting from the diverted traffic) also apply to system-wide metering. As such, system-wide metering strategies may provide for the omission of metering for some ramps in the section.

7.2.5.3 Metering Rate Selection Strategies

Metering rates may be developed and implemented in the following ways:

- **Pre-timed** – Pre-timed metering follows a preplanned rate schedule. This is the simplest form of ramp metering and requires neither mainline detection devices nor communication with a TMC (although many systems that use this technique have detection and communication capability). However, if there is no mainline or ramp detection, agencies must regularly collect data by another method in order to analyze traffic conditions on the freeway and determine the appropriate metering rates. The metering operation will require frequent observation so rates can be adjusted as traffic conditions change over time.

- **Traffic responsive** – Traffic responsive ramp metering algorithms calculate or select ramp metering rates based on current measured conditions on the freeway. Surveillance of the freeway mainline using traffic detectors is required. Different strategies are required for local traffic responsive ramp metering and system-wide traffic responsive ramp metering as discussed in subsequent sections of this chapter.

- **Operator selection** – Operator selection is usually used to address special conditions such as incidents or special events.

- **Controlling the ramp queue** -- Many operating agencies choose to limit the ramp queues such that any back ups do not physically interfere with surface street operations or require the motorists' wait in the queue to exceed a prescribed time period. This is a local, ramp – specific measurement that can be included in the algorithms.

7.2.5.4 Traffic Responsive Metering Algorithms

Local Traffic Responsive Ramp Metering

An objective of many local traffic responsive ramp metering algorithms is to keep the volume or density of the flows at the merge of the mainline and entry ramp from exceeding the values of which flow breakdown may occur[16]. Lane occupancy, the surrogate for density, is often used for

[16] As previously noted, safety vis-à-vis a reduction of crashes in the merge area is another possible objective of local metering.

this purpose. Ramp queue controls as described above are often incorporated into the algorithm. Two algorithms for accomplishing this are described below:

- **Open Loop Occupancy Control** – This algorithm provides a schedule of metering rates, one of which is selected based on the measured value of mainline occupancy. It is termed "open loop" control because it does not control the flow rate to explicitly achieve a parameter value sensed by the detectors. One of a number of predetermined metering rates is selected for the next control period (often 1 minute) on the basis of occupancy measurements taken during the current control interval. For a given entrance ramp, the metering rate for a particular value of occupancy is based on a plot of historical volume/occupancy data collected at each measurement location. Figure 7-7 shows an example of a typical plot (8).

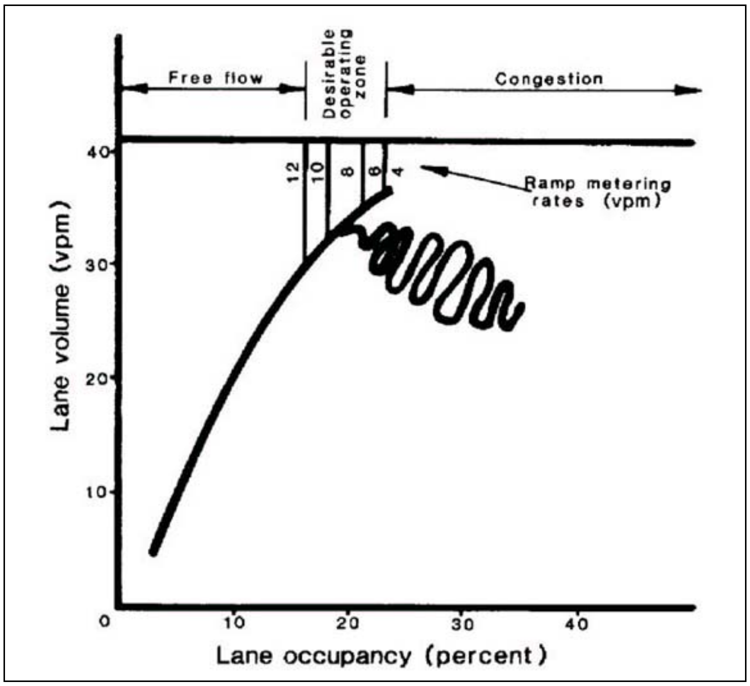


Figure 7-7: Typical Volume-Occupancy Plot Used in the Calculation of Entrance Ramp Metering Rates, Chicago, IL

Such a plot determines an approximate relationship between volume and occupancy at capacity. Thus, for each level of occupancy measured, a metering rate can be computed that corresponds to the difference between the predetermined estimate of capacity and the real-time estimate of volume. If the measured occupancy exceeds or equals the preset capacity occupancy, a minimum metering rate is selected. The lowest metering rate is also used when demand exceeds capacity. Table 7-2 shows another example (9).

Table 7-2: Local Actuated Metering Rates as a Function of Mainline Occupancy

(Reference 9)

Occupancy (%)	Metering Rate (Vehicles/Minute)
≤ 10	12
11 – 16	10
17 – 22	8
23 – 28	6
29 – 34	4
> 34	3

Some algorithms provide for interpolation between metering rate schedules in order to provide for more precise control (e.g., using a metering rate of 9.5 vpm).

A mode is sometimes enabled that allows ramp meters to use the more restrictive of the metering rates, either calculated on a traffic-responsive basis, or programmed on a time-of-day basis. While ramp metering is usually initiated and terminated on a time-of-day basis, this can also be done traffic-responsively, thus enabling off-peak control in response to incidents or construction. To perform this control effectively, adequate filtering must be provided in the algorithm to prevent short-period data fluctuations for initiating or terminating metering operation.

Inductive loop detectors with a physical dimension of approximately 6 feet (1.8 meters) in the direction of travel have, in the past, been used to provide the occupancy measurement for this control. The sensed region for inductive loop detectors exceeds the physical dimension by a small amount. In recent years, other detectors such as video processing detectors, radar detectors and passive sonic detectors (refer to Chapter 15) have been used for freeway surveillance. Due to differences in measurement techniques, the occupancy values provided by these detectors may vary from each other, and from that provided by inductive loop detectors.

- **Closed Loop Occupancy Control** – An alternative form of control adjusts the metering rate to bring the measured occupancy in line with the desired occupancy (i.e., control of occupancy is explicitly achieved). Haj – Salem et al. and Papageorgiou et al. describe the following control law for the ALINEA algorithm (10,11). The algorithm is intended for use with a mainline detector station downstream of the merge.

$$r(i) = r(i-1) + K_R\,(o_s - o_{out}(i)) \qquad (7.1)$$

Where:

i = Computation iteration

$r(i)$ = Metering rate
o_s = Preset desired value of downstream occupancy
o_{out} = Measured occupancy
K_R = Coefficient

The coefficient K_R establishes the "gain" of the control loop. As K_R is increased, the sensitivity and speed of response to changing inputs is increased, however it tends to make the control more oscillatory and more sensitive to random variations and errors in the measured occupancy.

The occupancy set point may be established at a value that reflects the metering strategy or aggressiveness to be employed. Smaragdis and Papageorgiou often use the occupancy corresponding to the critical (maximum mainline flow) volume as the set point (37). Figure 7-8 describes a method for computing this value for U.S. traffic flow characteristics for inductive loop detectors. Other detecting technologies have different occupancy sensing characteristics. The occupancy set point may be changed during the course of the peak period to reflect different needs as time progresses.

SD = Density for upper value of Level of Service E = 45 passenger cars/mi/lane (HCM 2000)

Assume:

Average passenger car length = 17 feet
Average commercial vehicle length = 25 feet
Commercial vehicle fraction = 5%
Detector loop length = 6 feet
Additional sensed distance by loop detector = 2 feet

Average vehicle length = 17*(1-0.05) + 26*0.05 = 17.45 feet

Calculation of set point occupancy for inductive loop detector mainline station

Set point occupancy = SO = (Average vehicle length (ft) + loop length + additional sensed distance) * SD (veh/mi)/feet per mile

SO = (17.45 + 6 + 2) * 45/5280 = .217

Set point occupancy = 22%

Figure 7-8: Calculation of Set point Occupancy

<u>System-Wide Traffic Responsive Ramp Metering</u>

A number of system-wide traffic responsive ramp metering algorithms are described below. A number of the algorithms also include stored pre-timed metering rates. In some cases, the metering rate implemented is the more restrictive of the traffic responsive and pre-timed rate. Before describing these algorithms in greater detail, it is worth noting that most of them – specifically, the Minnesota, Washington DOT Bottleneck and SWARM 1 algorithms – are based on the same philosophy of determining the number of excess vehicles entering (or in) a section of roadway or roadway location based on direct mainline measurements, and setting the metering rates accordingly.

<u>The Minnesota Algorithm</u>

Key features of the Stratified Zone Metering Algorithm (13) are:

- Ramp queue lengths are calculated based on queue detector measurements. The queue waiting time is limited to a prescribed value (e.g. four minutes), and the ramp meter rate is raised, as necessary to assure that this condition is met.
- Filtered mainline loop detector data at 30-second intervals is used for the meter rate setting algorithm.
- Spare capacity is calculated from mainline measured volume and speed data.
- Meters are grouped into zones. The intent of the metering algorithm is to restrict the total number of vehicles entering a zone to the total number leaving (including spare capacity). Zones are organized by "layers". Higher level layers feature larger zones with greater overlap among zones.
- Metering rates are calculated by distributing the spare capacity among the meters in a zone. If the required metering rates are lower than the minimum metering rates allowed, the metering rates are recalculated for the next higher layer. This process is repeated until all of the minimum metering rates are satisfied.

There are three variables by which vehicles can enter a zone (Inputs) and three by which they may leave (Outputs), as summarized in Figure 7-9.

Inputs:	
(M)	Metered Entrances: Entrance ramps onto any given freeway that are metered.
(A)	Upstream Mainline Volume: Total number of vehicles entering a zone through the station at the beginning of the zone. (See Appendix; HOV and Auxiliary Lanes)
(U)	Unmetered Entrances: Entrance ramps onto any given freeway that are not metered.

Outputs:	
(X)	Exits: all exit ramps off any given freeway.
(B)	Downstream Mainline Volume: Total number of vehicles leaving a zone through the station at the end of the zone often result in an unreasonable volume. (See Appendix; HOV and Auxiliary Lanes)
(S)	Spare Capacity: If a zone is free-flowing with little traffic, there is said to be "spare capacity" on the mainline, and meters will not need to be as restrictive. For this reason, the spare capacity is regarded as an output.

Figure 7-9: Minnesota Ramp Metering Algorithm Variables

The objective of stratified zone metering is to regulate zones through metering so that the total volume exiting a zone exceeds the volume entering. For this to happen, the relationship of inputs and outputs within a given zone is as follows:

$$M + A + U \leq B + X + S \qquad (7.2)$$

Therefore,

$$M \leq B + X + S - A - U \qquad (7.3)$$

M is the maximum number of vehicles allowed to pass through all meters in any given zone between stations A and B. The key to stratified zone metering is to disperse the volume M throughout the zone suitably depending on demand (D) on the metered entrance ramps.

Based on demand, the following calculation gives a proposed rate for every meter to run in according to a percentage of M.

$$R_n = (M^*D_n)/D \qquad (7.4)$$

Where R_n is the proposed rate for meter n (n is a meter within the zone), and D_n is the demand for the meter n.

Washington State Algorithms

Washington State DOT initiated traffic responsive system-wide metering with an algorithm based on metering for bottleneck conditions. This algorithm selects rates at each ramp in accordance with the system, as well as local demand-capacity constraints. Jacobson et al. (14) describe a system-wide traffic-responsive ramp metering algorithm that also computes a local rate based on a schedule of metering rate versus occupancy. A system metering rate based on bottleneck conditions is also computed, and the more restrictive rate is used.

A bottleneck is identified when:

- A threshold occupancy is exceeded, and
- Vehicles continue to be stored in the section.

A bottleneck section can occur between any pair of adjacent mainline detector stations and every pair is checked in every iteration of the algorithm. No pre-set bottleneck sections are identified. The algorithm automatically responds to incident conditions.

Equation 7.5 represents the rate at which vehicles are being stored:

$$U_{i(t+1)} = qIN_{it} + qON_{it}) - (qOUT_{it} - qOFF_{it}) \qquad (7.5)$$

Where:

$U_{i(t+1)}$ - Upstream ramp volume reduction for section i required in next metering interval (t+1)

qIN_{it} – Volume entering section across the upstream detector station during the past minute

qON_{it} - Volume entering section during the past minute from the entry ramp

$qOUT_{it}$ - Volume exiting section across the downstream detector station during the past minute

$qOFF_{it}$ - Volume exiting section during the past minute on the exit ramp

An area of influence (a group of ramps upstream of the bottleneck section) is defined. Ramps within this area are collectively metered to reduce the entering volume by $U_{i(t+1)}$. Assignable weighting factors determine how this volume reduction is apportioned among the upstream ramps in the area of influence.

One key algorithm feature is that the bottleneck identification and upstream volume reduction computations do not require direct knowledge of the bottleneck capacity. A number of adjustments may be made to the calculated metering rates (14).

<u>Fuzzy Logic</u>

Although the Washington State algorithm provided considerable improvement compared to non-metered operation, observations over a period of time identified the following areas where the algorithm could be improved:

- The algorithm required congestion to develop before it could react.
- The algorithm tended to oscillate between controlling mainline congestion and dissipating excessive ramp queues.

Taylor, et al. (15) describe a new algorithm employing fuzzy logic designed to address these deficiencies. Fuzzy logic has the ability to address multiple objectives (by weighing the rules that implement these objectives) and to implement the tuning process in a more user-friendly fashion (by the use of linguistic variables rather than numerical variables). Rule groups used by the algorithm include:

- Local mainline speed and occupancy
- Downstream speed and occupancy
- Ramp queue occupancy
- Quality of the ramp merge.

There are six inputs to the fuzzy logic controller (FLC). These include speed and occupancy from the mainline and downstream detector stations, the queue occupancy detector and the advanced queue occupancy detector (at the upstream end of the ramp storage location. "Fuzzification" translates each numerical input into a set of fuzzy classes. For local occupancy and local speed, the fuzzy classes used are very small (VS), small (S), medium (M), big (B), and very big (VB). The degree of activation indicates how true that class is on a scale of 0 to 1. For example, if the local occupancy were 20%, the medium class would be true to a degree of 0.3, and the big class would be true to a degree of 0.8, while the remaining classes would be zero (top of Figure 7-10). The downstream occupancy only uses the very big class, which begins activating at 11%, and reaches full activation at 25% (bottom of Figure7-10). The downstream speed uses the very small class, which begins activating at 64.4 km/hr and reaches full activation at 88.5 km/hr. The queue occupancy and advance queue occupancy use the very big class. For ramps with proper placement of ramp detectors, the parameter defaults are for activation to begin at 12%, and reach full activation at 30%. For each input at each location, the dynamic range, distribution and shape of these fuzzy classes can be tuned.

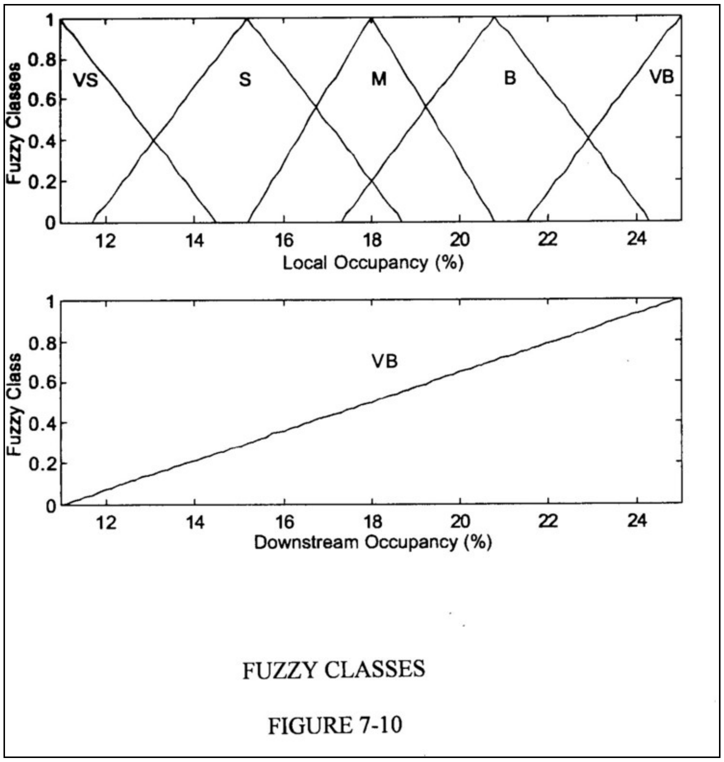


Figure 7-10: Fuzzy Classes

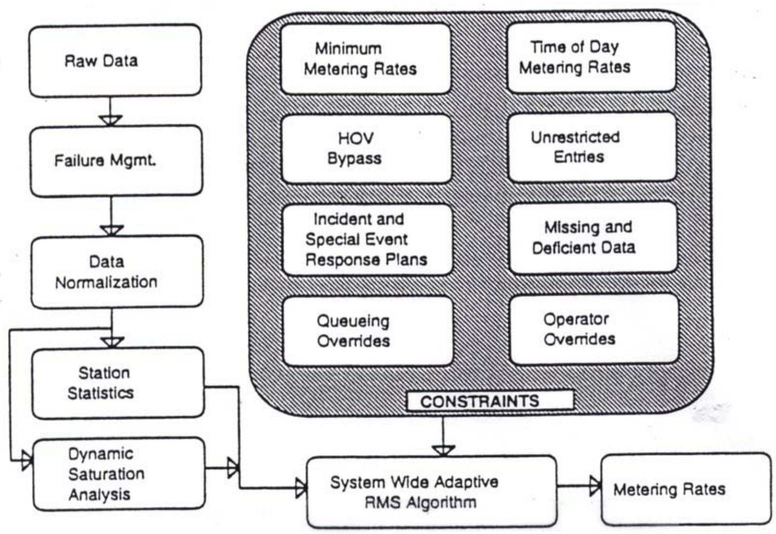
After the fuzzy states have been developed, weighted rules are then applied to develop the metering rate. Examples of weighted rules are shown below.

Rule	Default Rule Weight	Rule Premise	Rule Outcome
6	3.0	If local speed is VS AND local occupancy is VB	Metering Rate is VS
10	4.0	If downstream speed is VS AND downstream occupancy is VB	Metering Rate is VS
12	4.0	If advance queue occupancy is VB	Metering Rate is VB

The last step is to generate a numerical metering rate based on the rule weight and the degree of activation of each rule outcome.

The SWARM 1 Algorithm (16)

The system-wide adaptive ramp metering algorithm (SWARM) includes two primary functions, forecasting the onset of congestion and system-wide apportionment of ramp metering rates. Figure 7-11 is a general depiction of data flow.



SWARM DATA FLOW

FIGURE 7-11

Figure 7-11: SWARM Data Flow

Occupancy, used as a surrogate to estimate density, is monitored at each mainline detector station, as any station might represent the bottleneck location, and therefore the control point for metering calculations. The basic approach is to reduce the ramp flow for a number of ramps upstream of the bottleneck to a value that will keep the forecast future density at the bottleneck detector station below the critical density (density for which flow breaks down). Forecast future density is computed by means of a Kalman Filter. The Kalman Filter has the capability to filter random variations from the occupancy data and to provide a future forecast of occupancy.

SWARM 1 defines excess density as the value by which forecast density exceeds critical density. The reduction in volume necessary to eliminate excess density is computed and apportioned to ramps upstream of the bottleneck.

7.2.5.5 Freeway-to-Freeway Ramp Metering

This control aims to improve traffic conditions downstream of major merges. The technique has been applied in Minnesota, California, Texas and Washington. Freeway-to-freeway metering has generally improved flows downstream of the merge. Jacobson and Landsman offer guidelines for the selection of appropriate sites (17). These are summarized in Table 7-3.

Table 7-3: Guidelines for Freeway – to – Freeway Ramp Metering

(Reference 17)

• Consider locations where recurrent congestion is a problem or where route diversion should be encouraged. • Consider route diversion only where suitable alternative routes exist. • Avoid metering twice within a short distance. • Avoid metering single lane freeway-to-freeway ramps that feed traffic into an add-lane. • Do not install meters on any freeway-to-freeway ramp unless analysis ensures that mainline flow will be improved so that freeway-to-freeway ramp users are rewarded. • Install meters on freeway-to-freeway ramps where more than one ramp merges together before feeding onto the mainline, and congestion on the ramp occurs regularly (4 or more times a week during the peak period).	• If traffic queues that impede mainline traffic develop on the upstream mainline because of a freeway-to-freeway ramp meter, then the metering rate should be increased to minimize the queues on the upstream mainline, or additional storage capacity should be provided. • Freeway-to-freeway ramp meters should be monitored and be controllable by the appropriate traffic management center. • Whenever possible, install meters at locations on roadways that are level or have a slight downgrade, so that heavy vehicles can easily accelerate. Also, install meters where the sight distance is adequate for drivers approaching the meter to see the queue in time to safety stop.

7.2.5.6 Exit Ramp Control

Traffic backing up from exit ramps onto the freeway mainline is often a source of freeway congestion. Methods for improving congestion from this source include improving the flow discharge from the exit ramp by:

- Timing the signal at the intersection downstream of the ramp to provide greater ramp discharge capacity. This must be weighed against increased delay to traffic not originating from the freeway.

- Improving geometrics (e.g., adding an auxiliary lane for exiting vehicles) as discussed in Chapter 5.

7.2.6 Design and Related Considerations for Ramp Metering

The previous sections of this chapter have discussed the objectives and benefits of ramp metering, and have identified a variety of metering strategies that may be employed. This section describes design measures to implement ramp metering.

The Wisconsin DOT Intelligent Transportation System Design Manual (18) contains a good deal of information on the physical design of ramp metering installations. An overview of the process described in that reference is shown in Figure 7-12. That reference identifies the following ramp meter types:

- Single-lane (SOV) Ramps
- Metered Two-Lane (SOV/HOV) Ramps
- Metered Two-Lane (2 SOV) Ramps
- Metered Three-Lane (2 SOV/HOV) Ramps
- Metered Freeway Connector Ramps

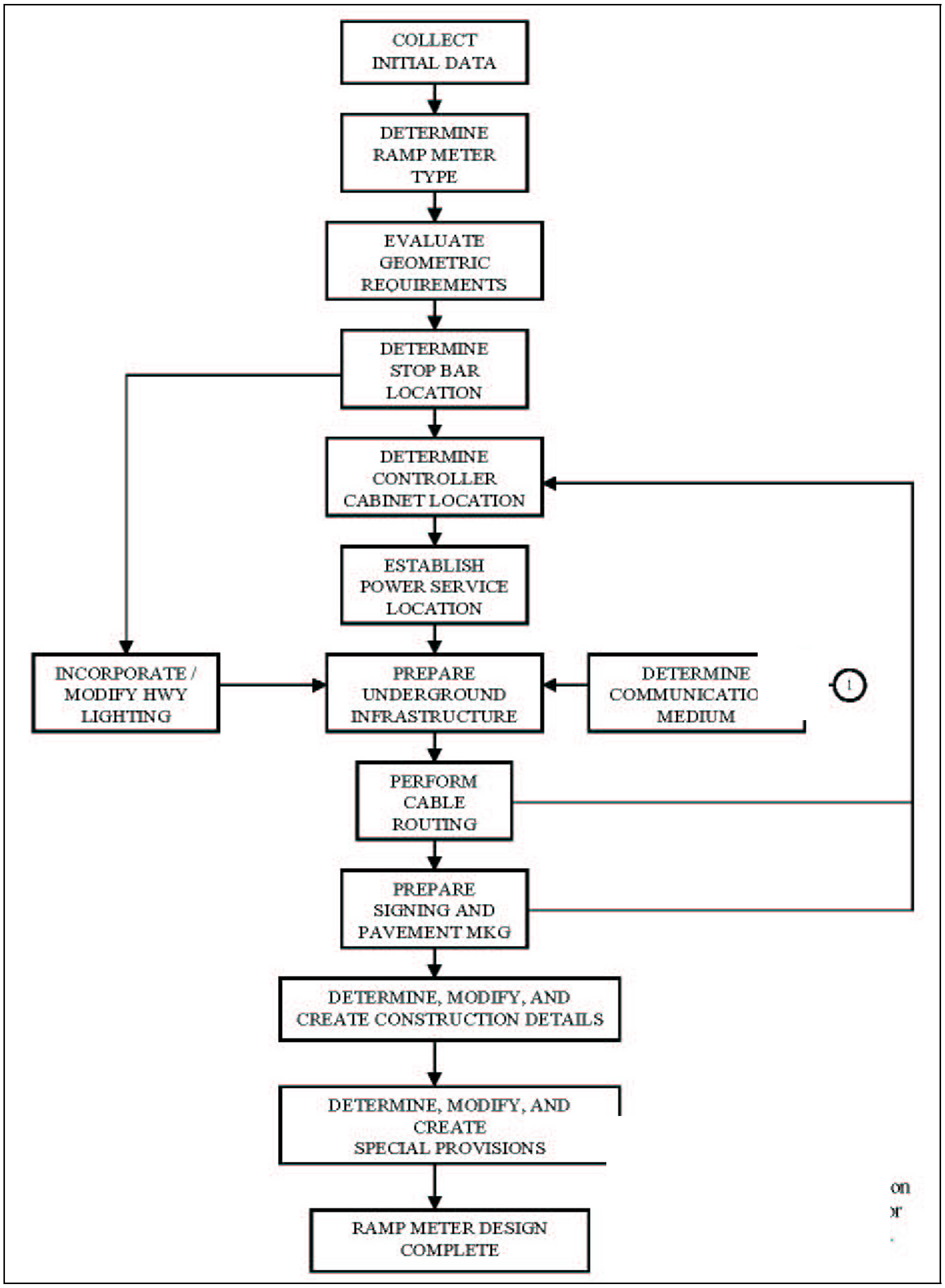
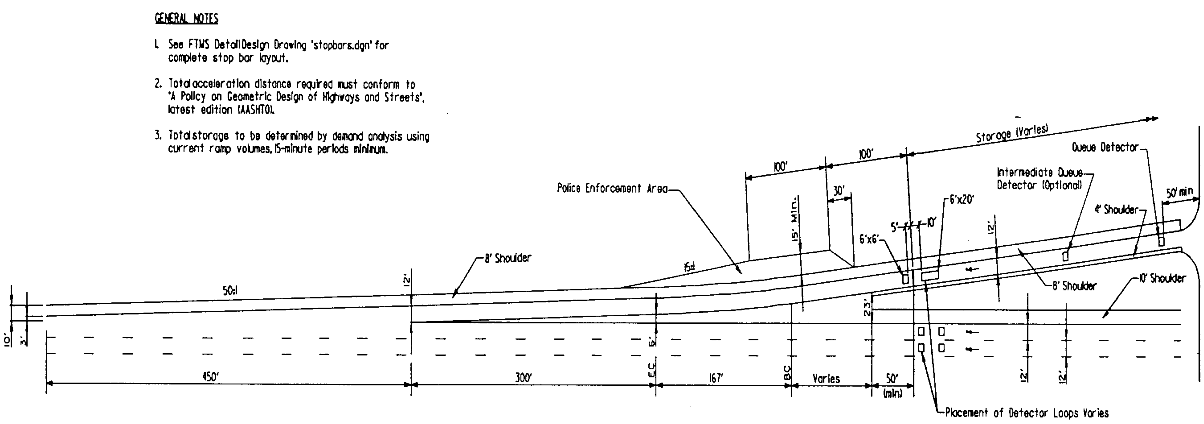


Figure 7-12: Wisconsin DOT Ramp Meter Design Process

(Reference 18)

7.2.6.1 Geometric Requirements

An example of the guidance provided by Reference 18 is shown in Figure 7-13.



Wisconsin DOT Ramp Meter Design Guidelines, 1-Lane Slip Ramp

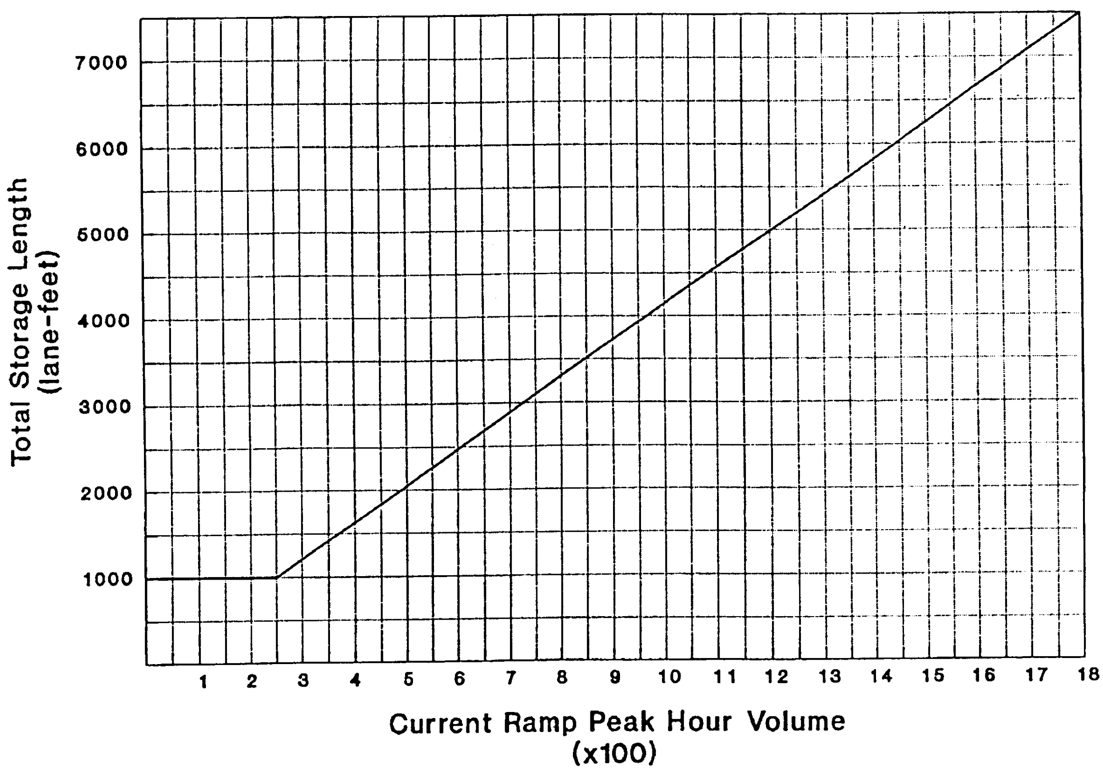
Figure 7-13

Figure 7-13: Wisconsin DOT Ramp Meter Design Guidelines

Other geometric design guidance is provided in Reference 19. Both references provide guidance on required acceleration lane characteristics and the relationship of the ramp meter location to the merge area. Other issues related to ramp geometry include:

- **Ramp Storage** – For restrictive ramp metering, adequate storage space must exist at metered ramps to assure that queues of waiting vehicles will not seriously impact non-freeway traffic. Queued ramp traffic should not block frontage roads or surface streets. In many cases, adequate ramp storage can only be obtained by using two or more lanes. Storage requirements depend on:
  - Ramp demand volumes and metering rates,
  - Ramp entry flow patterns (e.g., platoons caused by nearby signals upstream of the ram may increase storage requirements),
  - Availability of surface street storage.

  Caltrans has developed ramp meter design guidelines that include the storage requirements shown in Figure 7-14 (19).



Recommended Ramp Meter Storage (Caltrans)

Figure 7-14

Figure 7-14: Recommended Ramp Meter Storage (Caltrans)

Wisconsin DOT guidelines (18) 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.

- **Ramp Width** – 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.

7.2.6.2 Ramp Meter Operation

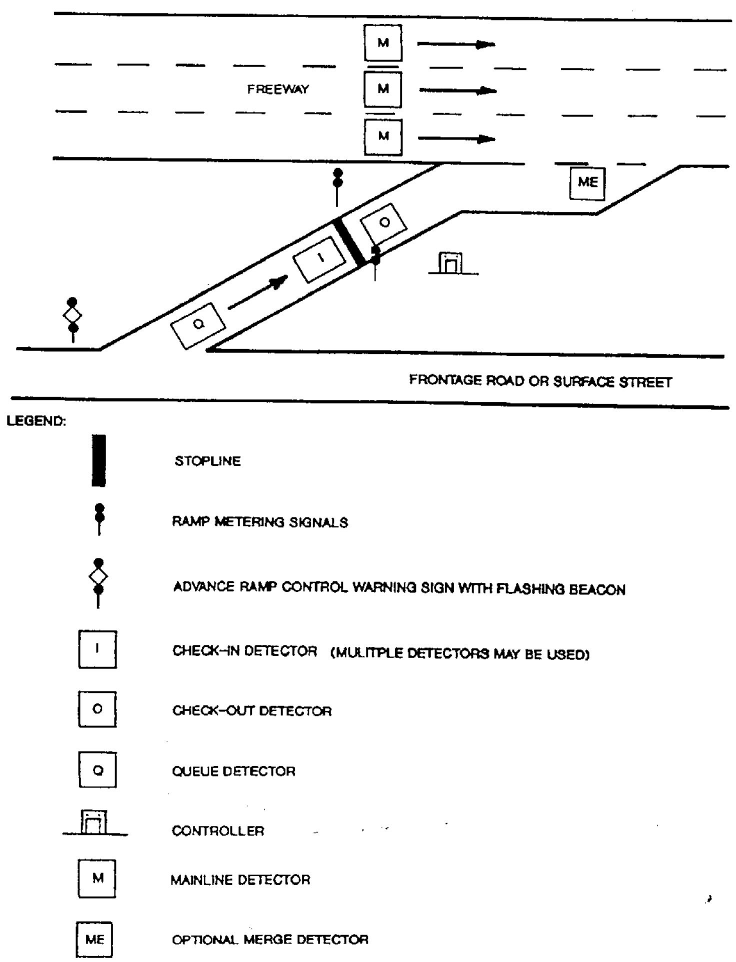
Figure 7-15 shows a typical arrangement of the field components for a single lane meter. These field components are described below:

- **Displays** – Signals on the ramp for vehicle drivers and advance warning signs, including:
  - Ramp metering signal. Usually a standard 3-section (red-yellow-green), or 2-section (red-green) signal display that controls the ramp traffic. The signals may be either mast arm or pole mounted as shown in previous Figure 7-1. A sign may be mounted on the signal pole or nearby indicating the number of vehicles permitted per green interval.
  - Advance ramp control warning sign with flashing beacon. A sign that indicates to traffic approaching the ramp that it is being metered (previous Figure 7-2). Alternatively, a blank out "METER ON" sign may be used.

  Chapter 4H – "TRAFFIC CONTROLSIGNALS FOR FREEWAY ENTRANCE RAMPS" – of the MUTCD addresses display requirements in more detail.

- **Local Controller** -- Device to receive and store vehicle detector information and operate signals according to internal logic or according to a central supervisory system. The controller processes detector data and controls the ramp meter timing. The controller may provide the following control functions:
  - Control ramp meter signal head(s).
  - Store and execute pretimed metering schedules.
  - Implement local traffic responsive control algorithms using mainline detector data.
  - Accept metering rate command signals from the central control system.
  - Adjust the metering rate or terminate metering to prevent ramp queues from becoming excessive.
  - Control the advance beacon or blank out sign.

  Controllers belonging to the Type 170 controller family are currently most commonly used for ramp metering. However, controllers belonging to the Type 2070 and ATC families are becoming increasingly popular.



Typical Entrance Ramp Metering System Layout

Figure 7-15

Figure 7-15: Typical Entrance Ramp Metering System Layout

- **Vehicle Detectors**. Devices to measure conditions on the freeway and ramp. These may include:
  - Check-In (Demand) Detector – When a vehicle is detected by the check-in detector, the ramp metering signal will change to green, provided the red time has elapsed. In some cases, two detectors are used to provide redundancy to reduce the impact of detector failures.

  - Check-out Detector – When a vehicle is permitted to pass the ramp metering signal, it is detected by the checkout detector, which is installed just beyond the stop line (usually about half a car length past it). The green interval is then terminated as soon as the vehicle is sensed by the check-out detector. In this way, the length of the green interval is made sufficient for the passage of only one vehicle. With platoon metering, the green interval is terminated after passage of the appropriate number of vehicles in the platoon.

- Queue Detector – One or more queue detectors are commonly used to prevent the queue from spilling back into the surface street traffic stream. Detection of vehicles by the queue detector results in increasing the metering rate or terminating metering. Strategies for accomplishing this are described in a subsequent section. In some cases the queue detector may be used to limit ramp waiting time to a specified value.

- Merge Detector – Some ramp metering installations use merge detectors. The merge detector senses the presence of vehicles in the primary merging area of the ramp and freeway mainlines. When the merge detector senses that a vehicle has stopped, blocking the merge area, the signal may be held in red for some preset maximum time in order not to clog the area and to reduce the possibility of a rear end collision. On a well-designed entrance ramp with adequate acceleration and merging distance, a merge detector is not necessary or practical.

- Mainline Detectors – Traffic responsive ramp metering require mainline detectors. Depending on the strategy, detector data averaged across all lanes may be used or alternatively, data from the lane adjacent to the shoulder may be used.

7.2.6.3 Flow Control at the Ramp Meter

With **single entry metering,** the ramp metering signal is timed to permit only one vehicle to enter the freeway per green interval. The desired metering rate is converted to a cycle duration. With vehicle passage, the passage detector on the ramp provides a signal to terminate the green. The signal remains red until the cycle duration is complete. If a vehicle is waiting at the demand detector, another cycle is initiated; otherwise the signal rests in red until the demand detector senses a vehicle.

When metering rates greater than 800 to 900 vph are required, **platoon metering**, which permits the release of two or more vehicles per cycle, may be used to achieve higher metering rates. The signal will stay green until the last permissible vehicle in the platoon actuates the passage detector. Experience indicates that 2-vehicle platoons can be handled satisfactorily and that 3-vehicle platoons are a practical maximum. In either case, a maximum metering rate of 1,100 vph can be expected.

With **tandem or two-abreast metering**, two (or more) vehicles are released side by side per cycle. This form of metering requires two (or more) parallel lanes on the entrance ramp, plus a sufficient distance beyond the ramp metering signal for the vehicles to achieve a tandem configuration before merging with freeway traffic. The more common practice in two-lane situations is to alternate the release – one from the left lane followed by one from the right. The timing of the cycle intervals for multiple-lane metering is similar to that for single-entry metering. The remainder of the cycle is red. With alternate release metering, maximum metering rates of about 1,700 vph may be achieved. It is also possible to control each ramp lane in an independent fashion, with different metering rates for each lane. This approach may be desirable when each lane is fed from a different direction or different road, and each has a different demand.

Compared to single-entry metering, platoon metering is a more complex operation and may cause some drive confusion, which may lead to disruptions of ramp flow. Therefore, single-entry metering should always be given first consideration, followed by two-abreast metering, with platoon metering being used if necessary to achieve higher metering rates.

7.2.6.4 Range of Metering Rates

In order to prevent an excessive number of violations, it is appropriate to use a minimum metering rate for single lane meters of approximately 240 vehicles per hour, equivalent to a 15 second cycle (4). For single lane meters, the highest metering rate is established by the period required to enable the vehicle to stop and then proceed. This rate is in the range of 800 vph to 900 vph. Often only "rolling stops" can be implemented at 900 vph. Table 7-4 summarizes metering rate ranges for different metering arrangements.

Table 7-4: Ranges of Ramp Metering Rates

Types of Metering	Number of Metered Lanes	Approximate Range of Metering Rates (v/hr)	Comments
Single vehicle entry per green interval	1	240 – 900 (4)	• Full stop at the meter usually not achieved at 900 v/hr metering rate
Tandem Metering Single vehicle entry per green interval per lane	2	400 – 1700	• Applies when required metering rate exceeds 900 v/hr • Requires two lanes for vehicle storage • Vehicles may be released from each lane simultaneously or sequentially
Platoon Metering Single lane multiple vehicle entry per green interval geometrics	1	240 – 1100 (4)	• Platoon lengths permit passage of 1 to 3 vehicles per green interval • Principally used to increase metered volumes when geometrics do not permit use of more than one metered lane • Requires changeable sign indicating permitted number of vehicles in green interval • MUTCD requires yellow interval after green

7.2.6.5 Managing Ramp Meter queues

For entry ramps of sufficient length, the length of the queue and queue waiting time is generally determined by the equilibration of travel time on the entry ramp and mainline with the travel time on an alternate route. Lower metering rates imply longer queue waits and greater diverted volume (by alternate routes, modes destinations or time). The equilibration point is determined by strategies and algorithms such as those described in Sections 7.2.5.4 and 7.2.5.5. In some cases the strategies explicitly consider queues while other strategies do not. In the latter case, the metering rates should be constrained so that the queue length is somewhat less than the available storage space. Even with this constraint, random or platoon arrivals may cause the queue to exceed the storage capability

It may be necessary to limit or control ramp meter queues for the following reasons:

- Prevention of the queue from spilling back to a surface street location that will impede traffic not entering the freeway – In order to prevent the queue from spilling back into upstream traffic, a queue detector may be placed relatively close to the location to be protected. In some cases an additional detector between this location and the ramp meter may be used. Control strategies include increasing the meter rate as a function of the occupancy at the “queue detector”, or terminating metering (22, 23). These algorithms often result in a queue whose length and waiting time vary excessively, resulting in a reduction in the efficiency of the ramp meter and in an inconsistent waiting time to the entering motorist. To improve this situation, the following approaches are available.
  - When a single queue detector location is employed, Gordon (24) shows that it is preferable to use a queue control algorithm that uses a short (e.g. 10 second) detector data sampling interval in conjunction with some anticipation. The appropriate placement of the queue detector varies with the ramp length, nominal metering rate and presence of an upstream traffic signal. In subsequent research it was determined that placement of the queue detector at a distance of 110 feet downstream of the location to be protected will be satisfactory for wide range of conditions on single lane ramps.
  - Smaragdis and Papageorgiou (25) describe a simple queue control algorithm for use when ramp detectors can measure the length of the queue. The algorithm is based on linear control theory.

- Limitation of motorist waiting time in the queue – Policy may dictate the need to limit queue waiting times. Data from the queue detector and from the demand detector may be used, as it is in Minnesota, in conjunction with an algorithm to limit waiting time (13). Shortening the waiting time is accomplished by an increase in metering rates.

- Use of queue waiting time as one element in a ramp metering control algorithm – Queue waiting time may be used, for example, along with mainline delay to minimize overall freeway delay. A related approach is to use queue waiting time or queue length to directly influence the metering rate by including it in the rules of a fuzzy logic control algorithm (see Section 7.2.5.5). It may still be necessary to include an explicit queue spillback prevention feature.

7.2.6.6 High Occupancy Vehicle (HOV) Ramp Meter By-Pass Lanes

HOV by-pass lanes on metered ramps are often employed to encourage the use of high occupancy vehicles and to reduce total user delay on the freeway. The HOV ramp meter by-pass is most often implemented by using an additional dedicated lane on the ramp. The lane may be closed by the use of blank out signs, other CMS or beacons during periods when metering is not being employed.

Ramp metering control algorithms generally compensate for HOV entry ramp volume by subtracting this volume from the volume that would be permitted in the absence of the HOV lane. The difference constitutes the actual volume to be metered.

7.2.7 Emerging Trends

Ramp meter operation is likely to be improved in the future in the following ways:

- Current research into an improved understanding of traffic flow in the region of flow breakdown is likely to result in improved ramp metering control strategies. For example, different metering strategies might be employed for sustained operation in the free flow region as compared with recovery from the congested flow regions.

- Improved estimation of the tail of the ramp queue will lead to better control of the queue. Improved estimation is likely to come about through improved estimation algorithms as described in References 13 and 15 and through the increased use of wider area detection technologies.

- Improved recognition of the multi-objective applications of ramp metering (e.g., freeway flow optimization, corridor flow optimization, safety improvement, merge flow smoothing, limitation of queue waiting time) and the design of systems that accommodate these functions at the required locations.

- Improvement in the ease of tuning ramp metering systems to accomplish their objectives. The use of fuzzy logic (15) and emphasis on evaluation of performance data are steps in this direction.

7.3 IMPLEMENTATION AND OPERATIONAL CONSIDERATIONS

7.3.1 Diversion of Traffic

A major issue that is raised in connection with metering is the potential diversion of freeway trips to adjacent surface streets to avoid queues at the meters. Extensive evaluations of existing metering systems show that adjustments in traffic patterns, after metering is implemented, take many forms (4). Use of simulation makes it possible to predict the likely impacts of metering before it is installed. Factors that enter into the analysis include trip length, queue length, entry delay, and especially the availability of alternate routes. The impact of attractive and efficient alternate routes can be a key factor in the effectiveness of a ramp metering system (26). The probable new traffic patterns, including diversion, can either be accommodated in the design and operation of the system, or become part of a decision that metering is not feasible.

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 and 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 so-called 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.

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 (20).

7.3.2 Relations with the Public and the Media

Ramp metering systems can be successful only if they receive public support from political leaders, enforcement agencies, and the motoring public. To gain this support in advance of implementation, a comprehensive public relations and information program should begin well in advance. To the public, ramp meters are often seen as a constraint on a roadway normally associated with a high degree of freedom. Although definite benefits may be achieved by metering and have been demonstrated statistically, the benefits may not be recognized by individual motorists. A 3-minute wait at an entrance ramp, however, is easily recognized. A proactive public relations program should be an integral part of every metering project (4).

It is important not to oversell the benefits of ramp metering. It is not a substitute for a new freeway lane. The benefits are measurable system-wide, but may not be readily discernable to the individual driver at the ramp signal. Successful public relations campaigns will explain the difficulties of mitigating freeway congestion problems and the cost effectiveness of management techniques such as ramp metering (4). The campaigns should also provide realistic expectations of the systems' benefits, and show how taxpayers will experience improved freeway conditions. The most common method of disseminating ramp metering information is through brochures or media advertisements on television and radio. Some examples of public relations brochures are shown in Reference 4. In Minneapolis and Los Angeles, the "public" has actually requested additional metered ramps. This public input has become one of the factors in evaluating and selecting new metered locations.

Public relations aspects of the ramp control systems should begin well in advance of turn-on. In Seattle, the Washington State DOT (WSDOT) has developed a methodical approach to implementing ramp metering (27). Their process describes what needs to be accomplished starting five years prior to ramp metering all the way up to one week before, and continuing through six months after start-up. The procedure includes public input, the design process, and the public relations focus. In Tacoma, Washington, the WSDOT went beyond the typical public relations campaign of brochures and media advertisements. WSDOT has incorporated a ramp metering lesson into both public and private driver education school curricula. The lesson, which lasts about 30 minutes, helps students to understand what ramp meters are and what they mean to the driver. The information packet for this lesson includes a lesson plan, information sheets, brochures, key chains, and a well-developed 12 minute video entitled "Ramp Meters: Signals for Safety".

A promotional videotape from the FHWA entitled "Ramp Metering: Signal for Success" is another example of how the merits of ramp metering can be presented to the public (4). This 17-minute videotape, which is intended for citizens and public officials, explains the principles and benefits of ramp metering. It addresses key issues such as safety, efficiency, equity, and public relations. Copies are available through the FHWA or the Institute of Transportation Engineers (ITE).

7.3.3 Media Relations

The print and electronic media can be great allies or great deterrents to the success of ramp control systems. When the Dallas Corridor Study metering system was implemented in 1974, a radio reporter in the control center (with CCTV and other displays) reported that the system was working great, while a television reporter interviewing the 20th vehicle in a ramp queue proclaimed the system a failure (28). The system perspective (which was understood by the reporter in the control center) must be stressed. As with the general public, the media must be informed as to system goals and expectations, schedules, operations, and results. It is also important to maintain communication with the media after system turn-on. Beat reporters are often reassigned, and the new reporter may need to be briefed before a uniformed, negative story is written.

7.3.4 Implementation Strategies

Scheduling of ramp control turn-on should be carefully considered. Incremental implementation of individual sections should be considered, rather than a total system launch. In particular, locations that have the best alternate routes and the highest probability of congested freeway flow should be considered first. Ramps may first be operated with metering rates that cause little disruption. As drivers become familiar with and accustomed to the system and how metering operates – typically a week or two – metering rates can be tightened and other locations implemented. (Note – Care needs to be taken with this approach. If the initial "relaxed" metering rates don't show any mainline improvements, the public might become very skeptical of the usefulness of ramp metering.)

An interesting approach has recently been employed in Houston. Some of the pioneering efforts in ramp control took place in the mid-sixties (29). However, due to reconstruction of freeways, ramp metering had not been in operation for some time. When ramp metering was recently re-implemented, a conservative philosophy was developed. The implementation philosophy was as follows (29):

> …drivers and their views are important and a very high priority. No ramp delays (for a while at least) will be more than 2 minutes, and this must be verified. When queues or delays get too long, the signals are shut off until the queues clear, no matter what happens to the freeway. For the first three months, metering during the peak of the rush hour was sometimes terminated. No written complaints were received. However, continuous quality improvement for the freeway traffic flow is stressed. Freeway drivers have called by cell phone and by Internet asking TranStar (the freeway management center) for "more" ramp metering. Now, the simple explanation for this is that we have "teased" the freeway traffic into this position. But we have not followed any ramp control strategy mentioned in the traditional freeway ramp control manuals. The traditional demand/capacity methods are for marginally overloaded well-disciplined systems, and that goal of demand/capacity control is only a faint vision in Houston at the moment. We are simply pushing back up the q/k curve toward capacity from stop-and-go conditions, and not from the other side.

7.3.5 Equity

The complaint that ramp metering favors longer trips at the expense of shorter trips can be a controversial issue (4). Close-in residents argue they are deprived of immediate access to the freeway, while suburban commuters can enter beyond the metered zone and receive all the benefits without the ramp delays.

Again there are strategies that have been employed to mitigate the equity issue. For example:

- Initial metering in Detroit 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.
- In the New York City area, ramp metering is primarily employed on suburban ramps of a radial freeway, but infrequently within the city.
- In Dallas, there was concern that suburbs were being favored over areas closer to the central business district. Ramp counts and license plate studies revealed that approximately as many vehicles were exiting the freeway before they reached downtown as were entering downstream of the adjacent suburbs, so equity was achieved.

Even if only a few drivers experience increased travel times, there may still be objections simply because some have to wait at the ramps and others do not. A reasonable analogy can be made between a metered freeway and a signalized arterial. Vehicles entering an arterial from a minor street must generally wait at a traffic signal while traffic already on the arterial is given priority. In both cases, the freeway and the arterial, the entering vehicles experience some delay in order to serve the higher volume facility (4).

7.3.6 Enforcement

The effectiveness of ramp metering, like that of any other traffic regulation, is largely dependent on voluntary driver compliance. As part of the public information effort, it should be made clear that ramp meters are traffic control devices that must be obeyed (4). The laws and penalties should be clearly explained. In cities where the advance publicity has been positive and plentiful, violation rates have been lower. Again, as with any other regulation, enforcement is needed. Cooperation with police agencies is essential. Effective enforcement requires good enforcement access, a safe area for citing violators, adequate staff, support by the courts, and good signs and signals that are enforceable. Enforcement needs must be considered and accommodated early in the project development and design stages.

Previous Figure 7-15 shows a ramp meter design that incorporates a police enforcement area. Enforcement personnel 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 be an extremely ineffective ramp metering system.

7.4 REFERENCES

1. "Highway Capacity Manual – HCM 2000", Transportation Research Board, Washington, D.C., 2000.

2. Persuad, B., Yagar, S., Tsui, D., Look, H., "Study of Breakdown Capacity for a Freeway With Ramp Metering", Presented at the 80th Annual Meeting of the Transportation research Board, Washington, D.C. 2001.

3. B. Kerner, "Congested Traffic Flow: Observations and Theory", Transportation Research Board, 78th Annual Meeting, Washington, D.C., January 1999.

4. Piotrowicz, G., and Robinson, J.R., "Ramp Metering Status in North America", Report DOT-T-95-17. FHWA, U.S. Department of Transportation, Washington, D.C. 1995.

5. "Manual on Uniform Traffic Control Devices" (MUTCD) 2000, Millenium Edition, Institute of Transportation Engineers, Washington, D.C., 2001.

6. "The National ITS Architecture, Version 4.0", http://www.iteris.com/itsarch/

7. "Traffic Software Integrated System, Version 4.2 User's Guide", Federal Highway Administration, Washington, D.C., March 1998.

8. McDermott, J.M., Kolenko, J.J., and Wojcik, R.J. "Chicago Area Expressway Surveillance and Control: Final Report, Expressway Surveillance Report No. 27". Illinois Department of Transportation, Springfield, IL, March 1979.

9. Blumentritt, C.W., et al. "Guidelines for Selection of Ramp Control Systems." NCHRP Report 232, Washington, D.C., May 1981.

10. Haj-Salem, H.; J.M. Blosseville; and M. Papageorgiou, "ALINEA" A Local Feedback Control Law for On Ramp Metering – A Real Life Study," Third IEEE International Conference on Road Traffic Control, London, United Kingdom, 1990, pp. 194-198.

11. Papageorgiou, M., H. Haj-Salem; J.M. Blosseville, "ALINEA: A Local Feedback Control Law for On Ramp Metering, "70th Annual Meeting, Transportation Research Board Paper 910659, Washington, D.C. 1991.

12. Papageorgiou, M., Hadj-Salem, H., Middleham, H., "ALINEA Local Ramp Metering Summary of Field Results", Transportation Research Record 1603, pp. 90-98, Transportation Research Board, Washington, D.C.

13. "Stratified Zone Metering – The Minnesota Algorithm", Minneapolis, MN.

14. Jacobson, L.N.; K.C. Henry; O. Mehyar. "Real Time Metering Algorithm for Centralized Control," Transportation Research Record 1232, Transportation Research Board, Washington, D.C.

15. Taylor, C., Meldrum, D., Jacobson, L., "Results of the On-line Implementation and Testing of a Fuzzy Logic Ramp Metering Algorithm", presented at 79th Annual Meeting of the Transportation Research Board, Washington, D.C., 2000.

16. "System-Wide Adaptive Ramp Metering Algorithm – High Level Design"; National Engineering Technology Corporation, LaMirada, CA, March 18, 1997

17. Jacobson, E.L., and J. Landsman, "Case Studies of Freeway to Freeway Ramp and Mainline Metering in the U.S. and Suggested Policies for Washington State," Transportation Research Board Paper 940331, Transportation Research Board Meeting, Washington, D.C., January 1994.

18. "Intelligent Transportation System Design Manual", Version 2.0, Wisconsin Department of Transportation, January 2001.

19. "Ramp Meter Design Guidelines," State of California, Department of Transportation, 1991.

20. Corcoran, L.J., and Hickman, G.A. "Freeway Metering Effects in Denver," ITE 1989 Compendium of Papers, September 1989.

21. Masher, D.P., et al. "Guidelines for Design and Operation of Ramp Control Systems." NCHRP Project 3-22 Final Report, December 1975. (Loan copy available on request to NCHRP).

22. Havinovski, G.N. "Operational Simulation Techniques for Ramp Metering on Long Island," Compendium of Technical Papers, ITE, 1989.

23. Havinovski, G.N. "Ramp Queues? Not in My Backyard: A Survey of Queue Detector Design and Operating Criteria for Metered Freeway Entrances", Compendium of Technical Papers, ITE, 1991.

24. Gordon R.L., "Algorithm for Controlling Spillback from Ramp Meters, Transportation Research Record 1554, pp. 162-171, Transportation Research Board, Washington, D.C. 1996.

25. Smaragdis, E. Papageorgiou, M., "A Series of New Local Ramp Metering Strategies", Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

26. Yagar, S., "Predicting Impacts of Freeway Ramp Metering on Local Street Flows and Queues", ITE 1989 Compendium of Technical Papers, September 1989.

27. "TSMC SC&DI Operations/Implementations Plan", Washington State DOT, October 1994.

28. Carvell, J.D., "Dallas Corridor Study Final Report", Report 953-29, Texas Transportation Institute, College Station, TX, August, 1976.

29. McCasland, W.R., "Freeway Ramp Control System", Report 24-26F Texas Transportation Institute, Texas A & M University System, College Station, TX, 1969.

30. "Twin Cities Ramp Meter Evaluation", Cambridge Systematics, Inc., Feb.1, 2001.

31. "Mn/DOT Ramp Meter Evaluation – Phase II Evaluation Report", Cambridge Systematics, Inc., May 10, 2002.

32. Taylor, C. Meldrum, D., "Evaluation of a Fuzzy Logic Ramp Metering Algorithm: Comparative Study Between Three Ramp Metering Algorithms Used in the Greater Seattle Area", Washington State Transportation Center, Settle, Washington, D.C.

33. Elefteriadou, L, Roess L., McShane, W., "Probabalistic Nature of Breakdown at Freeway Merge Junctions", Transportation Research Record, 1484, pp. 80-99, Transportation Research Board, Washington, D.C. 1995.

34. Zhang, L., Levinson, D. M., "Balancing Efficiency and Equity of Ramp Meters", Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.

35. Smaragdis, E., Papageorgiou, M., "A Series of New Local Ramp Metering Strategies", Presented at the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.