

**THE DESIGN AND OPERATION OF RAMP METERING
FOR FREEWAY-TO-FREEWAY CONNECTION**

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Prepared for
CVEN 689

Advanced Surface Transportation Systems

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August 1993

SUMMARY

This paper has been written to provide a source for current conditions at connector metering sites within the United States. The paper serves the direct purpose of disseminating details relevant to practices and perspectives of connector metering operations and design.

Study sites were selected that represent current connector metering practices in the United States. Information about site specifics was then used to suggest a general plan for connector metering design and operation.

This investigation concluded that connector metering is a cost effective and proven resource for relief of recurrent congestion. Connector metering provides for a smoother dispersion of vehicles on interchange ramps and, in conjunction with ramp metering, can be used to blunt sharp peak-hour arrival trends. Connector metering also provides incentives for drivers to participate in other Freeway Management Strategies such as car-pooling, busing, and transit. Furthermore, connector metering provides increased equity along the freeway corridor and improves the efficiency of metering rates at other ramp locations.

TABLE OF CONTENTS

INTRODUCTION	I-1
Purpose of Paper	I-3
Objective	I-3
Scope	I-3
LITERATURE REVIEW	I-4
A Basis for Ramp Metering	I-4
RAMP METERING	I-5
Metering Control	I-5
<i>Fixed metering</i>	I-5
<i>Demand-responsive metering</i>	I-5
<i>System metering</i>	I-6
Vehicle Dispersion	I-6
Ramp Meter Hardware	I-6
METERING EVALUATION	I-10
Advantages	I-10
Disadvantages	I-11
CONNECTOR METERING	I-12
Connector Metering Hardware	I-12
CONNECTOR METERING EVALUATION	I-14
Advantages	I-14
Disadvantages	I-14
STUDY SITES	I-16
State of Minnesota	I-16
<i>Minneapolis and Saint Paul</i>	I-16
State of California	I-19
<i>San Diego</i>	I-19
<i>Los Angeles</i>	I-21
CONCLUSIONS	I-24
RECOMMENDATIONS	I-25
ACKNOWLEDGEMENTS	I-26
REFERENCES	I-27

INTRODUCTION

Today's traffic engineer is charged with an ever increasing transportation problem that is beginning to take national notice. Congestion on the nation's highways has reached un-parallel levels. It is perceived that almost one-half of the nation's urban interstate mileage experiences peak hour traffic that moves at speeds less than 35 mph (see Figure 1.) and by the year 2005, it is predicted that the average commuter will experience congestion at five times the degree already experienced in the mid 1980s.(1) In San Francisco alone, a resident can expect to experience nearly a full work week every year in congested traffic. The costs incurred from such devastating trends are also becoming very real. In 1988, the cost of congestion in U.S. metropolitan areas exceeded \$34 billion dollars.(1) This amounts to more money per year than Congress allotted for the entire National Highway System in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991.(2) Along with such monetary costs also come environmental costs; approximately 78 million Americans (41 metro areas) live in areas exceeding carbon monoxide standards. Some institutional programs such as the Clean Air Act Amendment of 1990 have begun reforms aimed at reducing air pollution in urban environments. Such legislation has placed a new emphasis on traffic engineers to aid in reducing urban pollutants through better management of city freeways and highways.

As the nation's urban areas become increasingly overloaded, engineers are searching for better methods to cope with the expanding number of commuters. In an attempt to control congestion on today's urban highways and freeways, transportation engineers are looking for new tools to implement in their Transportation System Management strategies (TSMs). Some of these new methods are focused directly at diminishing the severity of re-occurring congestion on city freeways. These programs are commonly referred to as Freeway Management Strategies and focus directly on urban environments. The following list provides some typical Freeway Management Strategies used to alleviate recurrent congestion;

- Entrance ramp control,
- Mainline control,
- Priority control,
- Work rescheduling,
- Ridesharing,
- Transit subsidies,
- Congestion pricing,
- Parking fees.

These strategies employ a variety of methods to help stabilize and repress congestion in today's urban environments. One of these methods is the use of ramp metering at freeway-to-freeway connections (connector metering) during periods of peak congestion. The theory supporting connector metering shares some of the same principles as entrance ramp control (the metering of surface-street ramp traffic onto freeways).

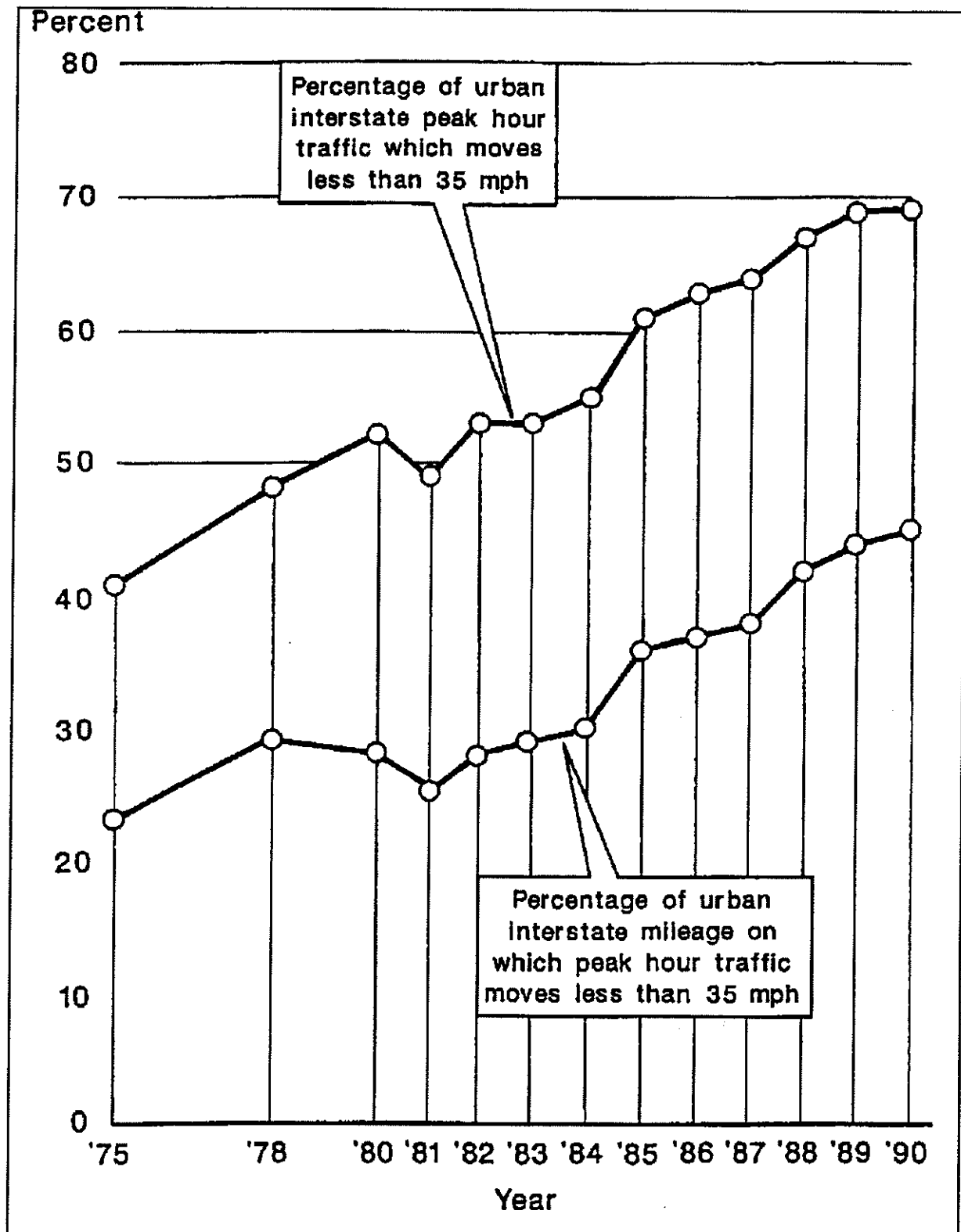


Figure 1. Congestion Trends in the United States (1).

One of the underlining concepts of the two types of metering is, that freeways can be maintained at high service levels through peak-congestion periods if; volumes entering the freeway combined with volumes on the freeway, are restricted so that the downstream volume is just below the freeway capacity. Studies have shown that ramp metering of surface streets to freeways can increase the capacity of freeway bottlenecks by preventing flow breakdown.(3) However, scant literature exists on how freeway-to-freeway connector metering should be designed and operated to achieve similar results.

Much of the information provided from studies on ramp metering is relevant to the concept of connector metering, because both systems attempt to prevent freeway breakdown through the control of access and the rate of arriving vehicles. In fact, some areas have the two systems operationally linked together.

Purpose of Paper

This paper has been written to provide a source for current conditions of connector metering sites within the United States. The paper serves the direct purpose of disseminating details relevant to practices and perspectives of connector metering operations and design.

Objective

This study researches current practices and identifies those measures that improve current conditions in connector metering design and operations. The influence of surface street ramp metering is also addressed, as it pertains to connector metering and the influence of metering operations.

Scope

Study sites were selected that represent current connector metering practices in the United States. Telephone interviews and written surveys were used to collect data pertaining to: geometric conditions of the connector, volume conditions on the connector and on the freeway, metering rates, perceived commuter attitudes of metering, and an appraisal of operations by the managing engineer. This information was then used to suggest a general plan for connector metering design and operation.

LITERATURE REVIEW

Freeway management techniques fall into two main categories: capacity management strategies and demand management strategies. Capacity management strategies seek to maximize throughput and improve the freeway level of service by managing vehicular demand on the freeway. Alternatively, demand management strategies attempt to reduce the number of vehicles using the freeway through various regulating policies.(4,5) The main objective of these Freeway Management Strategies is to improve the efficiency and safety of freeway traffic through better control of the factors leading to congestion.(5) Freeway connector metering is a capacity management technique that is a conceptual outgrowth of ramp metering. However, connector metering distinguishes itself by metering higher traffic volumes at higher vehicle speeds. In many cases, connector metering has been installed at approximately the same time as ramp metering so that it would appear as a logical component of a systemwide metering scheme.(6) In fact, many freeway management systems only use connector metering at interchanges when a majority of the surface street to freeway ramps on both of the intersecting freeways are also metered. Because ramp metering and connector metering share many of the same objectives, it is relevant to discuss the development and use of ramp-metering on freeways as a prelude to the discussion of connector metering.

A Basis for Ramp Metering

Recent research(3) probed the question, "Can surface street ramp metering increase the capacity of freeway bottlenecks by preventing flow breakdown?". The research recorded flow data from four bottlenecks in the San Diego. Data included detailed detector data and videotapes of traffic flow. Analysis of the data collected revealed that capacities at bottleneck locations decreased when queues formed. Furthermore, it was found that queues at on-ramps formed about 1,500 feet upstream of the merge point, rather than at the merge point itself. This situation occurred despite merge rates of approximately 2,500 to 2,800 vehicles per hour (vph) and flows downstream of on-ramps that commonly exceeded 2,400 vehicles per lane per hour (vphpl) and sometimes reach 2,600 vphpl.

One of the more startling findings was that merge conflicts were almost never the direct cause of flow breakdown at metered sites, despite merge rates at three of the sites that far exceeded the supposed capacity of the merge point. It was hypothesized that merge conflicts are more likely to lead to general flow breakdown at un-metered sites, especially at ramps where vehicles arrive at the merge point in groups.

RAMP METERING

The concept of ramp metering employs traffic signal technology to regulate the rate at which vehicles are injected into freeway traffic.(5) In controlling vehicle dispersion rates, the traffic engineer can also control the volume that is allowed onto the freeway. Since the early 1960s, freeway ramp controls have been installed in the United States and elsewhere, as stand-alone projects or as part of an overall freeway surveillance and control system.(7) These systems have utilized a variety of strategies to insert vehicles into mainline traffic by employing diverse applications of control and detector technology. In addition to fixed time and demand responsive approaches, some early methods sought to employ gap-acceptance models. Experimental systems such as *Pacer* and *Greenband*, attempted to use gap-matching algorithms to inject vehicles into mainline traffic. These earlier models used a series of detectors in the shoulder lane of the freeway, upstream of the ramp, to find acceptable gaps in the traffic stream. Meters on the ramp would then release a ramp vehicle so that its travel time would maximize the likelihood of a match with the gap in the traffic stream. However, the requirements of the gap-acceptance systems demanded complex and expensive equipment and results showed small incremental benefits.(7) Therefore gap-acceptance systems are not considered a serious option for current operational projects. As a result, many of the current metering operations rely on metering controls to disperse vehicles into mainline traffic.

Metering Control

Most of the current entrance ramp metering can be categorized by the type of control implemented for metering rates. There are three basic categories for metering; fixed metering, demand-responsive, and system metering.(8)

Fixed metering

The simplest form of control is the use of a fixed metering rate, with an optional vehicle detector for sensing the presence of the vehicle queue. The metering rate is determined by the expected mainline volume which is used to determine how much volume can be allowed onto the freeway at the particular ramp. Some of these systems use demand and passage vehicle detectors to initiate metering rates. Green indications vary from location to location, but generally the fastest metering rate is around 4 to 5 seconds long, translating to an entrance ramp volume of 900 (4 sec) to 720 (5 sec) vehicles per hour per a lane. Metering rates faster than 4 or 5 seconds are not used because the short cycle length does not provide adequate perception-reaction time for drivers. Fixed metering rate systems are operated in an isolated mode and do not adjust for changes in freeway traffic flow.

Demand-responsive metering

An enhancement of the fixed metering rate control is, demand-responsive metering. These systems are directly influenced by mainline traffic conditions. Metering rates are based primarily on real-time, locally measured traffic conditions. Vehicle detectors on the

mainline lanes provide occupancy levels which are used to establish the degree of metering. However, the effectiveness of this system is limited because there is no interconnection with other ramps, hence there is no faculty for global optimization of the freeway.

System metering

The next level of metering uses a system approach to manage the merging ramp demand. The system approach considers real-time information for traffic conditions on a section of the freeway. Metering in this scenario is typically imposed by a centrally controlled computer facility, but control intelligence may also be distributed among the individual ramps. Freeway traffic conditions are reflected by detectors throughout the system and analyzed at a central location, and then metering rates for all ramps are established in conjunction with a real-time metering plan. Recent system wide metering plans have emphasized local control of metering operations with a central control center serving as secondary level for metering supervision. Generally, centrally controlled operations are implemented with surveillance cameras to verify compliance of metering commands.

Vehicle Dispersion

How vehicles are released into the freeway traffic stream is usually a consideration of the demand volume at the ramp and the prevalent ramp geometrics. There are basically two types of vehicle dispersion: single-entry and platoon metering.

- Single-entry metering is when the signal timing permits one vehicle to enter the freeway per a green interval. This dispersion is predominantly used on single lane entrance ramps when demand volumes are below 900 vph, however it is perceived that this operation could be used on ramps with volumes up to 1200 vphpl.(9)
- Platoon metering is typically employed when ramp demand exceeds 900 vph. This metering technique allows for the release of two or more vehicles per a metering cycle. Platoon metering can be accomplished by either the use of tandem or two-or-more-abreast metering. Tandem metering is used on single lane ramps and deploys the vehicles one behind the other. Alternatively, two-or-more-abreast metering utilizes parallel lanes and allows vehicles to be released side by side in either parallel or staggered starts.(10)

Compared to single-entry metering, platoon metering has a number of disadvantages such as; greater driver confusion, greater probability of rear-end accidents, and greater possibility of disrupting freeway flow.(5)

Ramp Meter Hardware

Some state DOTs have created their own guidelines and standards for installing ramp metering hardware.(9) However, there are basically five main components to any ramp metering location; signal heads and standards, detector loops, signal controller, data line

services, and advanced warning signing. Placement of metering hardware is dependent upon lane geometrics and expected queue lengths.

- There are two types of signal heads that are commonly used for metering; the normal red-yellow-green three section traffic signal head or a two section, red-green signal head. These signal heads may be mounted in a variety of methods. The most frequent technique is to place a standard on the shoulders of the ramp lane(s) with a metering stop bar. One or two signals are mounted on each post depending on the estimated length of queue build-up. If one signal is used, it is directed at the driver in the front of the queue and if two signals are used the redundant signal is directed upstream of the queue. The two signals are usually employed to advise drivers in the back of the queue that metering is on and working. When there are three or more lanes of ramp traffic, each lane is provided with a signal head mounted on an overhead mast-arm support. This provides drivers in each lane with a clear signal message and reduces driver confusion. Typical signal mounting can be seen in Figures 2 and 3.(9)
- Vehicle detection on freeways and entrance ramps is commonly performed by loop detectors. Mainline detectors are usually located upstream of the entrance ramp nose and require two or more loop detectors per a lane of mainline traffic. The number of ramp detectors utilized depends on the type of metering control. Generally ramp operations require a check-in (demand) detector, a check-out (passage) detector, a queue detector, and a merge detector. The check-in detector is placed on the ramp approach and used to initiate metering. The check-out detector is located downstream of the meter stop bar and is used to note the passage of a vehicle. The queue detector is located upstream of the stop bar, usually at a point where maximum queue lengths are critical to operations. The queue detector is used to indicate severe delays and helps indicate when the metering rate may need to be increased. Some systems employ two queue length detectors to allow for an incremental increase in metering rates to diminish queue build-up. The merge detector is located in the vicinity of the ramp to freeway merge nose and is used to coordinate time and space entry for gap-acceptance metering.
- A controller is necessary at each ramp metering location to regulate metering rates. For systems that coordinate metering schedules and rates with a central computer, a standard controller type is used.
- Data and electrical services must be provided for each location that will employ metering. There are a variety of methods that can be used to transmit data requirements, but the most common is through telephone lines.
- Advanced warning is necessary at ramps where sight distance to metering operations is impaired or where queue lengths become excessive. Some areas have improvised the use of a flashing beacon mounted on a "Signal Ahead" (W41) sign.(9)

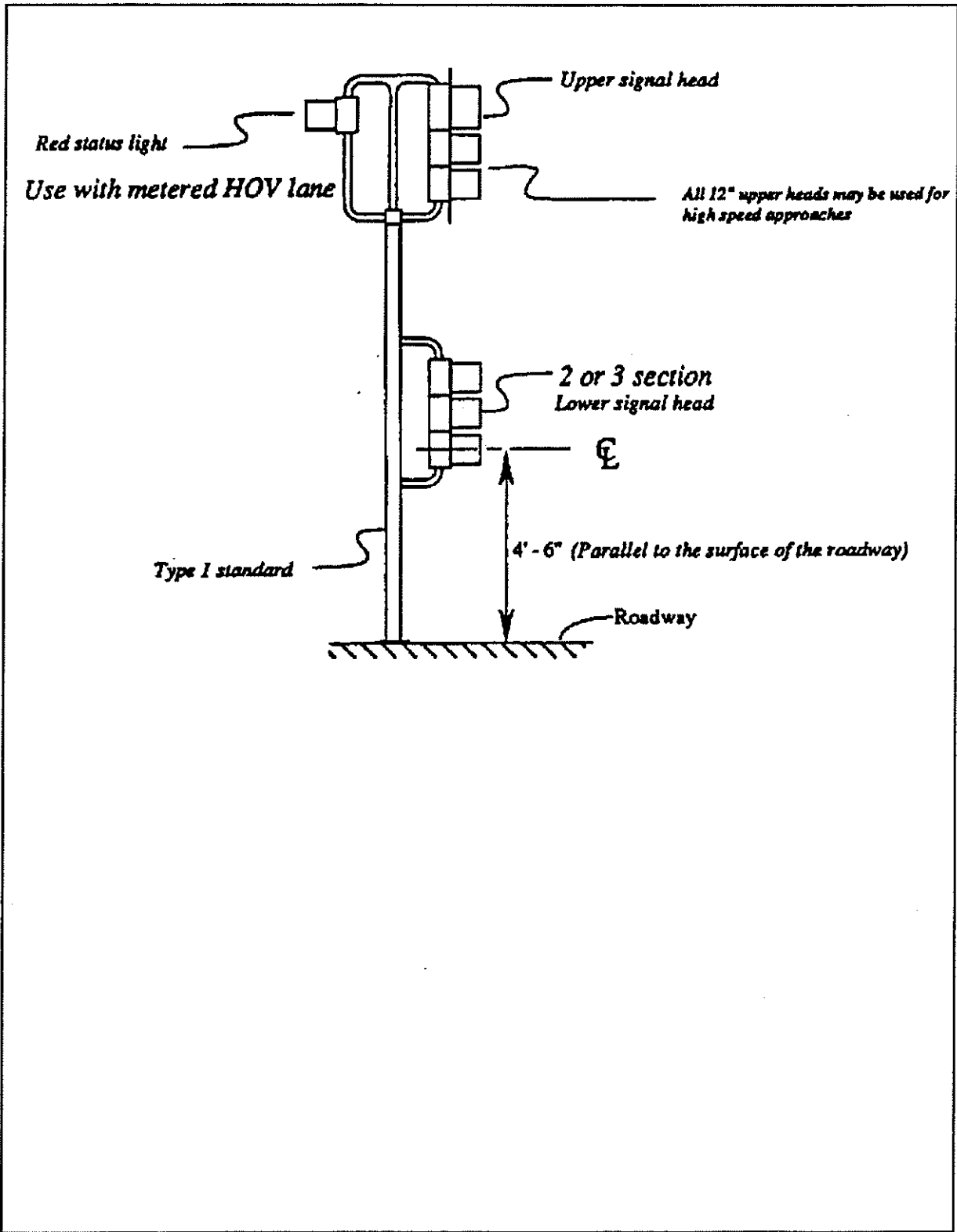


Figure 2. Typical post mounted signal standard (9).

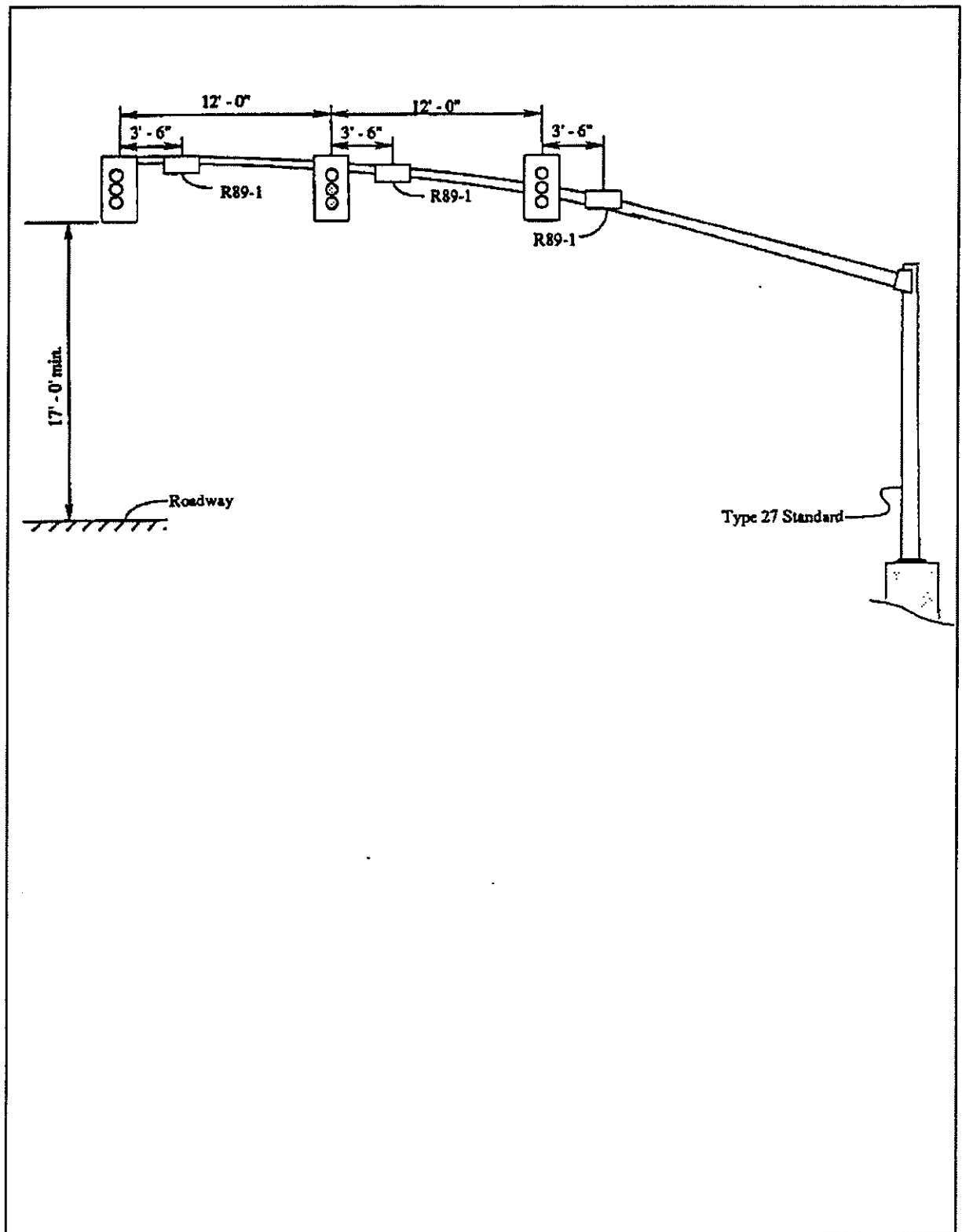


Figure 3. Typical overhead mounted sign (9).

METERING EVALUATION

There are several advantages provided by entrance ramp control. The principal concept behind ramp metering is in limiting the number of vehicles entering the freeway so that the demand on the freeway itself will not exceed capacity. Thus, the intended result of entrance ramp control is to maintain uninterrupted, uncongested flow on the freeway as long as possible. This is accomplished by transferring the delay factor from the freeway location to the entrance location. It is acknowledged that placing delay at the entrance ramps might compel some drivers to seek alternative routes in the corridor or choose another time period when demand is less, or choose an alternate mode of transportation. However the benefits seem to outweigh the costs. In Chicago, ramp metering was found to reduce congestion on expressways by up to 60 percent.(4) On the Houston Gulf Freeway a 25 percent reduction in travel times and a 50 percent reduction in accidents was attributed to ramp metering.(4) Other North American cities are reporting similar favorable experiences from implementing ramp control.(8) The Institute of Transportation Engineer's "*A Toolbox for Alleviating Traffic Congestion*" states that 'Ramp metering has proven to be one of the most cost-effective techniques for improving traffic flow on freeways.'(11) The following list contains a review of the advantages and disadvantages experienced from ramp metering.

Advantages

- Ramp metering provides a more predictable level of operation on both the mainline freeway and the on-ramp. Arrivals from nearby surface street signals can be smoothed out instead of overloading the freeway with periodic pulses of vehicles. Furthermore, metering can distribute the peak period demand and facilitate the merge of surface street traffic.
- Ramp metering can provide a reduction of friction in merging areas and may possibly reduce the work load of drivers in the merge area. Experience indicates that ramp metering will typically increase mainline traffic flow a minimum of five to six percent above un-metered conditions.
- The removal of congestion at entrance ramps directly translates to increased speeds on the mainline lanes. Speed studies have shown that areas with ramp metering have experienced mainline speed increases from eight to 50 percent when compared to the pre-metered conditions.
- Ramp metering is capable of diverting traffic to alternate routes when an incident occurs on the freeway. Combined with an Incident Management Strategy, ramp metering could improve emergency response time to an incident by diverting traffic around the incident area.

- Ramp metering has proven itself as an improved safety measure for entrance ramps. Accidents are a profound area of interest in freeway management strategies because they can cause major reduction in vehicle through-put and usually require a prolonged recovery time for freeway operations. Some areas have estimated as much as a 40 percent reduction in accidents after ramp metering was implemented.(5)

Disadvantages

- Ramp metering may divert traffic. This result has been argued as both an advantage and a disadvantage because diverting traffic from high volume problem ramps to other entry points may encourage shorter distance trips to avoid using the freeway. When diversion strategies are used, additional capacity should be available on the corridor to facilitate the shift in traffic volumes. The capacity should be great enough so that the diverted traffic does not simply appear as congestion elsewhere. Some agencies argue that very short trips should not be using the freeway and that diverting these trips may be viewed as an advantage.
- Ramp metering usually results in queue formation along the ramp. If excessive queuing occurs, queue lengths could extend onto the surface street system and disrupt local operations. In every case of ramp metering, adequate queue storage should be provided to avoid queue spillover into the surface street system.
- The issue of freeway user equity is one of the main arguments against ramp metering. This assertion states that ramp metering favors long distance trips at the expense of shorter trips, thus motorists living on the fringes of an urban area may not experience ramp metering or may have shorter metering rates than more centrally located motorists. Typically, as the mainline traffic reaches capacity more restrictive metering rates are employed to maintain an appreciable service level. However, the restrictive rates are generally employed in areas closer to the CBD and outlying areas are unaffected. Intuitively it would appear impractical to a motorist in the outskirts of the city to wait at an entrance ramp when the freeway in that area is uncongested.

Ramp metering provides improved reliability, increased mainline traffic volumes, increased mainline speeds, improved safety, rideshare incentives and temporal adjustments.

CONNECTOR METERING

Interchange metering is a form of entrance ramp metering that has been effectively expanded to better manage freeway traffic flow at freeway-to-freeway connectors. High volume and high speed traffic flow distinguishes connector metering from surface street ramp metering. Because freeway connectors discharge large demand volumes, it is perceived that such ramps would inundate local surface-street to freeway metering operations if they are left un-metered.(10) Thus, much of the same operational and design characteristics are shared between connector and surface street metering.

Connector Metering Hardware

Much of the same signal technology that is used for surface street ramp metering is also used in connector metering. Signal heads and standards, controller types, data line services, and the type of loop detectors are usually the same as those used in surface street metering. Most of the hardware differences are found in the placement of the queue loop detectors and in the placement and type of advanced warning displays. Generally loop detectors for connector metering are placed on the ramp to determine if queues are spilling into freeway mainline traffic. This is a critical area of importance to connector metering, because mainline freeway traffic operates at much higher speeds than surface street traffic. Therefore, a standing queue in mainline traffic presents a considerably higher risk to freeway drivers. Some areas have implemented more than one queue detection loop to allow incremental changes in metering rates to avoid the formation of extensive queues. Where extensive queues are expected, advance driver warning must be located well in advance of the queue. The metering plan shown in Figure 4. is a typical plan for connector metering on Los Angeles' Route 105 Century Freeway. This system employs an extinguishable message sign as advance warning, to alert freeway traffic of metering operations.

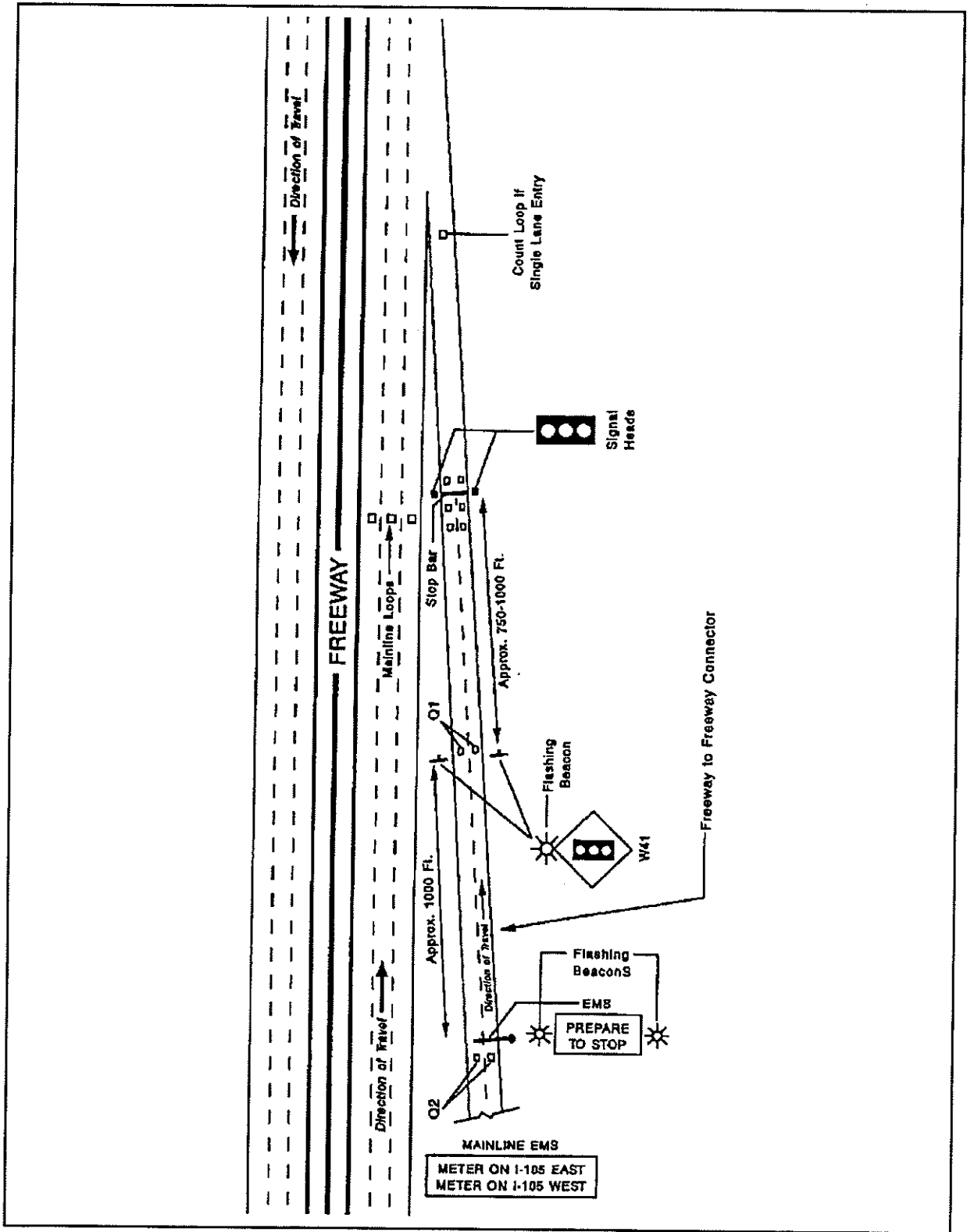


Figure 4. Typical connector metering plan (Source: Caltrans, Los Angeles).

CONNECTOR METERING EVALUATION

Despite some public opposition, connector metering is asserting itself as a viable tool in alleviating freeway congestion. Reports have indicated that the implementation of surface street to freeway ramp metering needs to be accompanied by connector metering to provide appreciable benefits.⁽⁶⁾ The following advantages and disadvantages outline where potential benefits can be found from connector metering.

Advantages

- Connector metering provides for displacement of queuing from the mainline to connectors, providing a consistent, controlled traffic situation with better safety characteristics.
- Connector metering in combination with ramp metering could provide additional support to Incident Management Strategies in avoiding an operational breakdown of the freeway due to an accident.
- Connector metering improves flow through the bottleneck area on the mainline, with attendant increases in traffic volume.
- Connector metering will improve the efficiency of on-ramp, entrance metering, upstream of the freeway-to-freeway interchange.
- Connector metering improves equity among drivers along the corridor.
- Connector metering provides diversion of connector traffic to alternate routes to provide better utilization of the freeway corridor.

Disadvantages

- Regulating traffic on an interchange connector will result in queues that may extend into the freeway mainline traffic and interrupt operations.
- Depending upon the location of the connector meters with respect to surface street meters, it is possible for a motorist to incur metering more than once for a single trip.
- Existing interchange configurations are not conducive to implementing metering and may require upgrading or geometric changes to provide the necessary storage requirements for queues.

- Probably one of the largest problems associated with any metering project is in convincing the commuting public that the systems do provide a measurable benefit. A successful project requires that the attitude of the public and of public officials be assessed and properly accounted for in presenting plans that include connector metering.⁽⁶⁾ Many projects have reported a barrage of complaints when initially implementing metering but find that these soon dissipate when time saving benefits from the system are realized.

STUDY SITES

An informal survey of several locations where connector metering is utilized was used to establish areas where differences occurred in operation and design of connector metering.

Many of the locations studied used metering at freeway connections during the morning peak period. The control of traffic during the morning, inbound rush is essential because it is generally impractical to meter outlying access to the freeway and therefore a large volume of inbound traffic is not controlled. In contrast, evening peak periods are managed by metering surface street traffic leaving the central business district (CBD). Metering of the outbound CBD traffic can provide a great degree of control in preventing the breakdown of the freeway.

The telephone interviews and written surveys established the location of several candidate study sites. Contacts were established in the Los Angeles and San Diego areas in California and also in the Minneapolis and Saint Paul areas in Minnesota. General information was collected pertaining to operation and design principles and, where available, details were collected for individual sites. Much of the information collected was found to be site-specific, relying on prevailing geometric conditions, sight distances, and traffic patterns for metering design and operation.

The following is a list of sites investigated:

State of Minnesota

Minneapolis and Saint Paul

Background:

Ramp metering has been used in the Minneapolis and Saint Paul metropolitan area, commonly called the "Twin Cities", since the 1970s. The Minnesota Department of Transportation (MN/DOT) has implemented extensive metering in the Twin Cities metro area. Ramp metering has proven to be the most effective element in MN/DOT's traffic management program for the Twin Cities, providing 316 metered ramps at the present day, of which 60 locations are freeway to freeway connector ramps.⁽¹²⁾ The sixty freeway to freeway locations encompass a variety of interchange ramps including: directional ramps, cloverleaf legs, cloverleaf loops, and collector distributor to mainline lanes. The metered collector distributor to mainline lanes each continue through two interchanges collecting two freeway ramps and one surface street ramps and then join the freeway. These lanes facilitate metering operations by providing a viable alternative to metering cloverleaf loops. Approximately thirty metered ramps, including four freeway connectors, have been designed to accommodate an exclusive High Occupancy Vehicle bypass lane.

Metered ramps are not treated individually, but as part of a system on a segment of the freeway or "zone". The beginning or upstream end of a zone is typically a free-flow location not subject to a high incident rate. Free-flow locations are generally downstream from a previous zone or locations on the fringe of urban areas. The downstream end of a

zone is typically where a controlling bottleneck occurs. These locations may be due to a lane drop or just downstream from major volume entrances. Typically these zones will be one direction of freeway travel for a three to seven mile length and will be established with a known capacity at a downstream bottleneck.(12)

Typically the mainline traffic at the upstream end of a zone is 40 to 60 percent of the total entering volume. Freeway connector volumes are generally 20 to 30 percent of the total entering volume and access from surface streets deliver the remaining 10 to 40 percent of the total freeway volume. MN/DOT surmises that metering is only effective if 40 percent or more of the entering traffic can be regulated, thus in some zones it is crucial to meter freeway to freeway connectors.

MN/DOT uses both isolated and system wide schemes for metering. The isolated systems rely on fixed metering rates that are programmed manually and locally. These sites do not use loop detectors and therefore, require field personnel to check operations on a regular basis. Typically these locations will be grouped together to form a zone. Currently there are eight isolated zones and 46 on-line zones established in the Minneapolis and Saint Paul area.

The system wide scheme is an on-line system that responds to real-time traffic conditions. To provide real time response, loop detector data is analyzed by a central computer every 30 seconds during operation and then commands are issued to the field controllers, which adjust the ramp metering rates. Commands issued to the field controllers are checked by video surveillance.

General Design:

Dual lane metering is MN/DOT's standard design for ramp metering operations. Where possible some ramps have been widened to two lanes, but usually this is part of a retro-fit project to allow two lanes of traffic on the ramp during off-peak hours. Signing and signal placement has been used to convert single lane ramps to two lanes of traffic during metering operations. Ramps that are one lane during non-metering times are converted to two lanes with advance regulatory signing stating the message, "FORM TWO LANES WHEN METERED". The metered freeway to freeway connector ramps are all two lanes of metered traffic with most locations merging to one lane before entering the mainline traffic. The connectors utilize the shoulder widths of the ramps as extra storage capacity when metering is on. This form of dual lane metering provides for additional queue storage capabilities and as a result, allows for operational flexibility of metering rates.

The general design of the signal control employs two signal pedestals located approximately three hundred feet back from the merging nose of the freeway and the connector ramp. The signal heads are located on both the left and right sides of the connector ramp which allows for an alternating release of vehicles. The signal lamps are mounted on pedestals at 5 foot and 10 foot heights. The 5 foot high meter is directed at the driver in the front of the queue and the 10 foot high meter is pointed upstream to inform drivers waiting in the queue that metering is on. Advance warning signing is usually a flashing beacon mounted above a "SIGNAL AHEAD" logo sign and is generally placed

300 to 600 feet upstream of the meters to give drivers advanced notice of metering operations. Approximately one-half of the connectors are designed with a post mounted flasher and signal logo sign to warn approaching traffic of metering operations. The connector ramps are usually cloverleaf legs or directional interchanges which provide 700 to 1000 feet of storage for queue formation. Increased geometric storage has been accommodated for a few of the connector ramps, however cloverleaf loop ramps remain an obstacle for construction of additional storage capacity. Cloverleaf loop ramps generally provide a length of 400 to 500 feet for queue storage.

Connector ramps are metered on all weekdays during the AM and/or PM peak periods. Generally, on-ramps delivering over 1500 vph have one metering rate during the peak period and the meters are turned off as soon as possible. The fastest metering rate for two lanes of ramp traffic has been determined to be 1700 vph, however the cloverleaf collector interchanges are not metered if volumes exceed 1600 vph. Instead, traffic volumes on these ramps are adjusted for in the algorithm used to establish the system metering plan.

General Perception:

Demonstrating the success of connector metering was difficult, but this was overcome by initially metering a small number of sites and then broadening the scope, once the success was apparent. Current conditions report excellent compliance to metering. It is believed that much of the driving population has a good understanding of metering operations and it is perceived that driver's are not assuming that metering is gap-matching.

Operations:

Studies of congestion, speed, and accidents are used to determine metering effectiveness, however, delay studies are not considered in evaluation. A study was performed by MN/DOT for a section of the freeway metering system near downtown Minneapolis during peak periods. The study revealed that during the peak period; roadway capacity increased from 1800 vphpl to 2200 vphpl, speeds increased 35 percent from 34 mph to 46 mph, accident rates (accidents per million vehicle miles) decreased 38 percent, fuel consumption was reduced by one million gallons per a year, and pollutant emissions were reduced by four million pounds per a year. It was estimated that one million dollars a year in road user benefits can be attributed to the reduction in accidents and congestion provided by the metering system.

State of California

San Diego

Background:

Ramp metering in the San Diego area began in the mid 1970s with the introduction of metering at a few sites. Today, there are approximately 124 metered ramps located within the San Diego area. The current system embraces a broad spectrum of metered ramp configurations, including one, two, and three lane ramps; single car and platoon dispersion; and preferential lanes for High Occupancy Vehicles (HOV). Some freeway connectors meter as many as three lanes and there are two locations where mainline metering has been employed. The San Diego metering scheme employs a modern traffic responsive system supervised by a central computer. The typical ramp meter is a locally controlled, demand-responsive controller which uses loop detectors in each mainline freeway lane and demand and passage detectors on each ramp lane to select proper metering rates. The controller chooses the metering rate as a function of mainline volumes but is also connected to a central computer to provide secondary level supervision. Metering rates vary from location to location, but generally the signal controller is programmed with a least restrictive and most restrictive release rate. From past experience with metering operations, San Diego DOT has surmised that the longest reasonable cycle length for metering is about 15 seconds, which establishes the most restrictive metering rate at 240 vphpl.(13) The least restrictive metering rate is based on the concept that each vehicle should come to a complete stop at the meter, so that there is never a question in the mind of the following driver about what the lead vehicle is going to do. Under these conditions, the minimum cycle length is about 6.5 seconds for one vehicle and 7 seconds for two vehicles in tandem, per cycle. Therefore, with two vehicles dispersing per a green, the least restrictive rate discharges 1000 vehicles per an hour. To avoid excessive queuing at metered locations where arrival rates exceed 1000 vph, the ramps are widened to two lanes before the meter and then downstream of the meter, narrowed to a single lane before the merge area. This provides additional storage for vehicles and allows for an increase in the dispersion volume at the meter.

General Design:

The California Department of Transportation has published a book of guidelines pertaining to ramp metering design. The publication delineates signing, signal placement, and loop detector placement for a variety of ramp types. Implementation of ramp metering has taken place over several years and therefore metering operations are conducted with a variety of signing and advance warning. Advance warning of metering operations has evolved from internally illuminated extinguishable message signs with flashing beacons to the more common changeable message signs. Some locations use a "SIGNAL AHEAD" logo sign with a "RAMP SIGNAL" supplemental plate for advance warning. Table 1. provides a list of freeway to freeway connector locations in the San Diego area and the lane type and peak period volumes at each location.

Table 1. San Deigo Connector Metering Locations.

Location	Lane Type	Peak Period Volume (VPH)
WB Route 94 to Route 94/125	2 SOV, 1 HOV	2400
NB (Loop) Route 15 to WB Route 94	1 SOV	150
SB Route 15 to WB Route 94	1 SOV, 1 HOV	800
NB I-805 to WB Route 94	1 SOV, 1 HOV	1000
SB Route 67 to WB Route 8	3 Mixed	1800

The Route 67 to Route 8 connector does not continue as three lanes along the entire ramp but is narrowed to two lanes downstream of the meter location. All of these connectors are metered for the inbound AM period. Although the ramp volume on the northbound loop at Route 15 and Route 94, is small in comparison to the other locations, it was initially metered to protect against diversion from other high volume ramps. In general, it is San Diego's policy not to meter a vehicle twice while they stay on an area freeway. Therefore, if the mainline lanes are metered in a certain location, then the surface streets upstream of the mainline metering location are left un-metered.

Operations:

Some connector metering sites have experienced queue storage problems resulting in spillover into the freeway mainline traffic. During the AM period, some ramps queue to about 1 mile causing delays of up to 7 minutes. However, conditions prior to metering at these locations experienced similar queue storage problems and therefore current conditions are considered an improvement to the freeway operations. There are no PM connectors that are metered. Table 2. provides some insight into the average and maximum delays and resulting queue lengths observed at each connector location.

Although the delays at the Route 94 to Route 94/125 and the Route 67 to Route 8 interchanges may appear to be excessive, both locations meter fast enough so that the queues never come to a complete stop. Instead, these locations process queues at a slow rolling or creeping pace. Despite the substantial delays at WB 94 to Route 94/125 and at SB Route 67 to WB Route 8 interchange, it is reported that there are relatively few complaints about operations. It is perceived that this is because drivers experience little congestion once vehicles are on WB 94 and Route 8. Even though these locations process about 2000 vph each during peak the peak period hour, there are fewer than one or two complaints in a two to three month period for each site.

Table 2. Delay and Queue Lengths for Connector Meters in San Deigo.

Location	Delay (minutes)	Queue Length (Feet)
WB Route 94 to Route 94/125	8 min aver./11 min max.	4000
NB (Loop) Route 15 to WB Route 94	less than one minute	-
SB Route 15 to WB Route 94	1 min aver./3 min max.	750
NB I-805 to WB Route 94	2 min aver./3 min max.	300
SB Route 67 to WB Route 8	7 min aver./8.5 min max.	3500

Los Angeles

Background:

Inquiries of connector metering in the Los Angeles area revealed several locations where connector metering operations are planned or are currently under construction for the implementation of metering. The locations found were at the following interchanges: the Santa Monica Freeway (I-10) at the Harbor Freeway (I-110) and the San Diego Freeway (I-405) and the Century Freeway (Route 105) at the San Deigo Freeway (I-405), the Harbor Freeway (I-110), the Long Beach Freeway (I-710/Route 7), and the Gabriel River Freeway (I-605/Route 605). Information on the Century Freeway metering plan has been included in this report because it depicts an aggressive, systemwide metering plan that has been planned in tandem with the conception of the Century Freeway design. An additional site, the interchange of the Golden State Freeway (I-5) and the Pasadena Freeway (Route 110) has also been included. This site is a metered freeway connector, however metering was implemented at the connector to "open up" the Pasadena Freeway to traffic from the Golden State Freeway during off-peak hours. This location is not a typical use of connector metering, but has been included to provide some insights of how connector metering can provide operational flexibility on freeways.

EB Golden State Freeway, I-5 & SB Pasadena Freeway, Route 110

Background:

The Pasadena Freeway exists as three lanes prior to the Golden State Freeway interchange, however at the interchange, the Pasadena Freeway becomes four lanes with the addition of one lane from the Golden State Freeway connector. During the AM peak period, the three lanes on the Pasadena Freeway were operating at capacity and the freeway downstream of the interchange could only accept additional traffic with the addition of the freeway lane from the connector ramp. The connector existed as a geometrically metered ramp (i.e. a location where throughput has been purposely constrained by the reduction in the number of lanes) that narrowed from two lanes to one before the on-ramp merge area

at the Pasadena Freeway. The connector ramp is on a 8 percent crest vertical curve which transitions to a horizontal curve with a speed limit of 25 mph. The two ramp lanes existed up to the crest curve but were then narrowed to one lane before the merge area. After the AM peak the Pasadena Freeway was capable of accepting more traffic from the Golden State Freeway, but the volume from the connector could not be increased because it was geometrically constrained. This resulted in congested traffic during all periods of the day on the Golden State Freeway, further resulting in recurrent breakdowns in mainline traffic. To alleviate this problem and open up the Pasadena Freeway, the connector was re-stripped for two lanes and metering operations were implemented.

General Design:

In addition to adding meters, designs for the new connector included re-stripping the two lanes along the entire length of the ramp. The lane assignment requires the inside ramp lane to merge with the outside freeway lane, but allows the right lane to exist as a continuous auxiliary lane to the next downstream exit. The metering signals are located before the crest curve begins, to avoid detaining vehicles on the vertical grade. The metering rate is 1800 vph (for two lanes) utilizing alternating 2 seconds of red and 2 seconds of green. Metering is only necessary during the AM peak period, from 6:30 am to 9:30 am.

Operation:

With metering in place the connector ramp is observing 1600 vph (for two lanes) and a reduced duration of congestion. Whereas, the old connector experienced queuing on the Golden State Freeway well into the afternoon, the new connector does not experience queues after 10:00 am. This location provides an example of how metering can provide operational flexibility in freeway management strategies.

Route 105 Under Construction from El Segundo to I-110

General Design:

This 18 mile long section of mostly concrete paved freeway, is an aggressive system employing full ramp metering and directional connector metering with four intersecting freeways. Design of the connector metering rates for the corridor was accomplished by using the Los Angeles Area Regional Transportation System (LARTS) traffic model to forecast traffic volumes. The freeway will be metered during both AM and PM periods when it opens in the fall of 1993. Utilizing the LARTS computer algorithm model a time of day metering plan was established for metering rates. Loop detectors or magnetometers (where concrete bridge decks inhibit the use of loop detectors) are utilized on all high volume connectors.

The metering plan previously shown in Figure 4. is the basic design for the connector metering used. The system is arranged to follow a preset scenario. When the meters are first activated the first and second extinguishable message signs (EMS) will display the appropriate messages, the W41 beacons will flash, and the ramp meter signal heads will

display a green ball. After a preset all green time, the first yellow will be displayed and then the time of day table programmed cycles will begin. The connector meters will operate above predetermined programmed threshold values utilizing system responsive, or location traffic responsive, or time of day program operations. It is expected that queues will form past the location of the first detector loop, Q1. When this occurs metering will be incrementally cycled to the fastest rate. If queues form to the position of the second detector loop, Q2 then the meter will go to a steady green until either the end of queue clears Q1 or the end of queue clears the meters as programmed. Once the queue clears its specified location (ie. the location of Q1) the meter will resume metering in accordance with the time of day specified rate. In instances where the connector ramps are combined to form one ramp, the smaller of the two Q1 distances will be used to initiate increased metering.

CONCLUSIONS

Connector metering is a cost effective and proven resource for relief of recurrent congestion. As a logical extension of ramp metering, it provides operational flexibility for freeway corridors and contributes to the large number of benefits that are found in Freeway Management Strategies. Connector metering provides for a smoother dispersion of vehicles on interchange ramps and in conjunction with ramp metering can be used to blunt sharp peak-hour arrival trends. Connector metering also provides incentives for drivers to participate in other Freeway Management Strategies such as car-pooling, busing, and transit. Furthermore, connector metering provides increased equity along the freeway corridor and improves the efficiency of metering rates at other ramp locations. Some additional user benefits from connector metering can be found in a decrease in accidents along connector ramps and at merge areas, a decrease in fuel consumption resulting in a reduction of emission pollutants, an increase of average freeway speeds during peak-periods, and a shortening of the peak-period duration.

RECOMMENDATIONS

Many interchanges that are experiencing local congestion due to lane drops or high merging volumes are candidate sites for connector metering. However, the site must be chosen carefully - not every connector can be successfully metered. The connector must be favorable for metering, that is, it should be capable of meeting queue storage requirements and practical metering rates. If necessary additional storage can be accomplished with construction of a lane addition on the ramp or re-striping of the ramp to accommodate two lanes of traffic. Connector metering relies on surface street ramp metering to effectively manage freeway corridors and should therefore not be implemented as a "stand alone" project. Connector metering locations should be part of a systemwide strategy for alleviating congestion and a central plan should be formulated to alleviate candidate bottleneck locations. Control of connector ramps should be kept at a local level, where mainline traffic data depicts the rate at which vehicles are dispersed. Supervision of metering operations can be done on systemwide basis from a central computer control facility. This scheme focuses on local control, but allows for a supervisory level of management and provides a method for overriding operations. The supervisory level of central control also permits the traffic engineer to ascertain and ensure driver equity along the freeway corridor.

Appropriate metering rates will vary from site to site and during initial implementation new locations should be kept at a high metering rate to avoid sharp public criticism. Gradual changes can be made to the metering rate once drivers have become accustomed to metering operations.

Advance warning is a critical issue in meeting safety concerns at new metering locations. Many systems are implementing changeable message signs as standard advance warning for connector meters. These signs allow for flexibility of information provided to the driver. These signs must be located well in advance of expected queue lengths to ensure that drivers are informed of metering operations before approaching slow moving queues.

The largest hurdle to overcome in implementing connector metering is public perception. Prior to installing metering on freeway connectors, a public education campaign can be used to inform commuters of the benefits that are attributed to metering. Adverse public reaction can be expected when metering is first initiated, but in several locations it was found that commuters actually asked for metering once the benefits of an uncongested freeway were realized.

ACKNOWLEDGEMENTS

The author would like to express his sincere gratitude to both Dr. Walter Kraft of Edwards and Kelcey Inc. and Mr. David Roper of Roper and Associates who served as mentor and co-mentor on this paper. Without their support this paper would not have been possible. The author would also like to thank Dr. Donald Capelle of Parsons Brinckerhoff Quade & Douglas, Mr. Joseph McDermott of the Illinois Department of Transportation, Mr. Edwin Rowe, and Mr. Gary Trietsch of the Texas Department of Transportation. To all of these mentors who I had the pleasure of meeting, I extend my warmest thanks and gratitude. The author also wishes to thank Dr. Conrad Dudek for his direction and guidance towards the completion of this paper. Special thanks to those professionals who managed time from their busy schedules to answer my questions:

Glen Carlson - Minnesota DOT
Richard V. Lau - Minnesota DOT
Max Wickham - San Diego Caltrans
Douglas Richter - Los Angeles Caltrans
David Gilstrap - Los Angeles Caltrans

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