MODULE 5. RAMP CONTROL

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MODULE 5. RAMP CONTROL

Figure 5-1. Ramp Meter with HOV By-Pass in Minneapolis, MN.

5.1 INTRODUCTION

The geometric design of a freeway ramp (width, curvature, vertical alignment, etc.) can have a positive or negative influence on both the operation of the ramp itself and on the freeway at, 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 sixties. It is estimated that ramp control systems are operated in over 20 geographical areas at present, with individual metered ramps numbering over 2300.[1]

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 accident reduction.) They are more effective when they are part of an integrated transportation management plan that incorporates other systems as described in other modules of this document. Deployment of ramp control systems has been somewhat limited due to some public resistance to being stopped on a freeway ramp for no readily apparent reason, although the ramp metering rate may reflect a downstream bottleneck such as an incident.

DEFINITION OF RAMP CONTROL

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 some operational objective. Typically, the objective will be to balance demand and capacity of the freeway in order to maintain optimum freeway operation and prevent operational breakdowns. Ramp metering may also be applied for safety considerations where certain geometric inadequacies or other constraints exist.

APPLICATION OF RAMP CONTROL

The primary application of ramp control, commonly known as ramp metering, has been on freeway entrance ramps. However, ramp control has been applied in other situations as well.

Entrance Ramp Metering

Metering on entrance ramps involves determination of a metering rate (typically "4 to 15 vehicles per minute" are minimum and maximum rates for single lane metering) 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 minute-by-minute (traffic responsive) based on measured traffic parameters. The entry of vehicles at that rate is regulated by one or more traffic signals beside the ramp at driver's-eye height. Vehicle sensors may be located at points along the ramp to signal the blockage of the merge area or backing of the ramp queue into a cross street.

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. Obviously, this extreme case may cause negative public reactions and should be applied only after considerable planning and a public information program.

Exit Ramp Closure

Metering of exit ramps is obviously not appropriate but closure with automatic gates or manually placed barriers, with adequate freeway warning signs, may be used to accomplish certain operational objectives. For example, if the exit ramp terminus at the cross street has such inadequate capacity that exit ramps queue onto the freeway, the ramp may be closed to encourage drivers to exit upstream or downstream where more capacity is available.

Systemwide Ramp Control

Although individual ramps may be metered or closed for specific reasons, ramp control is most effective when ramps are metered in an integrated system manner. Individual metering rates are determined by conditions over a larger portion of the freeway, not just in the immediate area of the ramp. Although local controllers may suffice in individual ramp metering as described above, system-wide control requires a central or distributed control system master with control algorithms and interconnection by some communications media.

RELATION TO OTHER FREEWAY MANAGEMENT FUNCTIONS

Ramp control is closely related to other infrastructure elements in a freeway management system. The widespread, widely embraced Intelligent Transportation Systems (ITS) movement has further emphasized the benefits of integrated system elements. Other modules in this handbook describe specific subsystems of a freeway management system. The following paragraphs briefly describe the relationship of those elements to freeway ramp control.

Surveillance

The surveillance subsystem includes various techniques for determination of freeway and ramp operating conditions that may have an influence on metering rates or operational overrides. Specific information on surveillance technology can be found in **Module 3** of this handbook. The paragraphs below provide a description of the types of surveillance used in conjunction with ramp control.

Vehicle Detection

Vehicle sensors located on the freeway can serve multiple purposes if located correctly during the design and construction phase. Detectors located in the freeway lanes generally have the purpose of input to incident detection algorithms and for system operation evaluation. Freeway detectors can also be used as input data in determining metering rates in traffic responsive operations. Counting detectors located on entrance and exit ramps serve as input and output data in defining a closed system operation for estimating average delay in the system.

Closed-Circuit Television

Closed-circuit television (CCTV) are used to detect and verify incidents in the overall surveillance subsystem. Cameras can also 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 entrance ramps has been used successfully in several locations on entrance ramps. These systems have primarily involved a separate lane to bypass the ramp signal, and single occupant vehicle queue.

Information Dissemination

Notification of travelers of ramp closures can be effected by either pre-trip information dissemination devices such as kiosks, Web site, and Community Access Television (CATV), or by on-road devices such as variable message signs or highway advisory radio. Other operational changes in ramp operations that may be of interest or assistance to travelers may also be communicated.

Communication

Unless the controlled ramps are isolated and operate in a nonsystem mode, the communication subsystem must accommodate for the control, detection, and signal hardware.

Control Center

While ramp control systems generally have the capability to operate in an isolated manner without supervision from a central or distributed master, most are interfaced to a central management system through the communication system.

BENEFITS OF RAMP CONTROL

Positive benefits of ramp control have been documented widely and can be found in the general literature.[1] Benefits have been most commonly reported in typical measurable traffic operations parameters such as reduced delay and travel time, increased throughput and operating speeds, and reduced accident experience. Other benefits less easily quantified may also accrue from ramp control. The case studies in the following section summarize some reported benefits of ramp control. The following paragraphs describe typical benefits, both quantifiable and less easily quantified.

Improved System Operation

Freeway traffic operating characteristics that can be expected to be influenced by ramp control systems are: speed, travel time, and delay. Typically, freeway operation has been described as a series of relationships between volume, speed, and density (or occupancy). The general objective of most freeway management systems is to optimize throughput while maintaining freeway operation in the non-congested area of the curve. By controlling the number of vehicles entering the freeway based on available downstream capacity to accommodate upstream freeway vehicles and entering ramp vehicles, freeway operation is enhanced. In another scenario, the objective may be to maintain some target level of service (as indicated by speed.) Again, by controlling the rate at which vehicles are metered onto the freeway, a target operating condition is maintained. Improvements on the freeway must be weighed against ramp delays and travel times which may be increased for travelers who choose to divert to other facilities.

Improved Safety

Freeway ramp control can effect decreased vehicle crash experience on both the ramp (and merging area) and on the freeway. By breaking up platoons of vehicles, which may enter the ramp from discharge at an adjacent intersection or traffic generator, the incidence of rear end 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.

Reduced Vehicle Operating Expense

Improved system operation has the direct and quantifiable result of reduced vehicle operating expense. Reductions in the number of stops and speed changes translate to related reductions in vehicle operating expense. The most significant savings are related to the reduction of vehicle crashes.

Means for Positive Freeway Traffic Control/Management

There are few opportunities to actively "control" freeway traffic on a routine basis. Obviously, police officers working freeway incidents control freeway traffic, but not on an everyday basis at the same location. Passive control, such as suggestions or advisories via pre-trip planning information sources or en route signing, may either be followed or ignored. Ramp control offers a means to regulate or control freeway bound vehicles.

Reduction in Vehicle Emissions and Fossil Fuel Consumption

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 as described previously 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.

Coordination With Other Corridor Management Elements

Intelligent Transportation Systems (ITS) defines certain core infrastructure elements known collectively as an intelligent transportation infrastructure. The importance of the interrelationship of the various subsystems applies to ramp control as a subsystem of Advanced Transportation Management Systems (ATMS) as well. Examples include the following:

- Ramp metering systems should be coordinated with surface street traffic signals to account for spill back of ramp queues.
- Information on ramp closures may be communicated by off-freeway information devices.
- High Occupancy Vehicle programs may involve special treatment of HOV at entrance ramps.
- Special ramp operating procedures may be instituted during incident conditions.

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.

MODULE OBJECTIVE

The objective of this ramp control module is to provide insights into and guidelines on the issues associated with planning, designing, constructing, operating, and maintaining a ramp control subsystem in a freeway management system. This module also gives guidance to planners, designers, managers, and operators in public relations aspects of freeway ramp control.

MODULE SCOPE

The scope of this ramp control module is intended to include general guidelines as well as serving as a guide to references and other documentation that may be of benefit to planners, designers, and operators of freeway management systems. 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.

5.2 DECISION PROCESS

Freeway ramp control is one of the few direct means of controlling access to the freeway main lanes. Indirect control would include such methods as encouraging diversion to other facilities, or mode changes through communications with travelers prior to their trips or en route. However, direct limiting of access through ramp control can be effective and accepted by the driver only if it is applied in those circumstances where traffic characteristics, demand patterns, and infrastructure are conducive to the technique.

PROBLEM IDENTIFICATION

Traffic engineers and other professionals will no doubt have an intuitive feel for where freeway operational deficiencies exist in a congested freeway environment. However, in order to address potential solutions to alleviate such problems, it will be necessary to quantify deficiencies in both time and space, i.e. during what portions of the day, and at which locations within the freeway system, are such deficiencies present. It is important to document the freeway operations from a traffic characteristics and infrastructure aspect in order to identify and define the problem as well as to provide a basis for measurement of effectiveness and to monitor for future changes. Several techniques may be used to illustrate a systemwide picture of freeway traffic characteristics, design features, capacity deficiencies, vehicle crash experience, and other features of interest, including the following:

- Schematic maps, color coded or otherwise delineated to show various levels of operation, other traffic characteristics, and crash experience at various periods of the day.
- Schematic maps, color coded or otherwise delineated to show various infrastructure characteristics.
- Spreadsheet or other tabular format.
- Descriptive write-up.
- A combination of the above items.

Level of Service / Capacity Deficiency / Bottlenecks

The *Highway Capacity Manual* provides definitive guidance in determining qualitative and quantitative pictures of freeway operations. Capacity deficiencies, or freeway bottlenecks, will be a function of traffic demand and characteristics as well as the geometrics and other design features of the roadway itself. It will be necessary to pinpoint where such deficiencies exist, and the contributing factors. Subsequent sections of this module provide a detailed listing of data required for analysis of capacity and level of service in relation to ramp control, as well as other analyses. **Module 2** provides more guidelines for capacity and level of service analyses.

Capacity and Level of Service (LOS) should be determined for existing traffic characteristics and infrastructure as well as those parameters for future conditions in some horizon or build-out year. Planned additions to the freeway section under consideration, or to alternative routes or modes, may either obviate the need for ramp control or influence its implementation schedule.

Vehicle Crash Experience

The occurrence of vehicle crashes on freeways may be attributed to a variety of factors, some of which may not be correctable by ramp control techniques. Those types of accidents most likely to be alleviated by ramp control include:

- Rearend crashes on freeway main lanes due to over-capacity operation (bottleneck conditions).
- Lane change crashes on freeway lanes due to over-capacity merging conditions.

- Lane change crashes on freeway lanes due to inadequate sight distance or to other geometric deficiencies in the merge area.

- Run-off-the-road crashes caused by drivers avoiding shock waves.

- Rearend crashes on the entrance ramp due to queuing in the merge area.

Crash records may be summarized by section of freeway, location, time of day, and type of crash to determine if ramp control has the potential to reduce collision experience.

Inventory of Infrastructure

Except in the case of an isolated, single entrance ramp location, a ramp control system is generally a subsystem of a comprehensive freeway management system. Much of the infrastructure data required for problem identification will likely be available. The following types of data should be assembled for the freeway system under consideration.

Freeway System

- **Lane Configuration.** Number and types of freeway lanes (through, weaving, acceleration, deceleration) should be determined and tabulated and/or graphically displayed.

- **Ramp Locations.** Entrance and exit ramps should be located, with link distances between ramps determined.

- **Geometrics.** Typical geometrics such as freeway lane and entrance ramp width, vertical and horizontal alignment, ramp length, ramp storage capacity, merging area, and sight distance restrictions should be determined and tabulated. Type of ramp design (loop, linear) should be noted.

- **Frontage Roads.** Presence of frontage roads and their lane configurations should be determined and tabulated.

- **Interface to Crossing Freeways.** Freeways will generally be interfaced or connected via a freeway interchange. The proximity of another freeway's connections to the entrance ramps being considered for ramp control should be noted to determine if any special measures are needed.

- **Interface to Crossing Arterials.** The relationship of entrance ramp metering to an upstream cross street is critical. If not properly considered, queuing from the ramp signal into the cross street can cause concerns to the agency responsible for arterial street operation, as well as public resentment. Type of crossing roadway, traffic control, mix of traffic, ramp storage area, and other factors should be noted for each ramp.

Existing Freeway Management Systems

Normally there will be only one agency responsible for freeway operations in a particular geographic area, but there are some situations where more than one agency may be involved. For example, a dense metropolitan area may extend into two States or a tollway operated by a toll authority may interface to a state-operated freeway. As part of the inventory, the existence of such systems should be confirmed and documented to include the following:

- Participating agencies.

- Type and location of control center facility.

- Type of control system (central, distributed, hybrid, local).
- Surveillance and detection.
- Information dissemination (pre-trip, en route).
- Communication system (medium, leased, or owned).

Existing Ramp Control Systems

In lieu of a full blown freeway management system, some entrance ramps may be metered in an isolated manner with a local, non-system controller. Inventory should include the following:

- Responsible agency.
- Type of controller.
- Surveillance and detection.
- Communication system.

Other Relevant Field Systems

Other relevant field operational systems that may have an effect on freeway operation should also be identified. Such systems would include the following:

- High occupancy vehicle lanes or ramps.
- Incident management teams.
- Accident investigation sites.
- Courtesy and motorist assistance patrols.
- Hazardous material routing and restrictions.

Inventory of Traffic Characteristics

Certain traffic and flow characteristics will influence the potential success and the design of freeway ramp control systems. Typical traffic characteristics are listed below. **Module 2** provides a more detailed description of individual traffic parameters.

Traffic Composition

The composition of the traffic stream on the freeway main lanes and the entrance ramp will influence both the type of control and the design of the system. A determination of the percentage of passenger vehicles, commercial vehicles, and transit vehicles should be made for peak periods.

Traffic Flow

Traffic volumes and traffic flow rates during peak periods will be required for capacity and level of service determinations to define the operating conditions and problem locations that might be addressed by ramp control techniques. Traffic flow data will also be used in determining metering rates and periods of operations. Traffic flow data requirements will include the following:

- Traffic volumes and flow rates, generally by 15-minute periods, on freeway lanes and entrance and exit ramps.
- Distribution of freeway vehicles by lane.
- Traffic volumes and flow rates on adjacent service roads.
- Traffic volumes and flow rates on cross streets served by the freeway ramps.

Other Traffic Parameters

Other typical traffic parameters that may be of value either in defining operating conditions and problem locations or in developing control strategies include the following:

- **Lane Occupancy.** Defined as the percentage of time a particular sampling "spot" on the freeway is occupied, this parameter may not be economically measured until such time as a surveillance system is in place**.** Its primary use is in selecting metering rates, although it can identify operational problems if reasonably available. It may be derived from speed and volume data, which may be more readily available prior to system implementation. The reader is referred to **Module 2**, or the *Highway Capacity Manual*, for a discussion of the relationship of lane occupancy to freeway level of service.[2]

- **Traffic Density.** Defined as the number of vehicles per lane per mile, traffic density may be determined with aerial photos or by freeway input/output counts. The reader is referred to **Module 2** or the *Highway Capacity Manual* for a discussion of the relation of traffic density to freeway level of service (LOS).[2]

- **Speed.** Vehicle speeds are another indicator of freeway LOS and may be determined by traditional speed measurement techniques prior to system installation.

- **Vehicle Occupancy.** As opposed to *lane* occupancy, *vehicle* occupancy is generally defined as passengers per vehicle and is usually determined by manual observation. This parameter may be useful in determining the viability of preferential treatment of high occupancy vehicles (HOV) at entrance ramps.

Temporal Variations

As previously mentioned, it is important that traffic operations characteristics be collected and analyzed in incremental time periods so that ramp control operation schedules can be developed optimally. Even though the system may be traffic responsive, it may be advantageous to operate either on a predictable schedule or with limited variations in schedule. Plotting various parameters by time period in 15-minute increments will help predefine those operational periods. Although ramp control is usually associated with peak periods, plotting data over a longer period may indicate other times when ramp metering may be appropriate.

Ramp Geometric Limitations

Inventory of infrastructure elements and field observations will provide information to evaluate the physical viability of individual ramps to support ramp metering. The following physical factors should be considered:

- **Ramp Storage.** How many vehicles can reasonably be stored or queued on the ramp upstream of the metering signal without interfering with cross street traffic?

- **Ramp Width.** Is there adequate width for side-by-side metering and/or preferential HOV bypass lanes?

- **Grade**. Are ramp grades restrictive during adverse weather or for certain types of heavy vehicles?

- **Merge Area.** Does the present design facilitate a smooth merge?

Cross Streets

Limited vehicle storage for queuing at ramp signals may adversely affect operation of an upstream cross street. Presence of such conditions should be noted so that they can be considered during design of control strategies.

Service Roads

As with cross streets, limited vehicle storage for queuing at ramp signals may adversely affect operation. The type of cross street (major arterial, collector, etc.), traffic demand, presence of signals, and their operation must be considered.

Summary of Problem Definition

Traffic characteristics and demand, as well as geometric factors, are important in evaluating existing and future conditions and the potential applicability of freeway ramp control. While not all data items listed above may be available to the designers and planners, it is important to collect and assemble as much relevant data as feasible for the analysis. Many of the data items noted above may also be used during the design of the system and development of the control strategies and software.

IDENTIFICATION OF PARTNERS AND CONSENSUS BUILDING

Freeway ramp control is the primary method of managing demand once drivers have committed to use the freeway for their trip. It has been proven to be an effective means of balancing capacity and demand and reducing delay and vehicle crashes. It can also be one of the most controversial traffic control techniques. Delay at ramp signals or closing of a ramp may be considered too drastic by some drivers, and even an infringement on their rights**.** Such delays will be offset by overall system improvement, but this is not always apparent to the driver. Without ramp control, drivers may experience even more delay on the freeway than they would have experienced at the signal. Again, this may not be readily discernable to the driver.

In most instances, a State Transportation Department or Toll Authority will have the responsibility for operation, but not necessarily enforcement, of a ramp control system. It is important for the agency responsible for operation of the ramp control system to identify and establish relationships and communications with all agencies that may have a role in operation and enforcement so that they may be brought into the planning and design process. It is also important that the benefits of ramp control, which are realistic and measurable, be fully explained and that it not be oversold as adding capacity (such as adding a lane). It should be characterized as a means to make maximum use of available capacity by managing capacity and demand.

Relation to Other Agencies

City/County Traffic Operations Agencies

Because of the close relationship and interface between surface street traffic operation and signalization and access to and from freeway ramps, it is important to involve those agencies and build a consensus for the system at all levels, from the agency head to the operations engineers to the control system operators. To the extent possible, system goals and objectives should be developed mutually.

Enforcement Agencies

Depending on State and local ordinances or interagency agreements, State, local, or transit police may be responsible for enforcement of ramp control devices. Compliance with ramp control signals is essential if the system is to operate efficiently. Enforcement agencies must be brought into the process early and must understand the goals and objectives of the system and the operating philosophies. The signals must be enforced, but over-enforcement can have a detrimental effect on driver attitude and, in fact, cause deterioration of operation as drivers are stopped on the freeway shoulder. Compliance with the signals must be established early and monitored to ensure that an acceptable level is maintained. A program of public information and police support is essential.

Emergency Management Agencies

Fire, police, medical, hazardous materials, motorist assistance patrols, and other agencies responsible for emergency management on the freeway system should be aware of the proposed system and be fully informed as to its operation and benefits. Any special support required of the particular agency should be solicited.

Public Transportation Agencies

Public transit agencies that access freeways via metered ramps**,** or that exit on ramps which may be closed during certain periods of the day, should be also be brought into the planning and design process at an early stage. This is particularly important where preferential treatment of high-occupancy vehicles such as buses is being considered.

Relationship to Elected Official / 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. As stated above, 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.

Importance of Enforcement / Judicial System

The importance of enforcement of ramp control has been previously stated. Accordingly, 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.[3] However, because ramp control systems are not as familiar as intersection signals, certain judges may be inclined to dismiss related citations. 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.

Relationship With 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. Methods for disseminating information about ramp control system include brochures, town meetings, and handouts.

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). It should be characterized as a means to make maximum use of available capacity by managing capacity and demand.

ESTABLISHING GOALS AND OBJECTIVES

Module 2 describes the process of establishing system goals and objectives. Goals and objectives of the ramp control system should complement and not conflict with overall system goals. In the rare case of stand-alone ramp control system, the goals and objectives may differ from those in an integrated system.

Typical overall system goals and objectives and how they may be supported by a ramp control system are listed below.

- **Reduced Accident Experience.** Maintaining smoother freeway flow by metering and improving merge conditions on the ramp.
- **Maintaining Acceptable Freeway Level of Service.** Metering on entrance ramps to maximize freeway flow rates within acceptable ranges.
- **Balancing Demand/Capacity in Freeway Corridor.** Metering on entrance ramps to encourage drivers to shift to other ramps or facilities with available capacity, or to change trip time.
- **Reduction of Single-Occupancy Vehicles.** Preferential treatment of car pools on entrance ramps.
- **Reduced Vehicle Delay.** Metering on entrance ramps to limit freeway flow rates within acceptable ranges.
- **Incident Management**. Closing ramps upstream of a freeway incident and increasing metering rates downstream.
- **Promotion of Multimodal Operation.** Preferential treatment of buses on entrance ramps.
- **Reduced Noise.** Smoother Traffic Flow Reduces Engine Revving.
- **Reduced Vehicle Operating Costs.** A result of smoother traffic flow and reduced stops.
- **Reduced Fuel Consumption**. A result of smoother traffic flow and reduced stops.
- **Reduced Vehicle Emissions.** A result of smoother traffic flow and reduced stops.

ESTABLISH PERFORMANCE CRITERIA / MEASURES OF EFFECTIVENESS

Performance criteria express broad goals in tangible or measurable terms. Better operation is obviously a goal to be strived for, but is difficult to measure and may have different meanings for different people. With the exception of the first goal (balancing capacity and demand), the goals and objectives listed above are tangible and measurable in readily understandable terms both before and after system turn-on. Level of service can be calculated, vehicle crash rates can be tabulated from law enforcement data bases, speed and delay studies can determine operating conditions that can be used to calculate delay, fuel consumption, and vehicle emissions. Transit records are available to establish changes in bus patronage, and field studies can measure vehicle occupancy.

DEFINE FUNCTIONAL REQUIREMENTS

Functional requirements for the ramp control subsystem are fairly straightforward and are summarized below:

- **Displays.** Signals on the ramp for vehicle drivers and advance warning signs.
- **Local Controller.** Device to receive and store vehicle detector information and operate signals according to internal logic or according to a central supervisory system.
- **Vehicle Detectors.** Devices to measure conditions on the freeway and ramp.
- **Control Logic.** Programs residing in the local controller for non-system operation, or at a central system processor for system operation.
- **Communications.** Leased or owned communication link between field location and central management site for data and control command transmission.
- **Central Control System.** Computer, peripherals, and operator interface devices.

DEFINE FUNCTIONAL RELATIONSHIPS, DATA REQUIREMENTS, AND INFORMATION FLOWS

The June 1996 ITS Architecture Executive Summary states (italics indicate adaptation to ramp control systems):

> The National ITS Architecture provides a common structure for the design of intelligent transportation systems. It is not a system design concept. What it does is define the framework around which multiple design approaches may be developed, each one meeting the needs of the user, while maintaining the benefits of a common architecture. The architecture design defines functions (*e.g., collect data from freeway and ramp detectors; and operate and monitor ramp meter signals*) that must be performed to implement a given user service, the physical entities or subsystems where these functions reside (*e.g., detectors on the freeway and ramp, signals on ramps, and local controller near the ramp*), the interfaces/information flows between the physical subsystems and the communication requirements for the information flows (*e.g., signal wirelines from the detector to the local controller and from the controller to the ramp signal; two-way wideband communication between the field controller and the central management site.)* In addition, it identifies and specifies the requirements for the standards needed to support national and regional interoperability.

In all likelihood, the functional relationships, data requirements, and information flows for a ramp control system will be dictated by the design of the broader freeway management system. However, in the case of an isolated ramp control system, the architecture will be more in the realm of typical signal design at an arterial street intersection. In any event, an open architecture (one that can be interfaced with in the future) should be employed.

5.3 TECHNIQUES AND TECHNOLOGIES

The great majority of improvements and innovations in freeway traffic management have been in the area of computing and communications technology capability. Computers are faster, have more memory and storage capability, and are more user friendly, and virtually every person involved in freeway management has ready access to a personnel computer. Development of improved communications technology has paralleled development of the more capable computers. Broad band fiber optic cable, which accommodates both high speed digital data and video, has become the standard in most freeway management systems, rather than twisted-pair and coaxial cable for hub-to-hub transmission. Wireless technology (such as cellular, microwave, packet radio, and other media) has provided a means for quick implementation until the more capital intensive construction of fiber can be funded. Many systems operate with a hybrid communication system that combines multiple media including leased telephone lines and fiber cable. The freeway management techniques and strategies documented in the 1983 *Freeway Management Handbook* were much the same as those documented in the 1985 *Traffic Control Systems Handbook,* although newer technologies were described.[5,6]

The 1996 *Traffic Control Systems Handbook* documented further developments in computing and communications hardware which had application in freeway management.[7] Other modules of this handbook specifically address hardware and software that have application in the freeway management arena.

The basic freeway ramp control techniques have not changed appreciably. Field displays and control strategies such as pretimed metering, traffic responsive metering, and system metering algorithms are still valid but with the increased computing and data transmission techniques, those algorithms can operate faster and virtually in real-time leading to more efficient control and evaluation. The techniques described below have been drawn from previous handbooks and updated as necessary to reflect changing techniques.

ENTRANCE RAMP CONTROL

Ramp Closure

Entrance ramp closure is a seldom-used technique except on a short term basis, and is included here for information purposes, and should not be considered comparable to other ramp control techniques. The closure of an entrance ramp during peak traffic conditions is the simplest and most positive form of entrance ramp control. It is also the most restrictive. Therefore, it is usually the least popular and it is also subject to considerable public opposition. However, it has been used successfully as part of a system in a number of cities in the United States and Japan (e.g., Houston, Los Angeles, San Antonio, and Fort Worth, and Osaka and Tokyo, Japan). Closure has also been effectively used in single spot improvements at entrance ramp applications, such as on freeways in Beaumont and Corpus Christi.[6] Closure may be the appropriate measure where an entrance ramp introduces serious weaving problems. Although this type of entrance ramp control can provide the same operational benefits to freeway traffic as the other types, it lacks flexibility. Consequently, if applied inappropriately, it can result in underutilizing freeway capacity, with the consequent overloading of alternate routes.

Application

Because of its limitations, entrance ramp closure should not be considered except under the following circumstances:

- Adequate storage is not available at the entrance ramp to prevent queues of vehicles waiting to enter the freeway from interfering with surface street traffic. The closure of the entrance ramp would eliminate the storage problem.

- Traffic demand on the freeway immediately upstream of the entrance ramp is at capacity, and an alternate route with adequate capacity is available. The closure of the entrance ramp would prevent demand from exceeding capacity on the freeway section immediately downstream from it, and it would divert the traffic demand at the ramp to an alternate route. Even if the upstream traffic demand is less than downstream capacity, the rate at which traffic could be allowed to enter the freeway might be so low that it would not be possible to control the entrance of ramp traffic without a large number of violations. In this case, it would be more practical to close the ramp in order to prevent congestion on the freeway.

With regard to the second circumstance, it should be noted that the required demand-capacity relationship could occur because of nonrecurrent congestion as well as because of recurrent conditions. Therefore, closure might be used as a response to incidents on the freeway, as is done in Japan.[8,9]

Ramps may be closed on a temporary basis, on a scheduled basis, or permanently.

- **Temporary Closures.** Entrance ramps may be closed temporarily in response to maintenance or construction activities either on the freeway or the adjacent frontage road or surface street. It is not uncommon for a ramp to be closed by police during management of a downstream incident.

- **Variable Schedule.** Because of extreme recurring downstream capacity deficiencies, ramps may be closed during certain peak periods and open at off-peak times.

- **Permanent Closure.** A ramp may be closed on a permanent basis due to changes in the freeway systems or demand patterns. Concrete barriers or other physical constraints are recommended.

Methods

Methods of entrance ramp closure that have been used in current systems include the following:

- Manually placed barriers such as cross bucks, barrels, or cones.

- Automated barriers such as those used at railroad crossings.

- Signing.

Experience in Detroit and Los Angeles has indicated that signs alone cannot effect a positive entrance ramp closure.[10,11] Automated barriers enable an entrance to be closed and opened automatically, which tends to increase the flexibility of closure as a means of control. Since manual placement of barriers is labor intensive, this approach is best suited for short-term or trial control projects.

Ramp Metering

Metering is a method of regulating traffic flow. When applied as a form of entrance ramp control, metering is used to limit the rate at which traffic can enter a freeway. Maximum practical single lane rate is generally at 900 vph, with practical minimum of 240 vph. When the metering rate is not directly influenced by mainline traffic conditions, the control is referred to as "pretimed metering." This does not, however, necessarily imply the absence of vehicle detectors.

Metering Rates

The calculation of metering rates depends on the purpose for which the metering is being used. Normally, metering is used either to eliminate congestion on the freeway or to improve the safety of the merging operation as follows:

Congestion. If the metering system is intended to eliminate or reduce congestion, demand must be kept at less than capacity. Therefore, the calculation of the metering rate at a ramp would be based on the relationship between upstream demand, downstream capacity, and the volume of traffic desiring to enter the freeway at the ramp. Downstream capacity may be determined by the merging capacity at the ramp or by the capacity of the freeway section downstream. Of course, if the sum of upstream demand and ramp demand is less than or equal to downstream capacity, metering is not needed to prevent congestion. On the other hand, if the upstream freeway demand alone is greater than downstream capacity, metering at the ramp would not eliminate congestion. Otherwise, the desired metering rate is set equal to the difference between upstream demand and downstream capacity (assuming upstream demand is less than downstream capacity and the metering rate does not create excessive queuing).

For example, in the situation shown in figure 5-2, the upstream demand is 5,100 vph, the downstream capacity is 5,400 vph, and the ramp demand is 500 vph. Since the total demand (5,600 vph) is greater than the downstream capacity, ramp metering might be a feasible solution. Therefore, if a metering rate equal to the difference between upstream demand and downstream capacity (300 vph) were used, the freeway would be able to accommodate the upstream demand and maintain uncongested flow while also handling 300 vph of the ramp demand.

However, the ultimate test of the feasibility of ramp metering at a rate of 300 vph would involve consideration of the following questions:

- Is adequate additional capacity available in the corridor for the 200 vph that are likely to be diverted? And, if so, is it likely that the 200 vph would utilize that extra corridor capacity? If not, capacity would have to be added to the corridor and/or made more attractive for this number of vehicles per hour to be diverted. Otherwise, ramp metering would solve only the problem on the freeway.

- Is adequate storage available at the ramp to accommodate the queue of vehicles that would have to wait at the ramp before entering the freeway? If adequate storage could not be provided at the ramp, alternatives to be considered would be closure of the ramp, or metering at other ramps upstream to reduce upstream demand, which would in turn permit a higher metering rate and require less storage at the ramp.

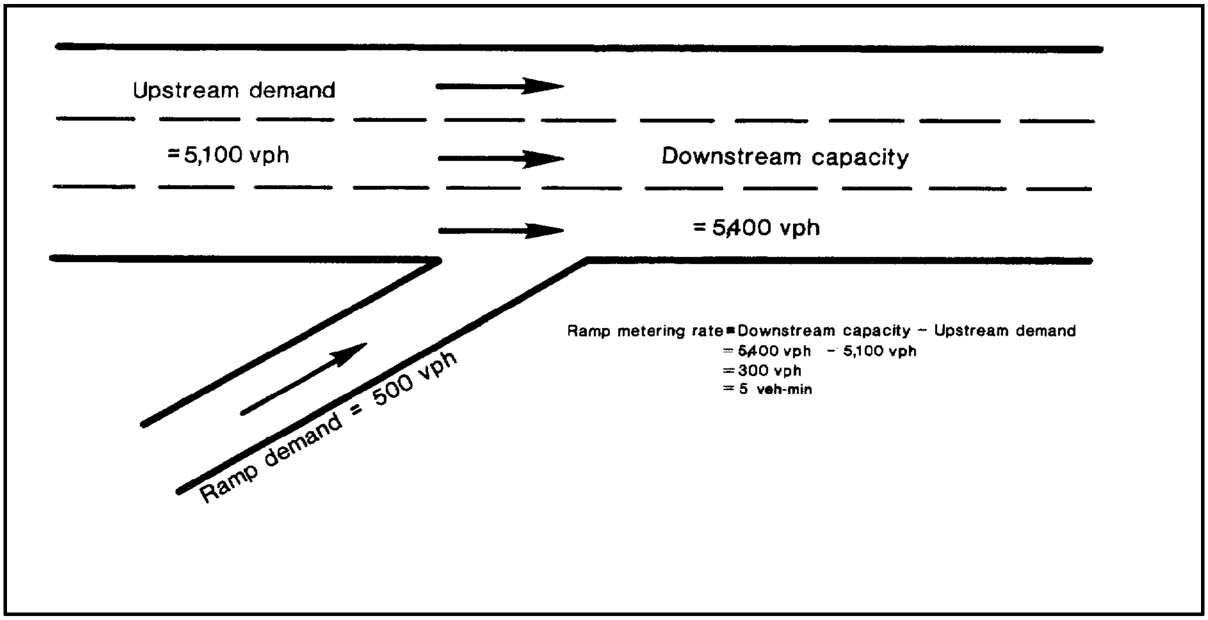


Figure 5-2. Example of Pretimed Entrance Ramp Metering Rate Calculation.

- Is the specified metering rate (300 vph) too restrictive? If so, consideration should be given to closing or metering other ramps upstream to reduce upstream demand, which would permit a higher metering rate at the ramp. However, metering other ramps upstream might lead to the underutilization of the freeway.

Signal Timing. Given that a metering rate has been set, specific signal timing parameters must be determined. (See figure 5-3 for general detector positioning.)

- **Signal Cycle.** Cycle is the inverse of the metering rate or forced headway between released vehicles. For example, a 10-second metering rate results in a 6-second cycle or headway between released vehicles.

- **Minimum Green.** The green interval is just long enough to allow one vehicle to cross the stop line at the signal, usually 0.5 to 1.3 seconds. Some systems use the checkout detector (a pulse detector) to signal the controller to terminate green.

- **Clearance Interval.** If a yellow clearance interval is used, it is typically 0.7 to 1.0 seconds, making the total green plus yellow 1.2 to 2.3 seconds. If no yellow clearance is used, the 1.0 second clearance is added to the minimum green to ensure safe clearance.

- **Red Interval.** The red interval is, then, the difference between the total cycle length and the green plus yellow or the green only interval.

- **Queue Detector.** If the queue defector (a presence loop) is occupied more than some maximum length of time (say 2.0 seconds) indicating an excessive queue, the controller may increase the metering rate in order to reduce or clear the queue.

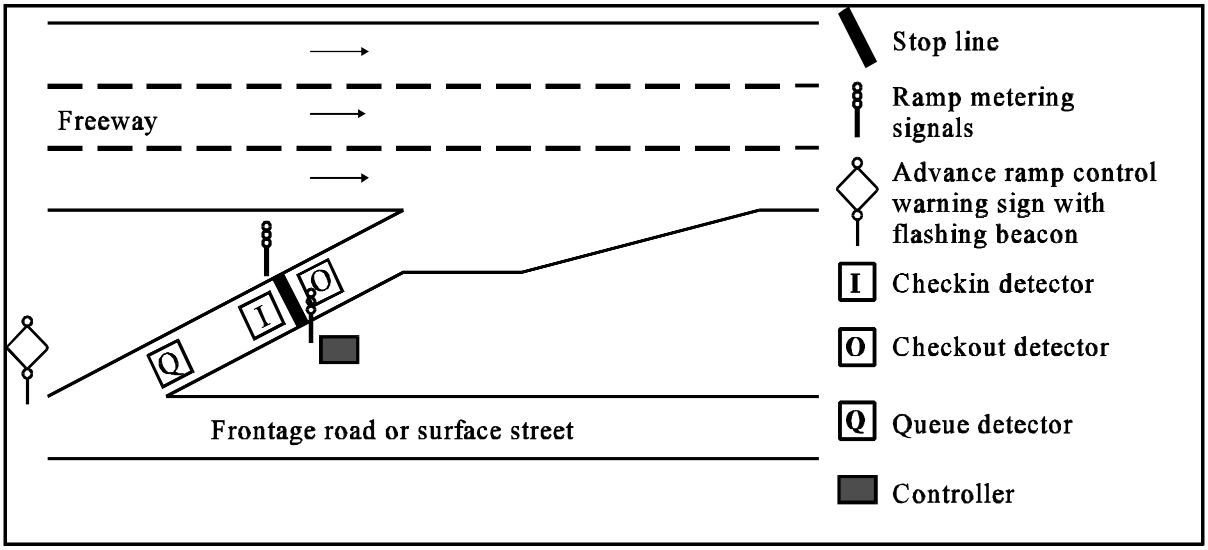


Figure 5-3. Pretimed Ramp Metering Layout.

- **Merge Detector.** If the merge detector (a presence loop) is occupied more than some maximum length of time (say 3.0 seconds), indicating the merging area is blocked, the controller may hold the ramp signal in red to avoid stacking on the ramp.

The settings given above are typical but should be fine tuned in the field to account for unique geometrics, grades, driver characteristics, vehicle mix, and other factors.

Safety. If metering is to be used primarily as a means of improving the safety of the merging operation, then the metering rate is simply set at a maximum consistent with merging conditions at the particular ramp. The primary safety problem of the merging operation is incidence of rearend and lane-change collisions caused by platoons of vehicles on the ramp competing for gaps in the freeway traffic stream. Therefore, metering is used to break up these platoons and to enforce single-vehicle entry. For this to happen, the metering rate selected must ensure that each vehicle has time to merge before the following vehicle approaches the merge area. The time it takes a vehicle to merge depends on the following factors:

- Distance the vehicle is stopped from the freeway.
- Geometrics of the ramp (grade, sight distance, and length of the acceleration lane).
- Type of vehicle.
- Availability of acceptable gaps in the freeway traffic stream.

If the average time to merge is 6 seconds, the metering rate will be 600 vph or 10 vpm.

Pretimed Metering

Pretimed metering refers to a fixed metering rate that is not influenced by current mainline traffic conditions. The rate will normally be set on the basis of historical data. However, pretimed metering does not necessarily imply the absence of detectors.

System Components

Pretimed metering is the simplest form of entrance ramp metering. Typical components are shown in figure 5-3 and are described below.

- **Ramp metering signal.** Usually a standard 3-section (red-yellow-green), or 2-section (red-green) signal display that controls the ramp traffic.

- **Local controller.** Frequently a standard pretimed or Type 170 controller with capability to vary metering rates by time of day or to accept detector inputs. However, national cooperative efforts among industry, operating agencies, and FHWA have developed a design for an open architecture protocol for local controller. This controller, more properly termed a "field processor,"acts as a communication processor with extended capability for other freeway management functions such as control of variable message signs, detector processing, and closed-circuit television cameras.

- **Advance ramp control warning sign with flashing beacon.** A sign which indicates to traffic approaching the ramp that it is being metered. In California, a blank-out type "METER ON" sign is used at many installations in lieu of the flashing beacon.

- **Vehicle Detectors.** There are four types of detectors that are generally used with this type of ramp metering strategy:

  - Check in (demand) detectors.

  - Checkout (passage) detectors.

  - Queue detectors.

  - Merge detectors.

In some applications of pretimed metering a check-in detector is placed on the approach to the ramp metering signal so that the signal will remain red until a vehicle is detected at the stop line, as shown in figure 5-3.[12] When a vehicle is detected by the check-in detector, the ramp metering signal will change to green, provided the minimum red time has elapsed. With this type of operation, it is desirable to have a minimum metering rate (e.g., 3 vpm) at which the signal is set in case there is no detector actuation, because of possible detector failure or because of vehicles stopping too far back from the stop line to actuate the detector. In some cases, two detectors are used to provide redundancy to reduce the impact of detector failures.

In some systems, a checkout detector has been used to ensure single-vehicle entry. 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 checkout detector. In this way, the length of the green interval is made sufficient for the passage of only one vehicle.

In some pretimed metering systems, a queue detector is used to detect backing of ramp traffic into frontage roads or surface streets. The queue detector is placed at a strategic point on the ramp, or on the frontage road, in advance of the ramp metering signal. When a queue is sensed by a vehicle occupying the loop for a selectable period of time, indicating that the queue of vehicles waiting at the ramp metering signal is sufficient to interfere with traffic on the frontage road or surface streets, a higher metering rate may used to shorten the queue length. This can be self-defeating, however, since shorter queues often attract higher demands.

A merge detector is a device that senses the presence of vehicles in the primary merging area of the ramp and freeway mainlanes. 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.

Placement of these auxiliary detectors is discussed in more detail in the subsequent section on traffic responsive metering. Figure 5-4 shows ramp metering signals and advance warning signs that have been used. Also, for a discussion of standards for various system components, refer to the recommended practice for freeway entrance ramp displays prepared by the Institute of Transportation Engineers (ITE).[13]

System Operation

In the operation of a pretimed metering system, the ramp signal operates with a constant cycle in accordance with a metering rate prescribed for the particular control period. However, timing the red, yellow, and green intervals of the cycle (many systems use ramp signals that have only red and green intervals) depends on whether the type of metering used is single-entry metering or platoon metering.

Single-entry metering. In the case of single-entry metering, the ramp metering signal is timed to permit only one vehicle to enter the freeway per green interval. Therefore, the green-plus-yellow (or just green if yellow is not used) interval is just long enough (usually about 1.5 to 2 seconds) to allow one vehicle to proceed past the signal. The red interval varies with the number of vehicles being metered. For instance, if a metering rate of 600 vph or 10 vpm were to be used, and the green-plus-yellow interval were 2 seconds, a red interval of 4 seconds would be used. If the metering rate were 300 vph, or 5 vpm, and the green-plus-yellow interval were 2 seconds, a red interval of 10 seconds would be used.

Platoon metering. When metering rates greater than 900 vph are required, platoon metering, which permits the release of 2 or more vehicles per cycle, may be used to achieve such high metering rates. For pretimed platoon metering, the cycle length is determined on the basis of the desired metering rate and the average number of vehicles to be released per cycle. For example, in the case of a metering rate of 1,080 vph, or 18 vpm, and a release of 2 vehicles per cycle, 9 cycles per minute would be required. Therefore, the cycle length would be 6.67 seconds. Similarly, if a release of 3 vpc were used instead, the cycle length would be 10 seconds. However, the timing of the cycle intervals (i.e., green, yellow, red) would depend on the form of platoon metering used, tandem or 2-abreast.

Tandem Metering. In the case of tandem metering, the vehicles are released one after another. Therefore, the green-plus yellow time is made long enough to permit the clearance of the desired number of vehicles per cycle. A yellow interval should be used to minimize the rearend collision potential. Thus, for the 7-second cycle with 2-vehicle platoons, a 4-second green-plus-yellow and a 3-second red might be used. And for a 12-second cycle with 3-vehicle platoons, a 9-second green-plus-yellow and a 3-second red might be used. Experience indicates that 2-vehicle platoons can be handled satisfactorily and that 3-vehicle platoons are a practical maximum. In either case, a

Figure 5-4. Typical Field Displays for Ramp Meter Installations.

maximum metering rate of 1,100 vph can be expected.[14]

Two-abreast Metering. With two-abreast metering, two vehicles are released side by side per cycle. This form of metering requires two parallel lanes on the entrance ramp plus a sufficient distance beyond the ramp metering signal for the two 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 in that the green-plus-yellow interval is just long enough (usually about 3 seconds) to allow one vehicle in each lane to proceed past the ramp metering signal. The remainder of the cycle is red. With alternate release metering, maximum metering rates of about 1,700 vph may be achieved.

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, and platoon metering should not be used unless it is necessary to achieve higher metering rates. However, platoon metering has been successfully used in several locations and drivers can adapt with proper design and pre-operation publicity.

It has been shown that entrance ramp control can be extremely cost effective.[1] Experience has indicated that the biggest net gain in benefits is realized in going from no control to pretimed metering. Pretimed metering offers both advantages and disadvantages. The most important advantages are that it gives the driver a dependable situation to which he can readily adjust, and that it tends to be associated with lower costs. The major disadvantage is that the system can neither respond automatically to significant changes in demand, nor adjust to unusual traffic conditions resulting from incidents. Because of this inability to automatically respond to changes in traffic conditions and the relative difficulty of dissipating resultant congestion, pretimed metering rates have usually been set so that operation will be at volumes slightly below capacity at the desired LOS.

Traffic-Responsive Metering

In contrast to pretimed metering control, traffic-responsive metering is directly influenced by the mainline and ramp traffic conditions during the metering period. Metering rates are selected on the basis of real-time measurements of traffic variables indicating the current relation between upstream demand and downstream capacity.

Fundamental Traffic Flow Relationships

In order to determine or predict demand-capacity conditions on the basis of real-time measurements of traffic variables, a description or model of traffic is necessary. Most frequently used as indicators of operating conditions for traffic-responsive metering are functional relationships between flow rate, q; space-mean speed, u; and density, k.[15]

A generalized relationship between each of the variables is depicted in figure 5-5 and can be summarized as follows:

- At zero density, or when no vehicles are on the roadway, the flow rate is zero. and traffic is permitted to travel at its free speed, u_f.

- As density increases to a value, k_m, the flow rate increases to a maximum value, q_m, which is the capacity of the roadway, and speed decreases to a value, u_m.

- As density increases from a value, k_m, to a maximum value, k_j (jam density), the flow rate decreases to zero because the roadway is blocked with too many vehicles for traffic to move.

The values of q_m, u_f, u_m, k_m, and k_j—and the shapes of the curves—depend on several factors including geometrics of the roadway, composition of traffic, and weather conditions. Therefore, these values may be different for different sections of the roadway, and each section may have more than one set of these values. Although these are theoretical relationships based on the assumption of uniform traffic flow, the trends expressed by these relationships do exist.[16]

Basic Strategy

As explained earlier, congestion occurs whenever demand exceeds capacity. Therefore, as indicated in figure 5-5, the values of q_m, u_m, and k_m define boundaries between congested flow and uncongested flow. The purpose of metering is to prevent or reduce congestion, or in other words, to keep the values of the fundamental traffic flow variables at levels that define points on the uncongested-flow portions of the traffic flow curves. Thus, the basic strategy of traffic responsive metering is as follows:

- Obtain real-time measurements of traffic variables on the freeway.

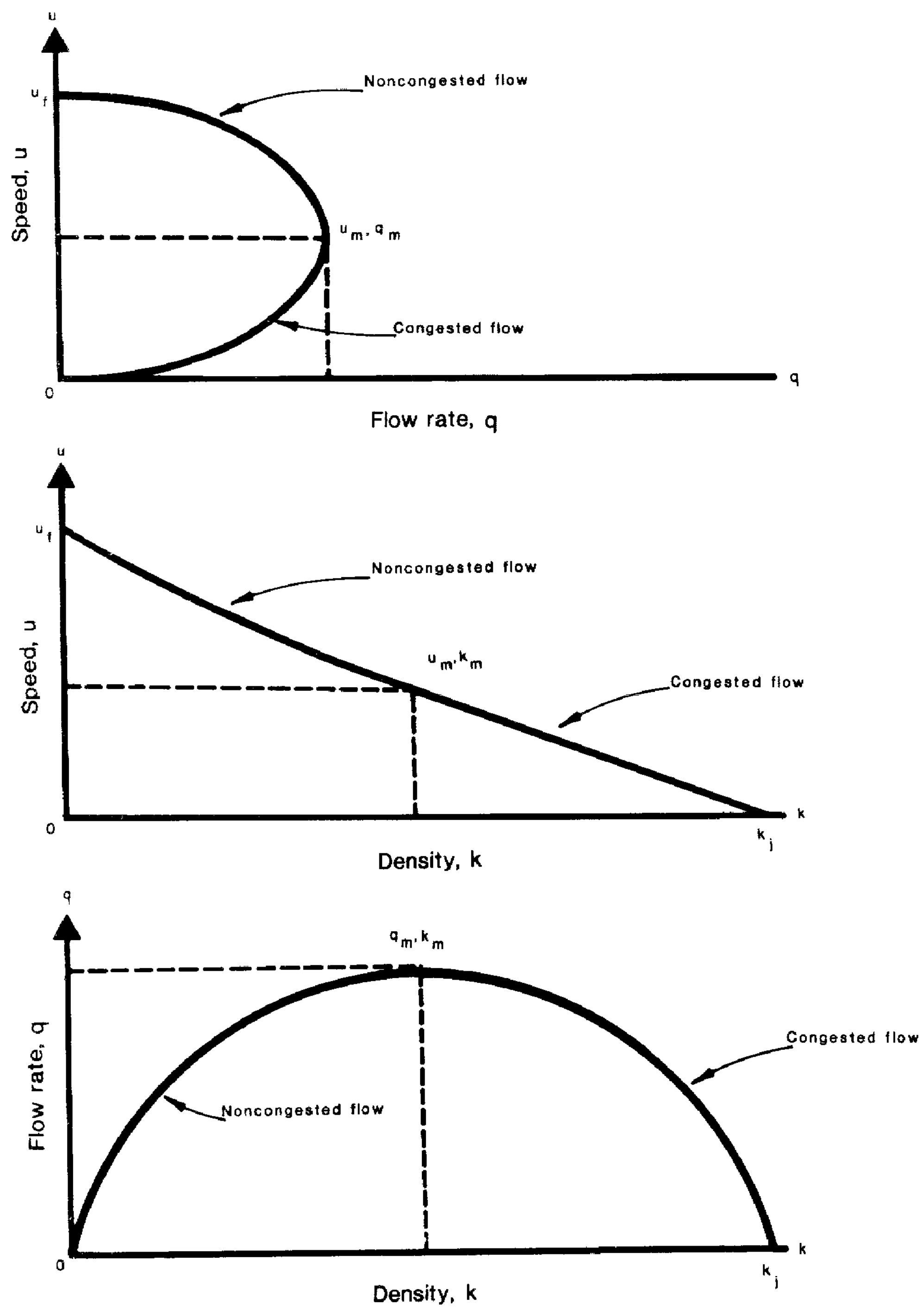


Figure 5-5. Fundamental Flow Rate-Speed-Density Relationships.

- On the basis of these measurements, determine where on the fundamental traffic flow curves the freeway section is operating with respect to capacity.

- Determine the maximum ramp metering rate at which vehicles can be permitted to enter the freeway.

A refinement that is often made to this strategy is to select the traffic flow curves on the basis of traffic composition and weather conditions.

Lane occupancy (a surrogate measure for density) and flow rate (volume) are the two traffic variables generally used to describe freeway traffic conditions for traffic responsive metering. These are the control parameters usually used, because they can be measured in real time using vehicle detectors.

Several variations on the basic strategy of traffic-responsive metering utilize different combinations of traffic variables. Although most are reported as having positive effects on freeway operations, none has been generally accepted as being superior to the others. In fact, new strategies are still being formulated to find better modes of control. However, the principal traffic-responsive strategies remain demand-capacity control and occupancy control.

Demand-Capacity Control

Demand-capacity control features the selection of metering rates on the basis of a real-time comparison of upstream volume and downstream capacity. The upstream volume is measured in real time and compared with either a preset value of downstream capacity determined from historical data or a real-time value computed from downstream volume measurements. To be most effective, the downstream capacity used should account for the effects on capacity of weather conditions, traffic composition, and incidents.

The difference between the upstream volume and the downstream capacity is then determined and used as the allowable entrance ramp volume. This ramp volume is expressed as a metering rate to be used during the next control interval (usually 1 min). If the upstream volume is greater than the downstream capacity, a minimum metering rate is used (e.g., 3-4 vpm). Theoretically, if the upstream volume were greater than the downstream capacity, a zero metering rate, or ramp closure, should be used in order to prevent congestion. It has generally been found that metering rates lower than 3 vpm are not effective, because vehicles waiting at the ramp will judge the ramp metering signal to be malfunctioning and will proceed through on red.

Downstream capacity may also be measured directly from freeway detector(s) to reflect for variations in traffic composition, weather, or other limiting factors which would not be accounted for in a fixed value of capacity.

Since a low upstream volume could occur in congested as well as uncongested flow, volume alone does not indicate degree of congestion. Therefore, an occupancy measurement also is usually made to determine whether uncongested or congested flow prevails. If the occupancy measurement is above a preset value (e.g., 18 percent, as used in Los Angeles).[17] which is determined from historical data, congested flow will be assumed to exist and a minimum metering rate used.

Occupancy Control

Occupancy control utilizes real-time occupancy measurements generally taken upstream of the entrance ramp. One of a number of predetermined metering rates is selected for the next control interval (usually 1 min) on the basis of occupancy measurements taken during the current control interval. For a given entrance ramp, the metering rate to be used for a particular value of occupancy would be based on a plot of historical volume-occupancy data collected at each measurement location. An example of a typical plot from Chicago is shown in figure 5-6.[18] From such a plot, an approximate relationship between volume and occupancy at capacity is determined. For each level of occupancy measured, a metering rate can be determined that corresponds to the difference between the predetermined estimate of capacity and the real-time estimate of volume. If the measured occupancy is greater than, or equal to, the preset capacity occupancy, a minimum metering rate will be selected instead of a zero rate or ramp closure. This choice would be based on effective and practical entrance ramp control considerations, as explained earlier for demand-capacity control. Table 5-1 shows a recommended range of metering rates based on measured occupancy.[19]

System Components

A traffic-responsive metering system contains the same components as described for pretimed metering. These include ramp metering signal(s), local controller, advance warning sign with flashing beacon, and detectors. The local controller unit for traffic-responsive metering requires additional logic over and above that required for pretimed metering in order to monitor traffic variable measurements, select or calculate metering rates, and respond to override-type conditions such as excessive queues. Queue, check in, checkout, and merge detectors are normally also included in traffic-responsive metering systems.

Some traffic-responsive metering systems have also included detectors used to determine traffic composition and weather conditions.[9, 17] Input from these detectors enables the system to account for the effects of these factors on traffic flow.

Table 5-1. Local Actuated Metering Rates as Function of Occupancy. [19]

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

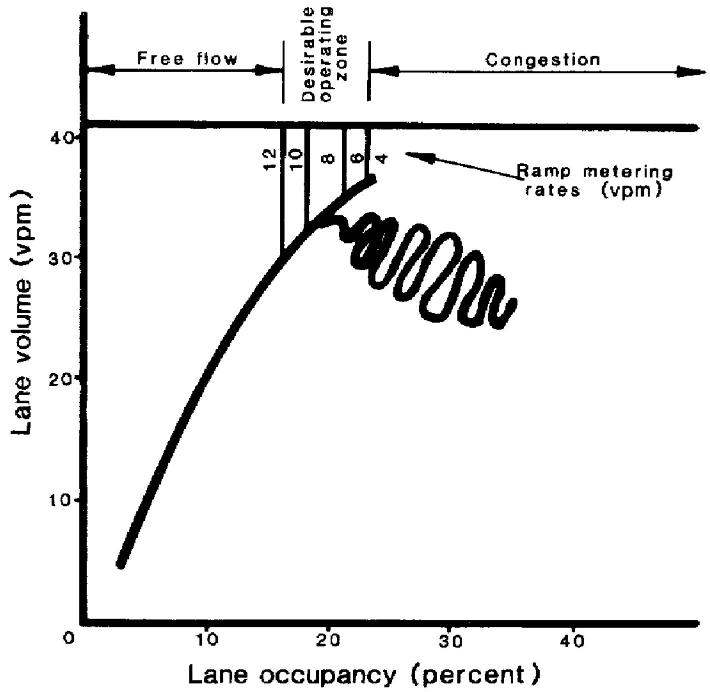


Figure 5-6. Typical Volume-Capacity Plot Related to Ramp Metering Rate. [18]

The typical location of these components on a ramp is shown in figure 5-7. For a discussion of standards for various components, the reader is referred to the publication on recommended practice for freeway entrance ramp control displays prepared by the Institute of Transportation Engineers (ITE).[13]

System Operation

The operation of a traffic-responsive metering system is similar to that of a pretimed metering system, except in regard to the following:

- **Metering Rate Selection.** Single-entry metering is normally used to time the red-yellow-green (or red-green) intervals for a given metering rate. However, if high metering rates (e.g., higher than 13 vpm), are required, platoon metering might be used. Single-entry metering and platoon metering should not both be used at any one ramp.

In a traffic-responsive metering system, the selection is based on real-time measurements of traffic variables which describe traffic flow conditions on the freeway. The control interval, which is the time period during which a selected metering rate remains in effect, is much shorter for a traffic-responsive metering

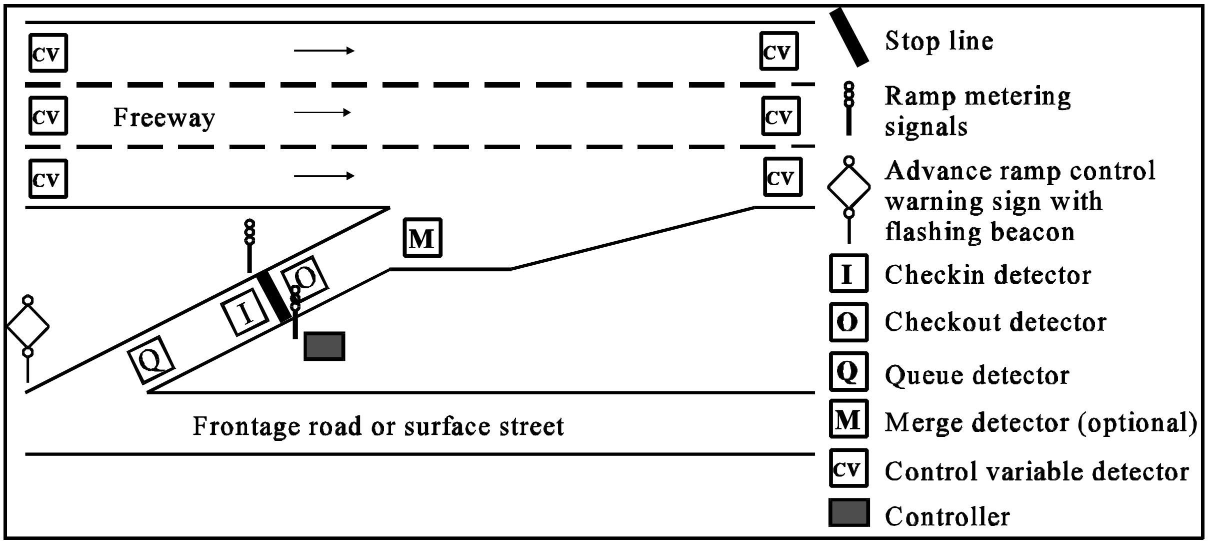


Figure 5-7. Traffic Responsive Ramp Metering Layout.

system (e.g., 1 min) than for a pretimed metering system (e.g., 30 min., 1 hr., or the entire peak period).

- **Override Features.** Override features of a traffic responsive system adjust metering rates in accordance with certain operational considerations as follows:

- **Continued Actuation of the Queue Detector.** Indicates that the queue of vehicles waiting at the ramp metering signal is approaching the frontage road or surface street and is likely to interfere with traffic on either or both. Therefore, a higher metering rate may be used to shorten the queue length.

- **Actuation of the Merge Detector.** Indicates that a vehicle is still in the merge area. Therefore, in the case of single-entry metering, subsequent green intervals are preempted until the vehicle merges.

- **No Actuation of the Checkout (Passages Detector After a Green Interval).** Indicates that a vehicle has missed the green signal. Therefore, the ramp metering signal is returned to or left in green.

- **Continued Actuation of the Queue Detector With No Actuation of the Check in (Demand) Detector.** Such a condition indicates that a vehicle on the ramp has stopped short of the check in detector. Therefore, the ramp metering signal is turned to green to allow this vehicle to proceed.

Gap-Acceptance Merge Control

Gap-acceptance merge control has been implemented and tested, but is little used, if at all, today. The concept of matching a merging vehicle to a specific freeway gap is attractive, but many variables can cause it to fail. Certain elements, such as slow vehicle detection, may have application in other types of ramp control operation. Gap-acceptance merge control might have application where geometries are substandard and the primary concern is safety.

The merge-control concept of entrance ramp metering is intended to enable a maximum number of entrance ramp vehicles to merge safely without causing significant disruptions in freeway traffic. The concept involves maximum utilization of gaps in the traffic stream of the freeway lane into which ramp vehicles are to merge. It may or may not involve the calculation of ramp metering rates in accordance with the demand-capacity constraint. The problem is mainly one of inserting entrance ramp vehicles into freeway gaps. However, a provisional metering rate based on system calculations may be established. If a gap is found in a "window", say 3 seconds either side of the calculated release point, it is considered to have satisfied the metering rate, and a vehicle is released.[20] Gap acceptance metering has not been widely used, but may be warranted where geometrics are substandard or the safety of the merging operation can be improved.

Basic Concepts

The concepts of gap acceptance at freeway entrance ramps are important in describing the interaction of the freeway and ramp traffic. It is assumed that the ramp driver measures each gap in the adjacent freeway lane and compares it with an acceptable gap which he/she judges as large enough for a safe merge.

The minimum acceptable gap is dependent on several factors, such as the following:[20]

- Entrance ramp and freeway geometrics.
- Vehicle performance characteristics.
- Driver behavior.
- Traffic conditions.
- Weather conditions.

Merge-control systems are designed to improve the merging operation at the entrance ramp by providing the driver with the information needed to coordinate in time and space entry onto the freeway. These systems operate according to the following basic guideline procedures:

- Detection of an acceptable gap on the freeway into which a ramp vehicle could merge.
- Projection of the arrival of the acceptable gap at the merging point of the entrance ramp.
- Release of the ramp vehicle in sufficient time for it to accelerate and merge into the moving gap.
- If a gap is not detected within some maximum time, say 60 seconds, the vehicle is released.

System Components

Gap-acceptance merge-control systems use many of the same components as those described for pretimed metering, which include ramp metering signals, local controller, advance warning sign with flashing beacon, and detectors. A mainlane gap/speed detector is located in the shoulder lane of the freeway upstream of the ramp merge to provide data from which the controller unit can determine presence and speed of available gaps in which to insert merging ramp traffic. Queue, check in, checkout, and merge detectors are normally included in gap-acceptance merge-control systems.

Another override-feature component that might be added to the system is a slow-vehicle detector, which senses the presence of a slow-moving vehicle on the entrance ramp between the ramp metering signal and the merge detector. A schematic layout for gap-acceptance operation combined with traffic responsive operation as implemented in the Dallas Corridor Study is presented in figure 5-8.[22] Also, for a discussion of standards for various system components, the reader is referred to the publication on recommended practice for freeway entrance ramp control displays prepared by the Institute of Transportation Engineers (ITE).[13]

System Operation

A gap-acceptance merge-control system does not normally operate in accordance with a constant metering rate for a specified control interval as do pretimed and traffic-responsive metering systems. Instead, it operates in response to the availability of acceptable gaps in the lane of the freeway into which ramp vehicles are to merge.

Usually, the system is designed to operate in a single-entry metering mode, with the ramp metering signal resting on red when no vehicles are waiting on the ramp. Experience on the Gulf Freeway in Houston has indicated that it is usually not desirable to operate the ramp metering signal in either of the following two ways:[24]

- If it gives a green indication at the proper time, whether or not there is a vehicle waiting.
- If it normally rests on green when there are no vehicles waiting.

Procedures can be summarized as follows for the nominal operation of a gap-acceptance merge-control system, with single-entry metering and the ramp metering signal resting on red:

- A vehicle stops at the ramp metering signal and actuates the check in detector.
- The controller begins to measure gaps and vehicle speeds which are sensed by the gap/speed detector that is located upstream from the ramp in the lane of the freeway into which ramp vehicles are to merge.
- The controller compares each measured gap to a preset minimum gap size to determine whether or not it is an acceptable gap.
- If the system includes demand-capacity features as described above, the controller determines if the gap falls within a “window” and adjusts the release time accordingly.
- If a gap is not acceptable, the controller considers the next gap. If it is acceptable, the controller computes the time at which the vehicle at the ramp metering signal should be released in order to arrive at the merge point at the same time as does the acceptable gap. This calculation involves the following factors:
  - Speed of the traffic flow measured in the lane of the freeway into which ramp vehicles are to merge.
  - Distance of the gap/speed detector location from the merge point.
  - Predetermined ramp travel time of a vehicle stopped at the ramp metering signal to the merge point.
- At the proper instant, the controller causes the ramp metering signal to change to green.
- The ramp metering signal remains on green for a fixed interval long enough to release a single vehicle. Then, it changes to yellow for a short fixed interval before

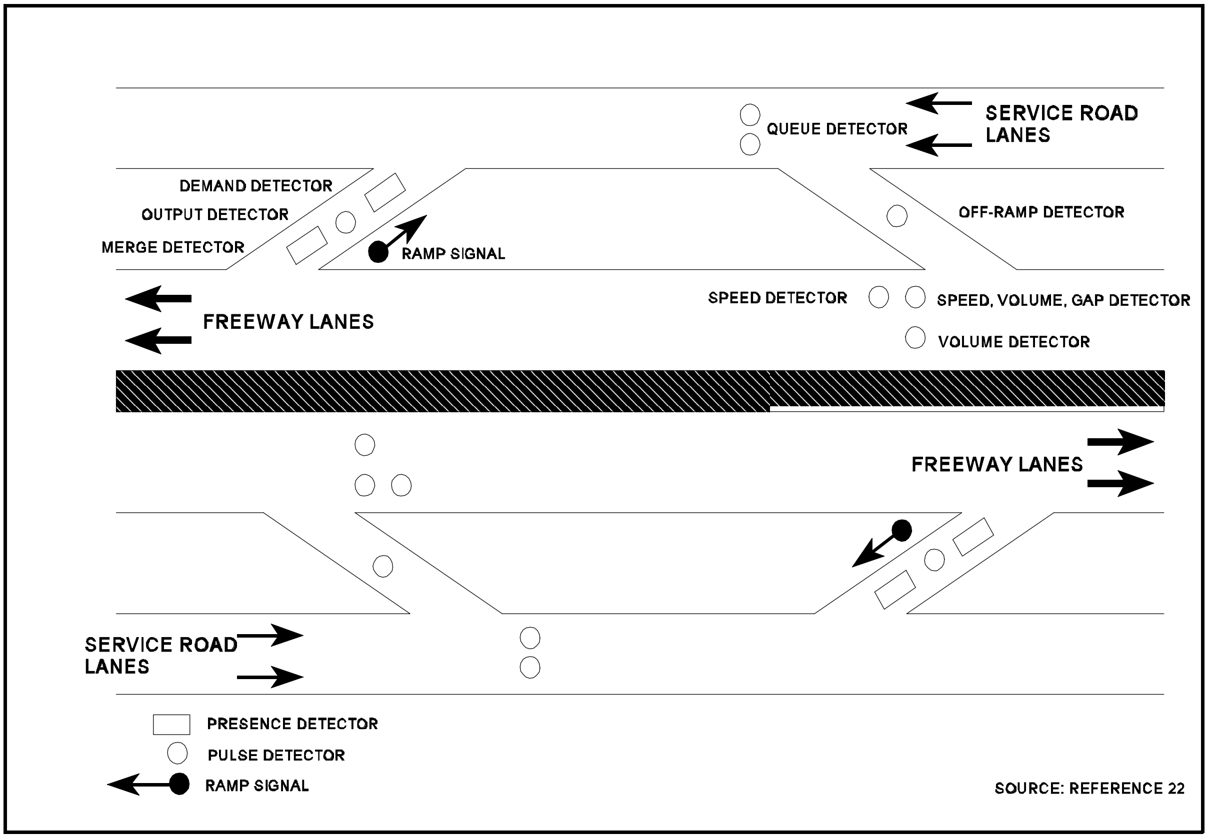


Figure 5-8. Gap Acceptance / Traffic Responsive Ramp Metering Layout.

it changes to red. (Where permitted by State law, the yellow interval may be omitted.) The green plus yellow (or green only) interval is usually about 3 seconds long. It is necessary that the ramp metering signal remain on red long enough to give the next vehicle in line time to pull up to the signal. Thus, the minimum time for a full green-yellow-red (or green-red) cycle should be 4 to 5 seconds.

The operation of the override features of a gap-acceptance merge-control system is essentially the same as for a traffic-responsive metering system. However, a gap-acceptance merge-control system may have the following additional override features:

- **Low-speed, Fixed-rate Metering.** When congested flow develops on the freeway, small space headways between successive vehicles constitute large time headways because of the low speeds. For example, if traffic on the freeway should come to a complete stop, the measured time headways will be infinitely large. Thus, unless an appropriate override were provided, the controller would release a number of entrance ramp vehicles to enter the freeway during the congested flow, a response which would be contrary to the objective of improving freeway operations. Therefore, if the speed of the freeway traffic drops below a preset value (e.g., 25 mi/h), ramp vehicles are metered at a minimum fixed rate {usually 3 to 4 vpm).

- **Slow-vehicle, Red-interval Extension.** At entrance ramps where there are relatively high percentages of trucks and buses, it might be desirable to make special allowances for their performance characteristics. Accordingly, a slow-vehicle detector might be provided to measure the travel time of vehicles from the ramp metering signal to their location. If the travel time is greater than a preset value, the ramp metering signal is held on red until the vehicle has cleared the merge detector or until the merge detector is actuated.

Benefits to be realized from a gap-acceptance merge-control system are similar to those realized from traffic-responsive metering system. A study conducted by the Texas Transportation Institute, which compares a gap-acceptance merge-control system with a demand-capacity-control, traffic-responsive metering system, has reported the following results:[23]

- Gap-acceptance merge-control resulted in a higher percentage of ramp-metering-signal violations by ramp vehicles, which was probably due to its irregular pattern of operation and longer queue delays (metering rates ranged from 1 veh/4 seconds to 1 veh/25 seconds).

- Gap-acceptance merge-control resulted in lower travel times from the ramp metering signal to the merge area, which indicates a smoother merging operation.

- Demand-capacity control resulted in higher metering rates and higher peak-hour entrance ramp volume.

In general, for entrance ramps that have well-designed geometrics, a gap-acceptance merge control is less cost-effective than either pretimed or traffic-responsive metering systems. However, gap-acceptance control might be warranted at locations where the geometrics are substandard and the primary concern is to improve the safety of the merging operation.

System Ramp Control

System ramp control refers to the application of ramp control to a series of entrance ramps where a single ramp meter cannot address the excess freeway demand. The primary objective of system ramp control is to prevent or reduce the occurrence of congestion on the freeway. Therefore, the control of each ramp in the control system is based on the demand-capacity considerations for the whole system rather than on the demand-capacity constraint at each individual ramp. This concept does not necessarily imply the use of large computer control systems, since small subsystems may be coordinated by the use of mutual coordination of adjacent ramp meter controllers.

If congestion is to be prevented or reduced on the freeway system, the concept of system ramp control must be used in the design of a system of controls for a section of freeway with more than one entrance ramp. It may be applied in the following types of systems:

- System pretimed metering (including ramp closure).

- Traffic-responsive metering.

- Gap-acceptance merge control.

A discussion of system ramp control applied to each of these systems follows.

System Pretimed Metering

System pretimed metering refers to the application of pretimed metering to a series of entrance ramps. The metering rate for each of these ramps is determined in accordance with demand-capacity constraints at the other ramps as well as its own local demand-capacity constraint.

Determining these metering rates, which are computed from historical data pertaining to each control interval, requires the following information:

- Mainline and entrance ramp demands.
- Freeway capacities immediately downstream of each entrance ramp.
- Description of the traffic pattern within the freeway section to be controlled.

This information provides the basis for establishing the demand-capacity constraints of the entrance ramps and their interdependencies.

Fundamental metering rate calculations—given the required data, the fundamental procedure for computing metering rates involves five steps:

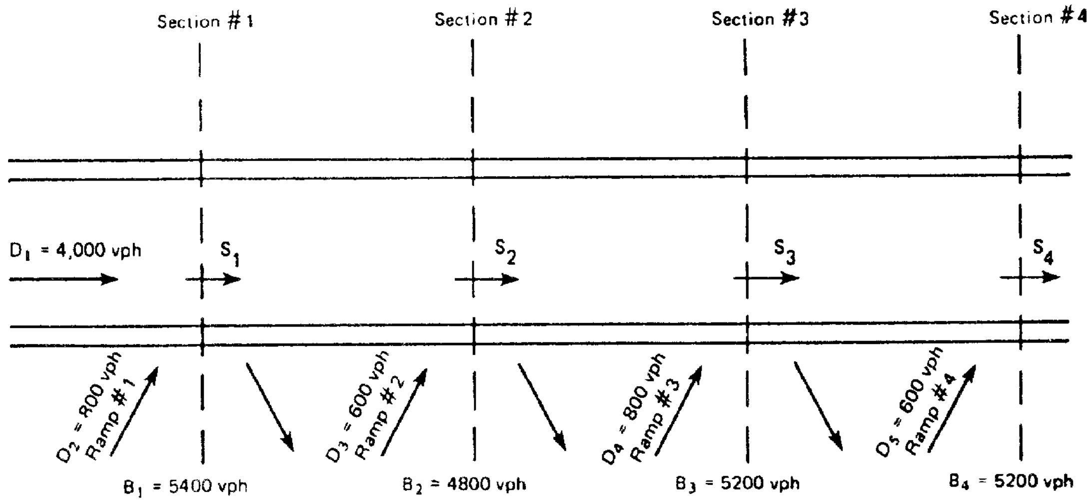
1. Start with the entrance ramp that is farthest upstream.
2. Determine the total demand (upstream mainline demand plus ramp demand) for the freeway section immediately downstream of the ramp.
3. Compare the total demand to the capacity of the downstream section, and proceed as follows:
    a. If the total demand is less than the capacity, metering is not required at this ramp by this demand-capacity constraint. Therefore, skip step 4 and go immediately to step 5.
    b. If the total demand is greater than the capacity, metering is required at this ramp by the demand-capacity constraint. Therefore, proceed to step 5.
4. Compare the upstream mainline demand to the capacity of the downstream section and proceed as follows:
    a. If the upstream mainline demand is less than the capacity, then the allowable entrance ramp volume (or metering rate) is set equal to the difference between the capacity and the upstream mainline demand.
    b. If the upstream mainline demand is greater than or equal to the capacity, then the allowable entrance ramp volume is zero, and the ramp must be closed. If the upstream mainline demand is greater than the capacity, the volumes permitted to enter at ramps upstream must be reduced accordingly. The total reduction in the allowable entrance ramp volumes upstream is equal to the difference between the upstream mainline demand and the capacity, adjusted to account for that portion of the traffic entering upstream that exits before it reaches the downstream entrance ramp being closed.
5. Select the next entrance ramp downstream and go back to step 2.

This procedure is illustrated by the following examples.

Example 1 [5,6]

In the example case shown in figure 5-9, pretimed metering rates are calculated for an integrated, pretimed control system comprised of four entrance ramps. In reviewing this example, the following points should be noted:

- Since only entrance ramp control is being considered and not mainline control, the allowable mainline volume at



X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = \underline{4000 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4000)+(1.00)(800) = 4800 \text{ vph} < B_1 = 5400 \text{ vph}; \therefore \underline{X_2 = 800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4000)+(0.75)(800)+(1.00)(600) = 5000 \text{ vph} > B_2 = 4800 \text{ vph}; \therefore \underline{X_3 = 400 \text{ vph}}$
- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4000)+(0.70)(800)+(0.90)(400)$
  $+ (1.00)(800) = 5320 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 680 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4000) + (0.60)(800) + (0.85)(400) + (0.90)(680)$
  $+ (1.00)(600) = 5432 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 368 \text{ vph}}$

Conclusion:

- Ramp # 1: No control needed.
- Ramp # 2 : Meter at a rate of 400 vph.
- Ramp # 3: Meter at a rate of 680 vph.
- Ramp # 4: Meter at a rate of 368 vph.

Figure 5-9. Integrated Entrance Ramp Control: Example No. 1 Calculation of Pretimed Metering Rates. (5,6)

Section 1, Xj is set equal to the mainline demand Dj.

- With the notation given in figure 5-9, the demand, S_j, at a section, j, is computed by the following equation:

$$S_j = (\sum_{i=1}^{j} A_{ij}X_i) + A_{j+1}D_{j+1}$$

where:

X_i = Allowable volume at input i

D_j = Demand at input i

A_{ij} = Decimal fraction of vehicles entering at input i which pass through Section j

S_j = Demand at Section j

As it happens, the metering rate computed for each entrance ramp in this particular example is determined solely by the demand-capacity constraint at the section immediately downstream and is not influenced by the demand-capacity constraints at other ramps.

Example 2 [5,6]

The data given in the example shown in figure 5-10 are the same as those given in the previous example. except that the mainline demand, D_1, is 4,600 vph instead of 4,000 vph. In this case, the metering rates at Ramps 2, 3, and 4 are determined solely by their respective downstream demand-capacity constraints, as was the case in the previous example. However, the metering rate at Ramp 1, rather than being determined by the demand-capacity constraint at Section 1, is established in accordance with the demand-capacity constraint at Ramp 2, as is described below.

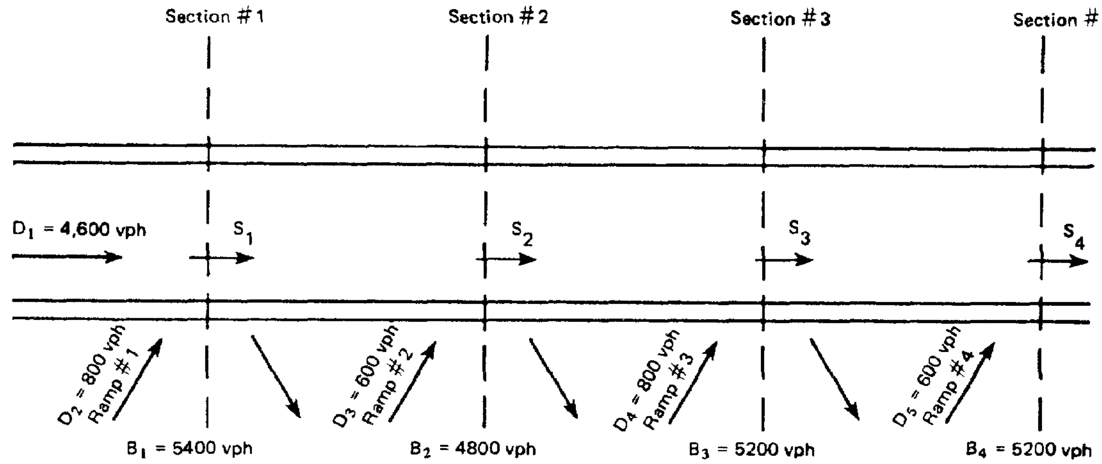
The demand, S_2, at Section 2 is 5,570 vph, which is 770 vph greater than the capacity, B_2, at Section 2 (4,800 vph). If Ramp 2 is closed, the demand at Section 2 is reduced to 4,970 vph, a volume which also exceeds the capacity, B_2. Therefore, it is necessary to reduce the allowable volume, X_2, entering at Ramp 1 (input 2). The allowable volume, X_2, must be reduced enough to reduce the demand, S_2, by 170 vph. The amount of the reduction is equal to the 170 vph divided by the decimal fraction, A_{22}, of the vehicles entering at Ramp 1 and passing through Section 2 (170 vph/0.75 - 227 vph). Therefore, the allowable volume, X_2, at Ramp 1 would be 573 vph instead of 800 vph.

In this procedure, excess demand, $S_j - B_j$, at any section, j, is removed by reducing the allowable volume on the entrance ramp immediately upstream. If' instead, the allowable volumes on entrance ramps farther upstream were reduced, a large number of vehicles would have to be removed from these ramps in order to reduce the demand, S_j, sufficiently at any section, j. This is necessary because some of the vehicles that enter at these ramps will exit the freeway before they reach Section j.

Example 3

Again, in the situation presented in table 5-2, allowable ramp volumes would be calculated as follows. If the excess demand, 1200 vph, at Section 2 were to be removed by reducing the allowable volume, X_2, at Ramp 1, the volume at Ramp 1 would have to be reduced by 267 vph. The allowable entrance ramp volumes are summarized accordingly in table 5-2.

The total input of 2,172 vph, however, is less than that of 2,248 vph, the volume obtained if Ramp 2 is metered as in Example 1. Thus, the fundamental approach



X_i = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section #1

- Set $X_1 = D_1 = \underline{4600 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4600)+(1.00)(800) = 5400 \text{ vph} = B_1 = 5400 \text{ vph}; \therefore \underline{X_2 = 800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 \text{ vph} > B_2 = 4800 \text{ vph};$

  $\therefore X_3 = 0$ and volume entering upstream must be reduced by 170 vph;
  $\therefore X_2 = 800 - 170/A_{22} = 800 - 170/0.75 = \underline{573 \text{ vph}}$

- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4600)+(0.70)(573)+(0.90)(0) + (1.00)(800) = 5341 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 659 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4600) + (0.60)(573) + (0.85)(0) + (0.90)(659) + (1.00)(600) = 5447 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 353 \text{ vph}}$

Conclusion:

- Ramp #1: Meter at a rate of 573 vph.
- Ramp #2 : Close.
- Ramp #3: Meter at a rate of 659 vph.
- Ramp #4: Meter at a rate of 353 vph.

Figure 5-10. Integrated Entrance Ramp Control: Example No. 2 Calculation of Pretimed Metering Rates. (5,6)

Table 5-2. Allowable Entrance Ramp Volumes for Example 3.

Ramp No.	Volume (vph)
1	533
2	600
3	687
4	352
Total Input	2172

described will result in the optimal utilization of the freeway. It maximizes the sum of the allowable entrance ramp volumes, a procedure which corresponds to maximizing system output for steady-state, uncongested flow conditions.(26) It also maximizes the total travel in the system.(27)

Linear Programming Formulation—The fundamental procedure described in Examples 1 and 2 can be formulated as a linear programming model.(26) This model may be used to compute optimal allowable entrance ramp volumes. In terms of the notation defined in figures 5-8 and 5-9, the linear programming model would be as follows:

- Maximize ΣX_j, where n is the number of inputs
- Subject to the following constraints:
  - Demand capacity:

$$\sum_{i}^{n} A_{ij} X_i \qquad B_j;\; j=1,.....n-1$$

  - At Section 1, allowable mainline volume $\leq$ mainline demand:

$$X_1 = D_1$$

  - Allowable entrance ramp volume $\geq$ entrance ramp demand:

$$X_1 \leq D_1;\; i=2,.....,n$$

  - Allowable entrance ramp volume equals minimum allowable ramp volume:

$$X_1 \geq \min x_i \;\; \geq 0;\; i = 2,.....n$$

The use of the linear programming model yields allowable entrance ramp volumes identical to those obtained by using the fundamental procedure described above.

Practical Considerations

The allowable entrance ramp volumes (or metering rates) calculated for an integrated ramp control system should be evaluated with respect to the following practical considerations:(6)

- Metering rates of less than 180 to 240 vph (3 to 4 vpm) are not feasible because drivers required to wait longer than 15 to 20 seconds at a ramp metering signal often believe that the signal is not working correctly. They will, therefore, proceed on a red indication by the signal. Thus, if a metering rate of less than 180 to 240 vph is calculated, consideration should be given either to closing the ramp or to metering it at a higher rate.

- Practical maximum metering rates are about 900 vph for single-entry metering and approximately 1,100 vph for platoon metering. Therefore, for a metering rate greater than the maximum for the metering type to be used, the setting should be less than or equal to the practical maximum rate, and the metering rates at the other entrance ramps should be adjusted accordingly.

- Metering rates at each entrance ramp should be evaluated with regard to available storage at the ramp and potential resulting congestion on the adjoining surface street system. If the storage is not sufficient, it may be necessary either to close the ramp or to increase the metering rate.

- Metering rates equal to zero indicate that an entrance ramp closure is necessary. However, the closure of a particular entrance ramp may not be acceptable. Therefore, it may be necessary to increase a zero metering rate to some minimum acceptable rate.

- The procedure described for computing metering rates gives preference to traffic entering the system near the upstream end. Consequently, metering rates at entrance ramps downstream may be too restrictive to be acceptable to the motoring public. Therefore, it may be necessary to increase the metering rates computed for some of the downstream entrance ramps, and thus to reduce accordingly the metering rates for some of the upstream entrance ramps.

If any of the computed metering rates were to be altered because of one or more of the practical considerations mentioned above, the metering rates at the other entrance ramps would have to be adjusted accordingly to ensure both an optimal utilization of the freeway and an uncongested flow.

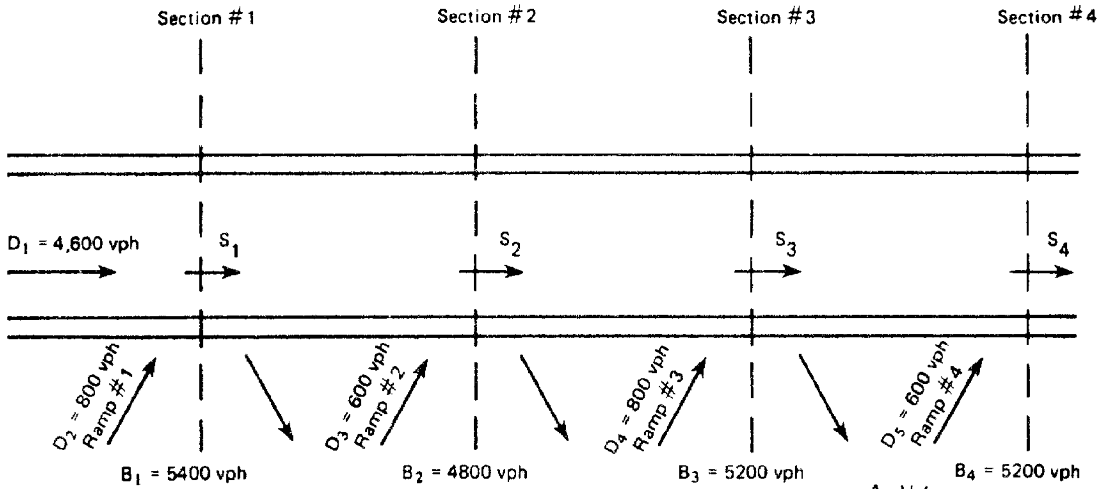
Example 4 [5,6]

If it were necessary to maintain a metering rate of at least 240 vph at Ramp 2 in the example presented in figure 5-10, it would be necessary to follow the adjustment procedure for the metering rates at the other entrance ramps (as shown in figure 5-11). The allowable volume. X_2 (573 vph), at Ramp 1 would have to be reduced by 320 vph in order to allow 240 vph to enter at Ramp 2 and still satisfy the demand-capacity constraint at Section 2. This reduction also decreases the mainline demand at Sections 3 and 4. Thus, the allowable volumes at Ramps 3 and 4 are increased to maximize the utilization of the freeway at these sections.

It is usually difficult to obtain reliable estimates of the A_{ij} values, because these vary with time and generally exhibit a high variance. Also, the O/D type studies used to collect these data are expensive and do not provide real-time data.

As indicated in the 1996 *Traffic Control System Handbook*, it may be unfeasible to reduce ramp volumes sufficiently to effect changes on freeway main lanes because of circumstances such as the following:[7]

- Minimum metering rate constraints.



X_j = allowable volume at input i

D_i = demand at input i

B_j = capacity at section j

A_{ij} = decimal fraction of vehicles entering at input i which pass through section j

S_j = demand at section j

A_{ij} Values

i \ j	1	2	3	4
1	1.00	0.95	0.90	0.85
2	1.00	0.75	0.70	0.60
3	–	1.00	0.90	0.85
4	–	–	1.00	0.90
5	–	–	–	1.00

Compute X_i's starting at section # 1

- Set $X_1 = D_1 = \underline{4600 \text{ vph}}$
- $S_1 = A_{11}X_1 + A_{21}D_2 = (1.00)(4600)+(1.00)(800) = 5400 \text{ vph} = B_1 = 5400 \text{ vph}; \therefore X_2 = \underline{800 \text{ vph}}$
- $S_2 = A_{12}X_1 + A_{22}X_2 + A_{32}D_3 = (0.95)(4600)+(0.75)(800)+(1.00)(600) = 5570 \text{ vph} > B_2 = 4800 \text{ vph};$

  Since X_3 must equal at least 240 vph; $\underline{X_3 = 240 \text{ vph}}$ and volume entering upstream must be reduced by 410 vph;
  $\therefore X_2 = 800 - 410/A_{22} = 800 - 410/0.75 \underline{= 253 \text{ vph}}$

- $S_3 = A_{13}X_1 + A_{23}X_2 + A_{33}X_3 + A_{43}D_4 = (0.90)(4600)+(0.70)(253)+(0.90)(240) + (1.00)(800) = 5333 \text{ vph} > B_3 = 5200 \text{ vph}; \therefore \underline{X_4 = 667 \text{ vph}}$
- $S_4 = A_{14}X_1 + A_{24}X_2 + A_{34}X_3 + A_{44}X_4 + A_{54}D_5 = (0.85)(4600) +(0.60)(253) +(0.85)(240) + (0.90)(667) + (1.00)(600) = 5466 \text{ vph} > B_4 = 5200 \text{ vph}; \therefore \underline{X_5 = 334 \text{ vph}}$

Conclusion:

- Ramp # 1: Meter at a rate of 253 vph.
- Ramp # 2 : Meter at a rate of 240 vph.
- Ramp # 3: Meter at a rate of 667 vph.
- Ramp # 4: Meter at a rate of 334 vph.

Figure 5-11. Integrated Entrance Ramp Control: Example No. 4 Calculation of Pretimed Metering Rates. (5,6)

- Lack of vehicle queuing storage.

- Too large a capacity deficiency.

The reader is referred to the handbook for a detailed example demonstrating the interaction among ramp metering requirements, diversion impacts, and ramp storage requirements. A detailed procedure can be found in reference 19.

Systemwide ramp metering strategies provide the opportunity to distribute vehicle demands over a larger number of ramps.

System Traffic-Responsive Metering

System traffic-responsive metering is the application of traffic responsive metering to a series of entrance ramps where the metering rates at each ramp are selected in accordance with both system and local demand-capacity constraints.

System Operation

During each control interval, real-time measurements are taken of traffic variables (usually volume, occupancy, and/or speed). The data are used to define the demand-capacity conditions at each ramp. Then, on the basis of these measurements, both an independent and an integrated metering rate are calculated for each entrance ramp. Of these two metering rates, the one that is the more restrictive is selected to be used during the next successive control interval.

Metering Rates

The methods used to calculate independent and integrated traffic-responsive metering rates are basically the same as those used to compute independent and integrated pretimed metering rates. Instead of calculating metering rates in real time, a set is precomputed for the range of demand-capacity conditions expected from which the metering rates are then selected in real time. The linear programming model is often used to calculate predetermined sets of integrated, traffic-responsive reentering rates. Also, the metering rates are usually subject to the merge-detector, queue-detector, and maximum-red-time overrides used in traffic-responsive metering

System vs. Independent Ramp Control

Comparisons of system and independent entrance ramp control indicate that increased benefits are realized with system ramp control.[26,27] Improvements occur in terms of the following:

- Lower travel time.

- Higher total travel.

- Fewer crashes.

In traffic-responsive metering, the greater system flexibility provided by system ramp control enables an optimal system response to individual variations in traffic demands and capacities resulting from incidents on the freeways.

Controller Interconnection

A significant feature of system ramp control is the interconnection among local ramp controllers, which permits conditions at one location to affect the metering rate imposed at one or more other locations. Real-time metering plans are computed and updated by a central master computer which issues metering rates to the respective local ramp controllers on the basis of freeway traffic information obtained from vehicle detectors throughout the system.

Although the decision-making capabilities are centralized within the central computer system, the processing of control intelligence may be distributed among the individual entrance ramps. For economic (and possibly reliability) reasons, there is a trend toward decentralized decision-making, distributed computation, and hierarchical control.[28]

RAMBO (Ramp Adaptive Metering Bottleneck Optimization) is a suite of programs developed for the Texas Department of Transportation by the Texas Transportation Institute.[29] RAMBO I is a software tool designed to assist in developing ramp metering plans using the TxDOT ramp meter specification, while operating either in the isolated mode or in local control. The program provides Transition Point Patterns for each metering level and evaluates traffic operations. RAMBO II likewise develops and evaluates ramp metering plans based on forecasted traffic conditions along an extended section of freeway containing up to 12 metered entrance ramps and 12 exit ramps operating either in the system mode, or in a hierarchically distributed system having real-time local control with systems-based metering objectives. The program was implemented in Houston, TX, in 1996.

The total software package can perform capacity analysis of the freeway system, assess projected metering operation, and assist in developing optimal ramp metering plans for either local ramp metering operations (using RAMBO I) or system ramp metering operations (using RAMBO II). RAMBO II can translate system-based results into local metering control parameters that can be downloaded into the local ramp meters if some minor modifications are made to the current ramp meter specifications. The programs include extensive interactive graphic screens.

Incremental Benefits of Various Levels of Control

As discussed earlier, the benefits offered by pretimed metering (including ramp closure) versus no access control include increased mainline speeds (reduced travel time), higher service volumes, less delay, safer merging operations, and reduced user costs. Beyond pretimed metering, the incremental benefits gained from traffic-responsive metering (local or systemwide) depend on the factors discussed below.[21]

Variations in the Ratio of Mainline to Entrance Ramp Demand

As mainline demand approaches capacity, the permissible metering rates become more and more constrained. On the other hand, as the mainline demand decreases. more traffic can be allowed onto the freeway from entrance ramps, and ramp metering control can exert greater impact on the quality of freeway flow, thus producing greater benefits.

Variations in Overall Traffic Demand Pattern

Traffic demand on the freeway and entrance ramps exhibits two types of variations: (1) shift in demand level, and (2) short-term fluctuations. The larger the magnitude of these types of demand variation, the higher the potential for benefits from traffic-responsive metering.

Mainline Capacity Reductions

Reductions in mainline freeway capacity result from accidents, traffic incidents, and adverse weather conditions. As the frequency and impact of these capacity-reducing factors increase, more need develops for traffic-responsive metering to cope with the variations in available capacity. To determine the appropriate level of ramp metering control for a given freeway, the incremental benefits produced by local and systemwide traffic-responsive metering (relative to a base of pretimed metering) must be estimated. Computer simulation can be effectively used in evaluating control benefits. In addition, the incremental system costs (installation, operation, maintenance) and the incremental user costs (travel time, vehicle operating costs, accidents, air pollution emission) must be estimated. Incremental benefits and incremental costs can then be used to conduct a benefit/cost or utility/cost analysis to decide upon the most desirable type of ramp metering.

The growth in traffic demand over the lifetime of a ramp metering project may reduce the incremental benefits of a traffic-responsive type of ramp metering control (local or systemwide). As traffic demand grows substantially over the lifetime of the project, the controllability index of the freeway decreases. Since the benefits are nonlinearly related to the controllability, it is possible that the benefits could decrease faster than the growth rate in demand. In planning ramp metering installations, the engineer should be aware of this effect. It is recommended that the analysis be repeated for as many years as are in the expected project-life duration.

The incremental benefits analysis is but one component of a system selection process which, in turn, is a component of a freeway traffic management decision process. The major components of this decision process include the following:

- Developing a basic analysis of freeway operations.
- Making a detailed analysis of freeway operations and determining improvement alternatives.
- Examining the feasibility of ramp control as an improvement alternative.
- Analyzing the site conditions and selecting the control level.

A detailed discussion of the incremental benefits of different types of ramp metering control is provided in NCHRP Report 232.[19]

EXIT RAMP CONTROL

Exit ramp control is seldom used as a means of freeway traffic control because the opportunities for its effective application are limited. In many situations, the use of exit ramp control may actually be contrary to the objective of safe and efficient freeway operations. Also, it should only be used where destinations can easily be reached by using alternate exits.

Exit ramp closure can be used effectively to reduce safety hazards and congestion caused by excessive weaving between closely spaced ramps and long queues on exit ramps. Also, exit ramp closure can be used at a lane drop location by closing downstream exit ramps in order to encourage more traffic to leave the freeway at the exit ramps before the lane drop and thus decrease the demand on the freeway section beyond the lane drop. However, as in the case of entrance ramp closure, exit ramp closure might not be acceptable because of the increased travel it creates for some motorists.

EMERGING TECHNOLOGIES

As mentioned in the opening paragraph of this section, most of the advances and emerging technologies in freeway management systems are in the computing hardware and communications technologies. While development of those fields will continue to enhance the ramp control process, there will be emergence or at least advancement, from preliminary stages of freeway ramp control systems. Such advancements include:

- **System Operation.** As freeway systems expand with more communications links, and detector data become available, there will be increased system operation of entrance ramp meters, with metering rates being determined on a system or subsystem basis.

- **Integrated Systems.** Earlier freeway management systems generally operated independently of the operation of surface street signal systems. In lieu of actually being integrated through hardware and communications links, traffic state and local system managers sometimes communicated informally to bridge the two systems. Future systems will likely be fully integrated, with data exchange and control decisions being made automatically with real-time data.

- **Information to Motorists.** Advanced information systems being installed or planned as part of the ITS deployment and expansion will assist motorists in selecting or bypassing entrance ramps where metering rates may be restrictive. Such diversion can be considered in integrated freeway and surface street systems.

- **Advanced Control Algorithms.** The National ITS Architecture Implementation Strategy provides an evaluation of ITS Technology Areas as to their maturity (mature, immature, mixed) to assess their potential deployment horizon.(2) While most of the elements are hardware oriented,"processing technology and advanced algorithms that enable advanced vehicle and traffic control application" are designated as mixed, meaning that there is opportunity for emerging applications.

- **Advanced Ramp Metering Concepts.** Because queues become critical under heavy ramp demands conditions, improved queue management algorithms based on multipoint detection are under development. Also, traffic responsive activation of ramp control will likely be used to manage traffic during off-peak or weekend incident conditions.(7)

5.4 LESSONS LEARNED

Although ramp control systems have been in operation in various metropolitan areas throughout the country for over a quarter of a century, they are still sometimes viewed as a "new or radical" approach to traffic control and management. Intersection traffic signals, on the other hand, are accepted by most drivers as necessary and, in fact, their installation is often requested by citizens. The two systems essentially perform the same function: **Facilitate use of available capacity between conflicting vehicular movements on the basis of demand levels and safety considerations with traffic signals.** However, the ramp signal may be viewed negatively by drivers, because freeways have been traditionally designed for unrestricted flow. In reality, the flow is often restricted by recurring and non-recurring congestion that may have a greater effect than that of the meter signal, which may encourage the driver to divert. For these reasons, there are certain "lessons learned" associated with ramp control which may not be a factor in other traffic and freeway control elements.

IMPLEMENTATION

Public Relations

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.[1]

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 systemwide, 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.[1] The campaigns should also provide realistic expectations of the system's 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 1. 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 system should begin well in advance of turn-on. In Seattle, the Washington State DOT (WSDOT) has developed a methodical approach to implementing ramp metering.[30] 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.[1] 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).

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.[31] 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 an uniformed, negative story is written.

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 disruption of traffic flow should be considered first. Ramps should be operated with metering rates that cause little disruption. As drivers become familiar with and accustomed to the system, metering rates can be tightened and other locations implemented.

An interesting approach has recently been employed in Houston. Some of the pioneering efforts in ramp control took place in the mid-sixties.[12] However, due to reconstruction of freeways, ramp metering had not been in operation for some time. When ramp metering was recently reimplemented, a conservative philosophy was developed. The Implementation philosophy was as follows: [32]

> *... 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.*

Implementation Summary

The successful implementation of a freeway ramp control system is dependent on many factors outside of the hardware, software, and control algorithms. The implementation plan must include involvement, education, and support by the public, media, and political leaders. Additionally, the strategy with which individual ramps and subsystems are "turned on" must be carefully considered, planned, and executed.

OPERATIONS AND MAINTENANCE

Operations and maintenance considerations are not unlike those for other freeway control subsystems or for other traffic signal control systems. While the strategies may differ, there is still a necessity for operating agencies to commit the funds for personnel to operate, maintain, evaluate, and update the control system.

- **Personnel.** Adequate personnel for system operation and maintenance are essential if systems are going to succeed and continue to succeed. While improved hardware and software capabilities have allowed many tasks to be automated in system operation, personnel must be assigned to ensure continued efficient operation.

- **Training.** Training for system operations and maintenance is usually provided by the systems contractor. Continuing training programs will be essential as new personnel are assigned and as hardware and software upgrades are implemented.

- **Documentation.** Initial documentation for system operation and maintenance should (**must**) be provided by the systems contractor. Operations and maintenance personnel must also ensure that documentation is updated as system changes or hardware upgrades are made. Detailed logs should be kept for such changes. Modern systems often incorporate automated logging capability to facilitate the task and ensure that records are consistent.

- **Evaluation.** Although effectiveness of ramp control techniques has been well documented in the literature, it is usually necessary to perform "before and after" studies to document results of each system. It will also be important to continue to sample system operation with the same type data used in the initial evaluation to detect changes in system operation performance.

- **Updating Initial Strategies.** Based on continued system monitoring, as mentioned above, changes in individual control parameters or control strategies may be warranted. These may require minor changes to the data base or more significant changes to the control programs. Changes in the roadway system, both freeway and surface streets, must also be monitored and considered.

- **Incorporating New Strategies.** As ramp control systems continue to grow and mature, new ramp control algorithms will likely also be developed and tested. Continued communications among system operators and participation in professional organizations such as the Transportation Research Board (Freeway Operations Committee), Institute of Transportation Engineers, and Intelligent Transportation Society of America will be beneficial in becoming aware of such strategies.

- **Hardware and Software Maintenance.** Hardware maintenance may be performed either by the agency or by contract, or by a combination of the two. The responsible agency will likely maintain standard traffic control equipment and communications cables. Computer and communications hardware will usually be maintained by contract. Software data bases will normally be maintained by the responsible agency, while applications and system software will be maintained by contract. Whatever the method, agency or contract, maintenance responsibilities should be clearly defined and understood in advance of system implementation. Sufficient funding must continue to be committed for hardware and software maintenance.

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.(1) However, it is 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.(33) The probable new traffic patterns, including diversion, can then 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 was not substantial. Evaluations of the impact of metering on adjacent streets have been conducted in Los Angeles, Denver, Seattle, Detroit, and other cities. Significant diversion from the freeway to surface streets did not occur in any of these locations. Formal and informal agreements are common between State and local jurisdictions in connection with metering projects, and close advance coordination between jurisdictions is highly recommended.(1)

In some cases, there may not be feasible alternates 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. (See discussion of Houston ramp metering above). Significant benefits in freeway flow and accident reduction still result from nondiversionary metering. The onset of mainline congestion consistently begins later in the peak period and ends earlier. On many days, the mainline does not break down 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.[34]

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.[1] The laws and penalties should be clearly explained. In cities where the advance publicity has been positive and plentiful, violation rates has 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. 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.

EQUITY

The complaint that ramp metering favors longer trips at the expense of shorter trips can be a controversial issue.[1] 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. 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 less objection. This strategy was used in Atlanta where northbound I-75, leaving the city during the evening peak, will be the first section metered. [33] In Seattle, the system was designed to allow more restrictive metering rates farther away from downtown. With the long trip length, motorists originating from the suburbs have the most to gain from improved freeway conditions. The minor additional delay experienced at the meters is more than offset by the reduced mainline travel times. In Milwaukee, where the question of equity has been a limiting factor in the expansion of metering, it is now proposed to expand the system by metering each ramp that contributes traffic to congested freeway segments. Metering rates will be designed to be comparable for all ramps. For example, if it is determined a 10 percent reduction in demand is needed on the freeway segment, metering rates will be established to reduce all ramp volumes by 10 percent. In addition, each ramp metering rate will be adjusted to the extent possible in order to ensure average motorist delays are about equal for outlying ramps and for closer in ramps.[35] 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.[36]

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. [1]

5.5 EXAMPLES IN RAMP CONTROL

There is extensive documentation of ramp control systems in the literature, much of which are cited in the reference lists in this handbook. An excellent summary of ramp control status, Ramp Metering Status in North America, was published by FHWA in 1995.[1] The history and case studies cited below were adapted from that report.

HISTORY OF RAMP CONTROL

The first metered ramp, as we know it today, was installed in Chicago on the Eisenhower Expressway in 1963. This first application, however, was preceded by successful tests of the effectiveness of metering traffic entering New York tunnels, and by ramp closure studies in Detroit. In Los Angeles, ramp metering began in 1968. That system has been expanded continually until there are now over 800 ramp meters in operation in L.A. County—the largest system in North America. Currently ramp meters are in operation in 23 metropolitan areas in North America These metering systems vary from a fixed time operation at a single ramp to computerized control of every ramp along many kilometers of a freeway.

Many reports have been written that document the potential successes and benefits of ramp metering. However, the true measure is in the continued growth of ramp metering installations. Since 1989, the number of operating meters in North America has increased from about 1600 to more than 2300, an increase of about 45 percent. Additionally, many existing systems are proposing expansions and/or upgrades. On the planning side, new ramp metering is being considered in numerous other cities as part of ITS early deployment plans or feasibility studies. By the year 2000, at least 33 cities in the United States and Canada will have functioning ramp meters. This will be 11 more systems than existed in 1989.

ENTRANCE RAMP METERING CASE STUDIES

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

Portland, Oregon

The first ramp meters in the Pacific Northwest were installed along a 10 kilometer section of I-5 in Portland in January 1981. The meters are operated by the Oregon Department of Transportation. I-5 is the major north/south link, and is an important commuter route through the metropolitan area. This initial system consisted of 16 metered ramps between downtown Portland and the Washington state line. Nine of the meters operated in the northbound direction during the p.m. peak, and seven controlled southbound entrances during the a.m. peak. The meters operate in a fixed time mode. There are currently 58 ramp meters operating on 5 different freeways.

Prior to metering, it was common along this section of 1-5 for platoons of vehicles to merge onto the freeway and aggravate the already congested traffic. The northbound PM peak hour average speed was 26 ki/h. Fourteen months after installation, the average speed for the same time period was 66 ki/h. Travel time was reduced from 23 minutes (but highly variable) to about 9 minutes. Premetered conditions in the southbound a.m. peak were much less severe, hence the improvements were smaller. Average speeds increased from 64 to 69 kph, resulting in only slight reductions in southbound travel times.

Additional benefits that were evaluated for the p.m. peak period included fuel savings and a before-and-after accident study. It was estimated that fuel consumption, including the additional consumption caused by ramp delay, was reduced by 2040 liters of gasoline per weekday. There was also a reduction in rearend and sideswipe accidents. Overall, there was a 43 percent reduction in peak period traffic accidents. [37]

Minneapolis/St. Paul, Minnesota

The Twin Cities Metropolitan Area Freeway Management System is composed of several systems and subsystems that have been implemented over a 25-year period by the Minnesota Department of Transportation. The first two fixed time meters were installed in 1970 on southbound I-35E north of downtown St. Paul. In November 1971, these were upgraded to operate on a local traffic responsive basis and 4 additional meters were activated. This 8-kilometer section of I-35E has been evaluated periodically since the meters were installed. The most recent study shows, that after 14 years of operation, average peak hour speeds remain 16 percent higher, from 60 to 69 ki/h, than before metering. At the same time, peak period volumes increased 25 percent due to increased demand. The average number of peak period accidents decreased 24 percent, and the peak period accident rate decreased by 38 percent.

In 1974, a freeway management project was activated on a 27-km section of I-35W from downtown Minneapolis to the southern suburbs. In addition to 39 ramp meters, the system included 16 closed-circuit television (CCTV) cameras, 5 dynamic message signs (DMS), a 2-km zone of highway advisory radio (HAR), 380 vehicle detectors, and a computer control monitor located at the MnDOT Traffic Management Center in Minneapolis. This project also included extensive "freeway flyer" (express bus) service, and 11 ramp meter bypass ramps for HOV's. An evaluation of this project after 10 years of operation shows that average peak period freeway speeds increased from 55 to 74 ki/h, or 35 percent. Over the same 10-year span, peak period volumes increased 32 percent, the average number of peak period accidents declined 27 percent, and the peak period accident rate declined 38 percent. Over one million dollars a year in road user benefits are attributed to reduced accidents and congestion. This system also has positive environmental impacts. Peak period air pollutant emissions, which include carbon monoxide, hydrocarbons, and nitrogen oxides, were reduced by just under 2 million kilograms per year. [38]

Over 300 additional ramp meters have been implemented from 1988 to 1995, and there are currently 400 meters in operation. Further projects are now in the design and construction phases. The plans are to complete the ramp metering system which will cover the entire Twin Cities freeway network over the next five years.[39] The success of the Twin Cities system has shown that the staged implementation of a comprehensive freeway management system on a segment-by-segment, freeway-by-freeway basis, over a long period of time, is an effective way of implementing an area-wide program.

Seattle, Washington

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

One evaluation of the initial 22 meter system showed that between 1981 and 1987, mainline volumes during the peak traffic periods increased 86 percent northbound and 62 percent southbound. Before the installation of metering, the travel time on a specific 11-km course was measured at 22 minutes. In 1987, the travel time for the same course was measured at 11.5 minutes. Over the same 6-year time period, the accident rate decreased by 39 percent.[40]

A somewhat unique application of metering was implemented in Seattle on SR-520 in 1986. While diversion caused by metering is often controversial, one of the objectives of metering SR-520 was to reduce commuter diversion through a residential neighborhood. The meters were installed on the two eastbound ramps on SR-520 between I-5 and Lake Washington. One of these ramps, the Lake Washington Boulevard on-ramp, is the last entry onto SR-520 before the Evergreen Point Floating Bridge. Because there were no bottlenecks downstream of this ramp, traffic would normally flow freely on the bridge and beyond. Motorists, especially commuters from downtown Seattle, were using residential streets to reach the Lake Washington Boulevard on-ramp to avoid congestion on SR-520. This on-ramp, however, was a major contributor to congestion on SR-520 because of the high entering volumes. By metering the ramp, it was anticipated that traffic diverting through the adjacent neighborhood from downtown would be discouraged by the delay caused by the meter. Motorists would instead use the Montlake Boulevard on-ramp, which was also metered at the same time. A HOV bypass lane was also installed at the Montlake Boulevard on-ramp. Two other objectives of this project were to improve flow on SR-520 and to encourage increased transit use and carpooling.

An evaluation of this two-ramp meter "system" after four months of operation showed there was a 6.5 percent increase in mainline peak period volume, a 43 percent decrease in the volume on the Lake Washington Boulevard on-ramp, an 18 percent increase in the volume on the Montlake Boulevard on-ramp, and a 44 percent increase in HOVs using the Montlake Boulevard on-ramp.[41] Another indication of the effectiveness of the combination of the HOV bypass and the improved SR-520 flow is a decrease of 3 minutes in METRO (King County Department of Metropolitan Services) transit travel times for buses traveling from downtown to the east, and a 4-minute decrease for buses traveling from University District to the east. The reliability of the bus travel times also improved, and METRO adjusted the schedules for these routes accordingly.

In 1993, the WSDOT implemented weekend ramp metering for the first time. Three ramps north of Seattle on southbound I-5 have been metered several hours due to heavy weekend volumes. Because of this success, in March of 1995, weekend metering was expanded to include four additional southbound ramps.

In April of 1995, WSDOT began operating seven southbound I-5 meters during the evening commute. This is WSDOT's first implementation of metering both directions of a corridor during the same peak period. The motivation behind this operational change is that the traditional reverse commute direction has become increasingly congested. Prior to this change, metering along this section had operated southbound (inbound toward Seattle) during the morning commute and northbound (outbound) during the evening commute.

Denver, Colorado

The Colorado Department of Transportation activated a pilot project to demonstrate the effectiveness of ramp metering on a section of northbound I-25 in March 1981. The initial system consisted of five local traffic-responsive metered ramps operated during the a.m. peak on a 4.7-km section of I-25 south of the city. Periodic after-evaluations revealed significant benefits. An 18-month after study showed that average peak period driving speed increased 57 percent and average travel times decreased 37 percent. In addition, incidence of rearend and side-swipe accidents declined 5 percent due to the elimination of stop-and-go conditions.

The success of the pilot project led to expansion of the system. In 1984, a central computer was installed and a System Coordination Plan was implemented that permits central monitoring and control of all meters. Since 1984, additional ramp meters have been added, until reaching the current number of 28. In late 1988 and early 1989, a comprehensive evaluation of the original metered section was conducted. A number of changes occurred between 1981 and 1989, the most significant of which was the completion of a new freeway, C-470, which permitted more direct access to I-25 from the southwest area and generated higher demand for I-25. Volumes during the 2-hour a.m. peak period increased from 6200 vph in 1981 to 7350 vph in 1989 (on 3 lanes). Speeds measured in late 1988 decreased from the original evaluation, but remained higher than the speeds before metering was implemented: 69 ki/h before, 85 ki/h after, in 1981, and 80 ki/h in late 1988. The frequency of accidents during the a.m. peak period did not increase between the time of original evaluation and 1989. As a result, the accident rate decreased significantly because of the increased volumes. Rearend and sideswipe type accidents decreased by 50 percent during metered periods.

An interesting unplanned "evaluation" of the system occurred in the Spring of 1987. To accommodate daylight savings time, all of the individual ramp controllers were adjusted one hour ahead. Unfortunately, the central computer clock was overlooked. The central computer overrode the local controllers, and metering began an hour late. Traffic was the worst it had been in years. However, this oversight did have a bright side for the Department of Transportation. Since this incident, the media has been even more supportive of ramp metering than before. [34]

In 1988, the Colorado Department of Transportation conducted a study to evaluate different levels of ramp metering control. The study compared ramp meters operating in local traffic-responsive mode versus meters operating under centralized computer control. The results showed that if local traffic-responsive metering could maintain freeway speeds above 90 ki/h, centralized control offered little or no additional benefit. However, if local traffic-responsive metering was unable to maintain speeds near the posted speed limit of 90 ki/h, centralized control was very effective. Data showed speeds increased 35.5 percent, from 50 to 68 ki/h, and vehicle hours of travel were reduced by 13.1 percent.[42] This evaluation shows the importance of implementing operating strategies that correspond to the needs of the freeway network.

Detroit, Michigan

Ramp metering is an important aspect of the Michigan Department of Transportation's (MDOT) Surveillance Control and Driver Information (SCANDI) System in Detroit. The SCANDI metering operation began in November 1982 with six ramps on the eastbound Ford Freeway (I-94). Nineteen more ramps were added on I-94 in January 1984 and three more in November 1985. An evaluation performed by Michigan State University for MDOT determined that ramp metering increased speeds on I-94 by about 8 percent. At the same time, the typical peak hour volume on the three eastbound lanes increased to 6400 vehicles per hour from an average of 5600 VPH before metering. In addition, the total number of accidents was reduced nearly 50 percent, and injury accidents came down 71 percent. The evaluation done by Michigan State also showed that significant additional benefits could be achieved by metering the three freeway-to-freeway connectors on this section of I-94.[44]

Austin, Texas

In the late 1970s, in Austin, the Texas Department of Transportation implemented traffic responsive meters at 3 ramps along a 4.2 km segment of northbound I-35 for operation during the a.m. peak period. This section of freeway had two bottleneck locations that were reducing the quality of travel. One was a reduction from 3 to 2 lanes and the other was a high volume entrance ramp just downstream of a lane drop. Metering resulted in an increased vehicle throughout of 7.9 percent and an increase in average peak period mainline speeds of 60 percent through the section. The meters were removed after the reconstruction of I-35 eliminated the lane drop in this section. [44] This situation shows the versatility of ramp metering in that it can also be used effectively as a temporary solution.

Long Island, New York

At the other end of the spectrum from Austin is the INFORM (Information For Motorists) project on Long Island. The INFORM project covers a 64-km long by 8-km wide corridor at the center of which is the Long Island Expressway (LIE). Also included in the system is an east-west parkway, an east-west arterial and several crossing arterials and parkways, a total of 207 kilometers of roadways. System elements include 70 metered ramps on the LIE and the Northern State/Grand Central Parkway.

In 1989, an analysis of the initial metered segment was conducted after 2 months of operation. For the peak period, the study showed a 20 percent decrease in mainline travel time (from 26 to 21 minutes) and a 16 percent increase in average speed (from 47 to 56 ki/h). Motorists entering at metered ramps also experienced an overall travel time reduction of 13.1 percent and an increase in average speed from 37 to 45 ki/h. The MOEs for this project include vehicle emissions. For this initial segment, the analysis indicates there was a 6.7 percent reduction in fuel consumption, a 17.4 percent reduction in carbon monoxide emissions, a 13.1 percent reduction in hydrocarbons, and a 2.4 percent increase in nitrous oxide emissions. The last is associated with the higher speeds. Initial observations of the effect of metering the 4-lane parkway on the INFORM project indicates the benefits may be even greater than those achieved on wider freeways. Intuitively this makes sense, because the impact of an unrestricted merge on only two lanes (in one direction) can be severe. (45)

A more extensive evaluation of the INFORM project was completed in 1991. Data from this study showed much more conservative results. It is believed that this study is more representative of the true traffic conditions. The main reason for this is related to the "queuing off" (shut-down of the meter due to excessive queuing) of the ramp meters. The original study did not include areas where metering was usually shut off due to heavy ramp volumes, while the later study accounted for all ramps. This evaluation showed that while throughput had increased only about 2 percent, the average mainline speeds had increased from 64 to 71 ki/h, or about 9 percent. However, for two separate bottleneck locations, data showed increases of 53 to 84 and 53 to 89 ki/h, or gains of about 36 and 40 percent respectively. This evaluation also included calculation of a "congestion index." This index is the proportion of detector zones for which speeds were less than 48 ki/h (30 mi/h). While no benefit was shown in the evening peak period, the morning peak period showed an improvement of 25 percent in the congestion index. The accident frequency rate also showed encouraging improvement, with a 15 percent reduction as compared to the control section. (46)

San Diego, California

In San Diego, ramp metering was initiated in 1968. That system, installed and operated by the California Department of Transportation (Caltrans), now includes 134 metered ramps on 110 plus kilometers of freeway. No detailed evaluations of metering have been conducted on the San Diego system since the early installations, but sustained volumes of 2200 vph to 2400 vph, and occasionally even higher, are common on San Diego metered freeways. A noteworthy aspect of the program is the metering of eight freeway-to-freeway connector ramps. Metering freeway-to-freeway connectors requires careful attention to storage space, advanced warning, and sight distance. If conditions allow, freeway connector metering can be just as safe and effective as other ramp metering. (47)

SUMMARY OF RAMP METERING BENEFITS

Metering entrance ramps can significantly improve mainline traffic flow. These case study evaluations, as well as others, show that metering consistently increases travel speeds and improves travel time reliability, both of which are measures of reduced stop-and-go, erratic flow. It should be emphasized that these benefits occurred even though, in most instances, mainline volumes had significantly increased. Metering helps smooth out peak demands that would otherwise cause the mainline flow to breakdown. A strong case can be made from the data reported that metering actually increases the throughput of a freeway. The data from Minneapolis, San Diego, Seattle, Detroit and Denver shows mainline volumes well in excess of 2100 vph per lane on metered sections, and sustained volumes in the range of 5 percent to 6 percent greater than for pre-metered conditions. Improved traffic flow, particularly the reduction in stop-and-go conditions, also reduces certain vehicle emissions. This has been shown in both the INFORM project and in the Twin Cities Freeway Management System.

The other direct benefit, but one that has not been fully quantified, is the reduction in accidents attributed to metering. The Dallas corridor provided a unique opportunity to compare vehicle crash experience in a ramp metering system.[(48)] Evaluation studies showed significant improvements in system operating characteristics as compared to the "before" conditions. However, during the first year of operation, metering was exercised only in the peak direction of flow. During that year, crashes in the metered direction decreased by 24 percent as compared to the previous year, while crashes in the non-metered direction increased by 12 percent. During the first three years of metering, total weekday (24 hour/day) crashes increased by 8 percent while accidents during ramp metering decreased by 18 percent. The other case studies presented in this report consistently show a reduction in crash rates of 24 to 50 percent. Minnesota Department of Transportation estimates over 1000 vehicle crashes are prevented each year on Minneapolis/St. Paul metropolitan area freeway due to ramp metering.[39] However, the benefits derived from accident reduction go well beyond the direct costs related to medical expenses and vehicle damage. To illustrate, assume an incident blocks one lane of three at the beginning of the peak period on a freeway with a 2-hour peak demand of 6000 vph. Studies show that an accident blocking one of three lanes reduces capacity by 50 percent. A 20-minute blockage would cause 2100 vehicle-hours of delay and a queue over 3 kilometers long, and take 2 1/2 hours to return to normal, assuming there were no secondary accidents or incidents. Clearly the safety aspects of metering are a major benefit.

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