Geometric Design of Metered Entrance and High-Occupancy Vehicle Bypass Ramps

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Freeway entrance ramp meters and high-occupancy vehicle bypass lanes are being used more frequently as one tool to address increasing traffic congestion. The geometric design standards and practices of states that operate these two technologies are reviewed. Signing, marking, signalization, enforcement area designs, and operating policies are also summarized to identify the significant aspects relating to the geometric design standards. Some of the installations are designed to less-than-desirable geometric standards as a result of constrained urban rights-of-way. Additional information or traffic control devices are often necessary to overcome these deficiencies.

Freeway entrance ramp meters are being used more frequently as one tool to address increasing traffic congestion. Allowing fewer vehicles to enter a freeway during peak traffic periods reduces the potential for accidents, encourages the use of streets for short distance trips, and can allow the freeway to move more vehicles at higher speeds. Regulating the flow of vehicles onto the freeway also eliminates the effect of upstream signalized intersections, which tend to produce platoons of vehicles separated by little or no volume. Entering vehicles can merge more easily with freeway traffic if the pressure from following vehicles is alleviated. A recent survey (*1*) of state departments of transportation (DOTs) indicates approximately 1,800 metered freeway entrance ramps in operation in North America.

Bypass lanes at metered entrance ramps represent a relatively low-cost priority treatment that can provide travel time savings to high-occupancy vehicles (HOVs). In some cases the amount of time saved on an HOV bypass of a metered ramp is sufficient to induce increased use of carpooling and transit, but more frequently it is a small incentive that can be combined with other measures to make high-occupancy travel more attractive. Approximately 450 HOV bypass lanes were in operation in 1991 (*1*).

This paper focuses on the current practice in design of these two freeway interchange elements. Most of the ramp meters and HOV bypass lanes that have been constructed to date are the result of "retrofit" design policies that made the most efficient use of space and funding. Where there are design standards or guidelines, it is frequently difficult to provide desirable design dimensions for freeway ramps that were not designed for the different operating characteristics of a metered entrance ramp. This paper, therefore, presents both "desirable" and "retrofit" design practice to illustrate both the application of typical design standards and what has been successfully operated by local transportation agencies. Whereas desirable standards are important to the design process, it is also important to note in a summary of the state of the practice the designs that appear to work well.

The American Association of State Highway and Transportation Officials guidelines (*2–4*) provide some guidance for the design of metered entrance ramps and HOV bypass lanes. Additional research may be required, however, to identify acceptable trade-offs between desirable standards, project benefits, and implementation concerns.

ELEMENTS OF METERED RAMPS AND HOV BYPASS LANES

The general configuration of the design elements of a metered freeway entrance ramp with an HOV bypass lane is shown in Figure 1. The figure shows a ramp from a cross street. A paint stripe is used to separate the HOV and general traffic flows from a point upstream of the queue to downstream of the ramp meter. Both lanes are metered in Figure 1. The lower signal heads face the vehicles at the stop bar, and the upper signals reinforce the Signal Ahead When Flashing sign and alert approaching vehicles.

Whereas there is no single arrangement of these elements that is common to all ramp metering projects, Figure 1 provides an overview of the design, signing, and marking details that are discussed in this paper. The entrance ramp could connect to a frontage road with a separate ramp for HOVs (Figure 2), or there could be two lanes available for queue storage of general-purpose vehicles. Some projects have used a buffer island to separate the HOV traffic and provide a location to install the signals. Most operating projects do not meter the HOV bypass lane as it enters the freeway. The HOV lane could be on either the right or the left side of the general traffic ramp lane.

REVIEW OF STATE PRACTICE AND GUIDELINES

The states of Arizona (*5,6*), California (*7,8*), Michigan (conversation with Michigan DOT officials, November 1991), Oregon (*9*), Virginia (*10*), and Washington (*11*) have specific

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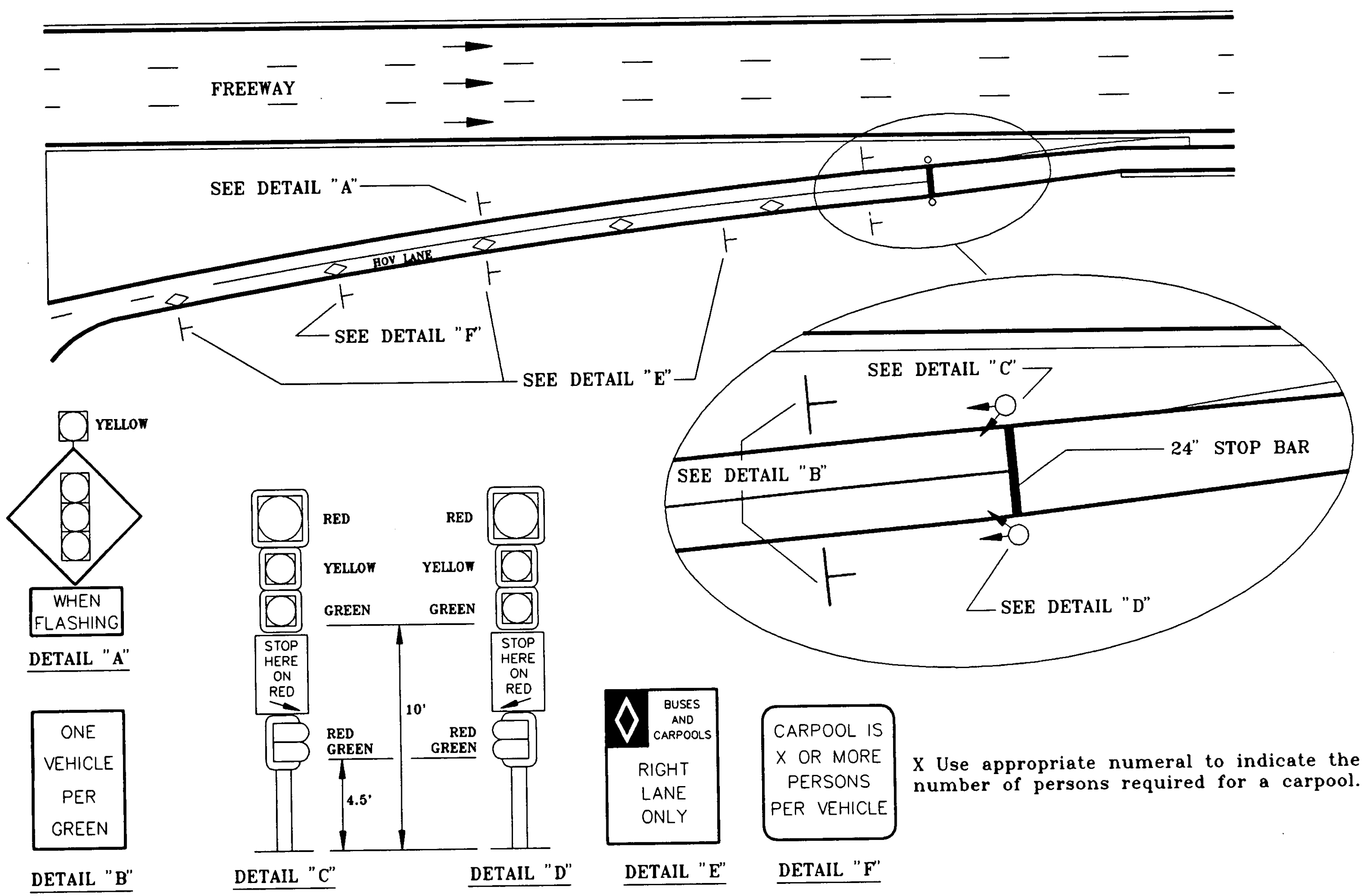

FIGURE 1 Typical ramp meter and HOV bypass lane installation (*2*).

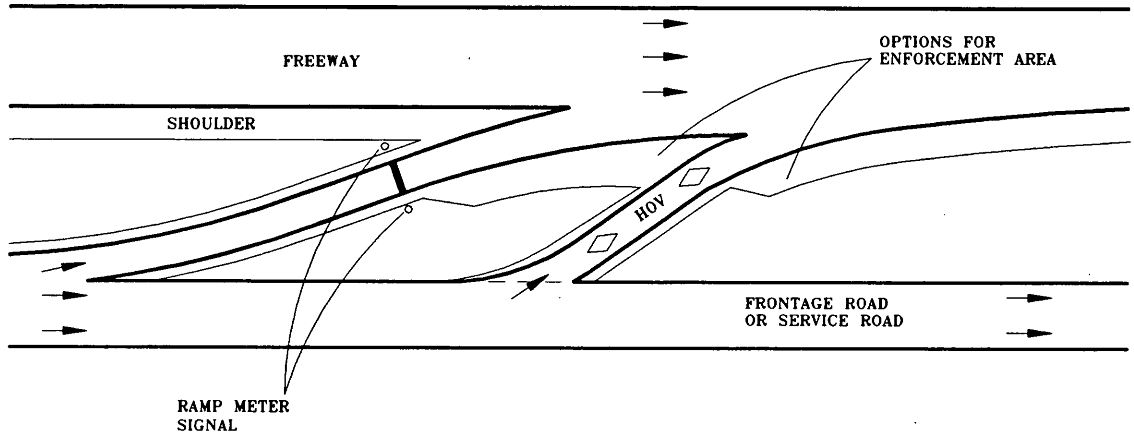

FIGURE 2 Separate HOV bypass lane at metered entrance ramp (*12*).

documents related to the design of ramp metering or HOV bypass lanes, or both. Several other states with operating ramp meters that were contacted for this paper had only general guidelines (conversations with officials of Colorado, Illinois, and Minnesota DOTs, November 1991) or used AASHTO documents as the source of design guidance. The major items specified in these documents included the following:

- Width of the entrance ramp lane and shoulders,
- Length of the entrance ramp and the merge area to the freeway lanes,
- Signalization,
- Signing and marking,
- Queue storage considerations,
- Separation of HOV and general ramp traffic, and
- Enforcement of HOV restrictions.

This section presents a summary of the design guidelines and existing practice of the state DOTs involved in ramp metering and HOV bypass lane operation.

Vidth of the Metered Entrance and HOV Bypass Ramps

Two methods of providing space for metered entrance ramps have been used on freeways in the United States. The more common method is for the metered lane or lanes to be striped for use during the day. If two lanes are provided to handle peak traffic demands, there is a significant amount of unused capacity during off-peak times.

An alternative method used in Minnesota (conversation with Minnesota DOT officials, November 1991) does not require new striping or additional lanes but rather uses signs and flashing lights to alert motorists to the need to form two lines on the ramp when metering is in operation. The signing directs the motorists to use the main ramp pavement and the paved shoulders to separate into two traffic queues during the low-speed operation during metering.

The desirable width reported most frequently for a one-lane ramp includes a 4-ft left shoulder, a 12-ft lane, and an 8-ft right shoulder. The range of desirable total ramp widths was between 20 and 27 ft (Table 1). These ramp widths are typical of those used in the initial freeway design; the introduction of ramp metering in these cases did not require any significant construction.

Two-lane metered ramp designs are usually installed in cases where a single-lane ramp would not provide sufficient storage capacity for the ramp queue that develops at the desired metering rate. If space permits, the design is similar to a regular two-lane ramp, with a 4-ft left shoulder, two 12-ft lanes, and an 8-ft right shoulder (which can be widened to three lanes by restriping). Some states use a ramp width of as little as 26 ft (two 13-ft lanes with no shoulders) to provide the additional storage capacity of two lanes.

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Priority treatments for high-occupancy vehicles at metered entrance ramps are provided as both separate ramps and additional lanes to existing general-purpose ramps. The separate ramp locations are designed with single-lane ramp design standards. The more common case of a lane being added to an existing ramp is usually handled using a paint stripe to separate HOV traffic (Figure 3). Most existing installations and design guides follow the dimensions reported for two-lane ramps, with one of the lanes being designated for HOVs. The Minnesota DOT (conversation with Minnesota DOT officials, November 1991) uses a 6- to 8-ft-wide buffer island (Figure 4) to separate two general ramp lanes from a 16-ft-wide HOV lane. The island is 300 to 500 ft long and is also used to provide a location to install the ramp meter signals for one general-purpose lane and for the HOV lane.

TABLE 1 Design Guidelines for Width of Metered Entrance Ramps

State	One-Lane Ramp	Two-Lane Ramp	Three-Lane Ramp
Arizona	22' Des.	24' Ret. 28' Des.	NS
California	24' (if less than 900 veh. per hour)	36' (if more than 900 veh. per hour)	40'
Colorado	18' Ret. 20' Des.	26' Ret. 32' Des.	8' island[2] 22' HOV lane
Illinois	20'[1]	None	None
Michigan	NS[1]	None	None
Minnesota	None	18' absolute min 22' Ret. 26' Des.	6'-8' island[2] 16' HOV lane
Oregon	26'	26'[3]	40'[3]
Virginia	NS	34'	
Washington	27'	36' Ret. 38' Des.	48'

Des. - Desirable dimension
Ret. - Retrofit dimension
NS - Not specified
None - No ramps of this type are in operation

[1] Width is determined by existing freeway entrance ramp
[2] Dimensions added to two-lane entrance ramp for HOV bypass lane
[3] Dimensions are currently being reviewed and may be increased

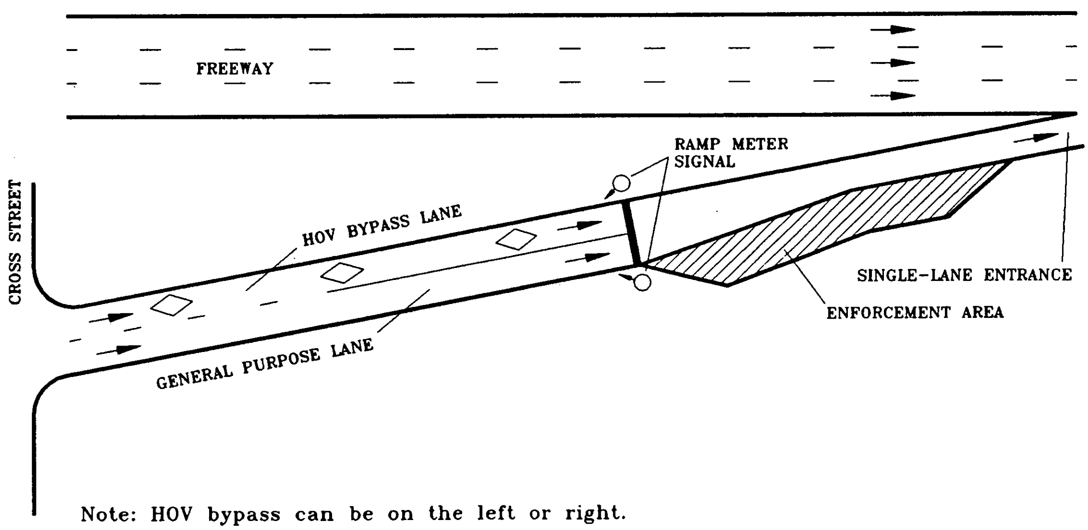

FIGURE 3 HOV bypass lane adjacent to general-purpose ramp lane (*2*).

Length of the Metered Entrance Ramps

The lengths of three design elements were specified in the design guides to illustrate metered entrance ramp design. Those elements were

- Cross street to the beginning of the ramp,
- Queue storage length on the entrance ramp, and
- Length from the stop bar to the freeway entrance gore point.

As with many aspects of metered entrance ramp designs, however, these three elements are heavily influenced by the general-purpose ramp design that was installed originally. The design process of metered ramps and HOV treatments in these cases usually focuses on dividing the available length to accomplish the most effective design. Factors considered in this design balancing process include cross street signal operation, available queue storage length, type of ramp meter operation (e.g., traffic responsive or fixed-time), enforcement area requirements associated with HOV restrictions, and accelera-

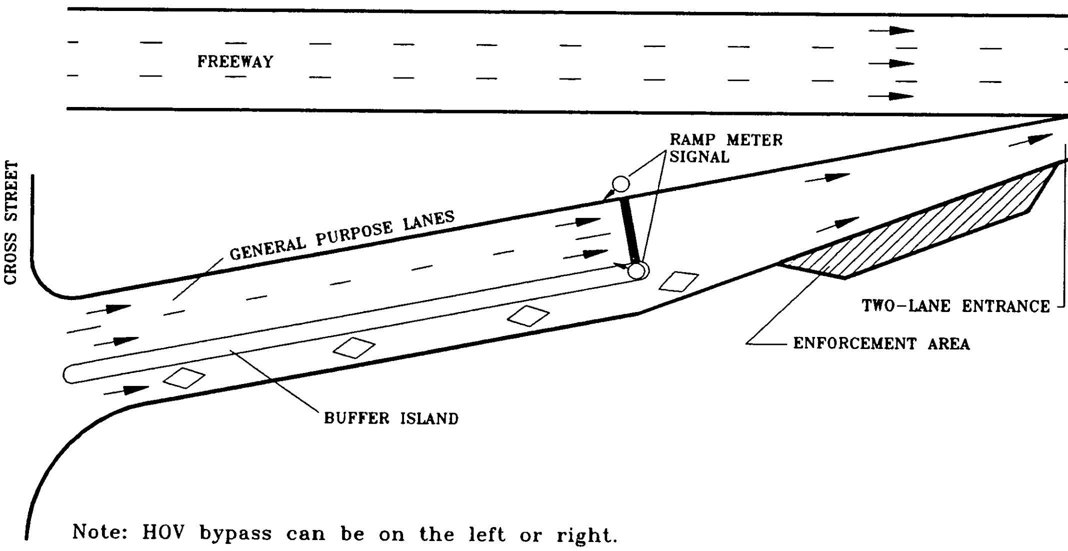

FIGURE 4 HOV bypass lane separated by buffer island from general-purpose ramp lane (*2*).

tion distance required to attain safe merging speed with the freeway traffic.

The distance from the cross street to the beginning of the entrance ramp is a dimension associated with freeway entrance ramps that begin from a frontage road or side street, rather than connecting directly to the cross street. The Minnesota DOT (conversation with Minnesota DOT officials, November 1991) has the only guidelines (Table 2) that include this dimension and lists 150 ft as a minimum distance, with 300 ft being desirable. This distance provides additional storage capability if the vehicle demand exceeds the metering rate by more than the amount that can be handled on the entrance ramp.

The desirable case, however, is for the queue to be contained on the entrance ramp. Street operating condition and safety can be increased if the queue does not interfere with the street traffic. The dimensions for required queue storage will vary on the basis of the freeway capacity and vehicle

TABLE 2 Design Guidelines for Length of Metered Single-Lane Entrance Ramps

State	Section of Entrance Ramp		
	Cross Street to Ramp	Queue Storage	Stop Bar to Freeway Gore
Arizona[1]	NS	760' Ret. 1010' Des.	340' 40 mph design 450' 45 mph design
California	NS	1000' Des.[2]	660' (30:1 taper)[3]
Colorado	NS	NS[4]	NS[5]
Illinois	NS	NS	300'
Michigan	NS	NS	250'[6]
Minnesota	150' Ret. 300' Des.	300' Ret. 500' Des.	250'-300' Ret. 400 Des.
(if HOV lane)			500'-600' (15:1 taper)
Oregon	NS	NS	250'
Virginia	NS	400' Ret. 1400' Des.	300'-350'
Washington	NS	500' Ret. 1000' Des.	700' Des. (50:1 taper)

Des. - Desirable dimension
Ret. - Retrofit dimension
NS - Not Specified; usually determined by site investigation and existing ramp design
[1] Document notes a desirable total distance from the center line of the cross street to the freeway gore of 1400 feet
[2] For three-lane entrance ramps and ramps with peak-hour volume exceeding 1500 vehicles, also need 1000' acceleration lane
[3] Document recommends study of individual ramp volumes to determine storage needs; allows use of cross street lanes to provide for adequate storage
[4] Provide maximum length possible for each site
[5] Put stop bar as close to freeway gore as possible and extend acceleration lane on freeway as needed
[6] Metered ramps are on a depressed freeway (ramps are on a downgrade approach)

demand and, therefore, are very localized design decisions. The retrofit distance referred to in the design guidelines ranges from 300 to 750 ft from the stop bar to the access street. The maximum or desirable distance ranged from 500 to 1,400 ft.

The type of ramp metering operation also affects the amount of queue storage required. Where traffic-responsive ramp metering is used, a higher-than-normal level of congestion on the freeway mainlanes could result in a longer queue than can be handled on the ramp. A queue detector induction loop located near the beginning of the entrance ramp can be used to modify the metering rate so that the queue does not impede operation on the cross street or frontage road.

The distance provided from the stop bar to the freeway lanes is a function of the speed that an entering vehicle needs to achieve at the gore point and the design of the ramp. The design guidelines identified in the preparation of this paper included a requirement that the speed at the end of the ramp be within 5 to 15 mph of the freeway speed. The distance that results from this requirement depends on the grade of the entrance ramp approaching the freeway. An additional consideration used by many DOTs is that the distance along the ramp may be reduced if there is an auxiliary lane present downstream of the entrance ramp junction. The auxiliary lane is used in these cases as an extended acceleration lane.

The reduced dimensions used by state DOTs for the location of the stop bar are those implemented with a downstream auxiliary lane; those dimensions ranged between 250 and 350 ft. The desirable distance for ramps without HOV bypass lanes ranged from 450 to 700 ft from the stop bar to the freeway gore.

Multilane ramps and ramps with HOV bypass lanes require more distance to merge the two or more lanes before they join the freeway mainlanes. The Minnesota practice (conversation with Minnesota DOT officials, November 1991) allows for at least a 15:1 taper (and desirably 45:1) to reduce the ramp to one entering lane. At HOV bypass locations where buffers are applied to segregate the parallel traffic streams, the minimum condition translates to a transitional distance of 500 to 600 ft. California's ramp meter guidelines (*7,8*) call for a 30:1 taper, with an additional 1,000 ft acceleration lane (12 ft wide) required beyond the ramp/freeway gore for three-lane entrance ramps (e.g., two general lanes and one HOV lane) or for ramps with high traffic volume (more than 1,500 vehicles in the peak hour). The Washington DOT guidelines (*11*) list a 50:1 taper beginning at the stop bar and continuing until the outside edge of the ramp pavement is within 2 ft of the auxiliary lane or freeway lane as the method of channelizing traffic flows from entrance ramps to freeway mainlanes. Some states, Colorado among them (conversation with Colorado DOT officials, November 1991), use a red indication extension on the general ramp lanes to provide an easier merge for HOVs.

As additional guidance to ramp designers, the Arizona DOT *Design Procedures Manual* (*5*) indicates that the desirable distance from the centerline of the cross street to the freeway is 1,400 ft.

Signal Design Considerations

Signal design on metered ramps should consider four functions of the ramp meter signalization:

- Signal operating condition: A three-headed signal mounted high on a pole is used in many states to alert approaching motorists to the status of the ramp metering operation. The signal is operated in a green indication for some period before metering begins, is then switched to amber for a short period, and is then switched to red. The signal then alternates between red and green for normal operation.
- Metering traffic flow: A two-headed signal mounted low and next to the stop bar is used as the driver's signal in most cases of single-lane metered ramps. For multilane ramps the signal is mounted above and in front of the stopped vehicle or on a pole adjacent the vehicle.
- Enforcement: A signal head or red indicator facing down the ramp can be used to alert enforcement officers to the signal indication. The officers can enforce both the signal and occupancy violations from a point downstream of the signal with this "tattletale" signal indication.
- HOV lane metering: Most HOV ramp bypass lanes are not metered because of a concern about a lack of perceived times savings if buses and carpools are required to stop at a signal. The design guidelines in California (*8*) and Minnesota (conversation with Minnesota DOT officials, November 1991) refer to the use of a ramp meter on the HOV bypass lane to reduce the speed differential between priority and nonpriority ramp traffic. Oregon also applies ramp metering to HOV bypasses. The meter is set at a relatively rapid rate so that HOV traffic is not significantly delayed. The meter has also been credited with increasing public acceptance of the bypass lane by requiring all vehicles to stop for at least some time and by reducing the presence of high-speed traffic immediately adjacent to traffic departing the signal at low speed.

Signing and Marking Considerations

The *Manual on Uniform Traffic Control Devices* (MUTCD) (*13*) includes a few examples of HOV lane signing practice. Many of the most frequently used signs at ramp meter installations, however, are not included in the MUTCD. A brief summary of the signs and their installation location is included in this design review to note the importance of the operational aspects of a successful ramp metering project. Additional guidance on ramp meter and HOV ramp signing in the MUTCD could improve the usefulness of that document for these facilities.

A sign located in advance of the entrance ramp alerts motorists to the presence of the ramp metering installation (Section 2C-17, MUTCD). This sign carries the diagram of a signal or the message Ramp Metered or, if implemented with a flashing signal, Ramp Metered When Flashing, Prepare To Stop When Flashing, or Signal Ahead When Flashing. The signing guidelines suggest that this sign should be located so that motorists can understand the message and stop before reaching the end of the ramp meter queue, especially in situations with limited sight distance to the end of the queue.

The One Vehicle per Green sign is used to notify motorists approaching the ramp meter and is located near the stop bar. In some states, when insufficient queuing space exists and more capacity is needed at the ramp meter, two vehicles will be allowed to proceed on each green. The additional message Each Lane is used where appropriate.

Stop Here on Red (Section 2B-37, MUTCD) is used with an arrow pointing to the stop bar to reinforce the meaning of the ramp meter signal. Wait Here for Green is also used to convey the same message in Illinois.

A special sign used in Minnesota (conversation with Minnesota DOT officials, November 1991) alerts motorists to the change necessary for peak-period operation. The Minnesota DOT has designed the metered ramps to operate as one lane during the off-peak periods and as a two-lane ramp during the metering operation. The sign carries the message Form Two Lanes When Metered and is located at the beginning of the ramp.

A lane reduction transition sign (Section 2C-19, MUTCD) and an optional Lane Ends sign are used downstream of the ramp meter signals on multilane installations to warn motorists of the reduction in the number of ramp lanes. The number of lanes is reduced to one before the ramp traffic merges with the freeway traffic.

HOV bypass lanes require signing to alert motorists to the restricted nature of the facility. Signs such as Right/Left Lane Carpools 2 or More Only When Metered (with some time period noted) or Carpools 2 or More Only (for 24-hr use) (Section 2B-20, MUTCD) are used with the diamond symbol to identify the restrictions.

The striping necessary to implement a ramp metering project is not a significant change from the usual ramp striping requirements. A stop bar is usually installed at the ramp meter signal. If a one-lane ramp meter project is placed on a full-width entrance ramp, chevron striping or jiggle bar tiles may be used to channelize the traffic flow and discourage motorists from passing the queue on the ramp shoulder. The diamond symbol is used on the HOV bypass lane pavement to reinforce the regulatory signing.

In addition to the signing that is used to designate ramp meter bypass lanes for HOVs, Car Pool Only markings have been installed on the HOV lane. A solid 8-in.-wide paint stripe has also been used in many states to separate the general traffic flow from the HOVs where there is no buffer or island provided to discourage vehicles from crossing into the HOV lane. On many operating projects, however, there has been no special striping involved in the HOV lane implementation other than that required to restripe a one-lane ramp into a two-lane ramp.

Enforcement of Ramp Meter and HOV Bypass Lanes

Several design elements and operating policies associated with metered ramps and HOV bypass lanes can assist the enforcement of the metering and HOV restrictions. The treatments used for enforcement of both are relatively similar and are discussed in the following section of this paper. Among the items considered by state DOTs and local police agencies are the following:

- Public information campaign: The successful public information programs have presented the goals and operating strategies of the ramp meter system and explained the traffic laws and penalties for violations. Among the items discussed are the function of the meters and the benefits of ramp metering implementation to the freeway system and to motorists. Briefings for traffic reporters have been used to convey the impact and benefits of ramp metering to individuals who have an effect on public opinion.
- Vehicle metering rate: The minimum acceptable metering rate varies by city and freeway condition, but the guidelines used in California are representative of the experience of operating agencies (*1,6,7*). The theoretical rate of vehicle flow through a meter is about 850 vehicles per hour per lane. The rate can be increased to 1,000 to 1,100 vehicles per hour per lane if two vehicles are allowed for each green. If the metering rate is faster, control over the ramp and the benefit to the freeway are diminished. Metering rates below 240 vehicles per hour (15-sec intervals between green signals) usually result in high violation rates and disrespect for the concept.
- Placement of enforcement areas: The success of a ramp metering project depends on the voluntary compliance of motorists. Early in the project, however, the presence of enforcement officers can significantly reinforce the meaning of the signs, signals, and markings. A paved enforcement area can encourage patrolling enforcement officials to provide this assistance to the concept. The involvement of enforcement officials at an early stage of the planning and design process can improve the usefulness of the enforcement areas and can increase the cooperation that is necessary for effective enforcement.
- Enforceable signs, signals, and markings: Traffic control devices that are consistent with the motor vehicle code and supported by the court system are important determinants for police support and, therefore, of the success of the project. California now posts the value of the fine at metered ramps; this has been effective in managing violations.

REVIEW OF AASHTO GEOMETRIC POLICY

The AASHTO *Policy on Geometric Design of Highways and Streets* (*4*) contains no specific guidelines for the implementation of either entrance ramp metering or HOV bypass ramps. AASHTO has produced two documents (*2,3*) that provide information concerning the design of HOV facilities and some information on ramp metering in general.

This section summarizes the recommendations of the more recent policy guidelines with regard to HOV bypass lanes, as well as the general remarks regarding metered entrance ramps.

Design of HOV Bypass Entrance Ramps

The 1992 AASHTO *Guide for the Design of High-Occupancy Vehicle Facilities* (*2*) discusses the need to balance the length along the entrance ramp for vehicle storage with the distance needed for vehicles to accelerate from the stop bar to freeway speeds. The 1990 AASHTO geometric design guide (*4*) uses a vehicle speed within 5 mph of the posted freeway speed at the end of an entrance ramp to design the acceleration lane. The 1992 HOV guide (*2*) suggests the use of the cross street for storage space if there is not sufficient length on the entrance ramp for both queueing and acceleration distances.

The AASHTO HOV guide (*2*) recommends that "the design of the ramp meter bypass . . . be determined by the conditions at each location." The HOV guide identifies a 12-ft lane with full ramp shoulders as the desirable cross section. The cross section should extend 300 ft beyond the metering signal to permit the priority and nonpriority traffic to merge before entering the freeway.

Bypass Lane Signing and Marking

The HOV guide (*2*) recommends the typical signing and markings found in the MUTCD (*13*) to identify the restrictions for HOVs. The regulatory signs summarized in the section on current state practice that are used to identify the appropriate lane and occupancy level are included in the guide. The use of the diamond symbol on the signs and on the pavement in the HOV lane is also recommended. A Yield sign may be necessary to assign the right of way downstream of a ramp meter location if both general and HOV traffic flows are present.

Bypass Lane Signals

The HOV guide (*2*) refers to both of the strategies used in current practice of signal design of HOV bypass lanes—metering and not metering the lane. The use of a meter on the lane, though decreasing the time advantage for buses and carpools, provides the opportunity to decrease the speed differential on the lane. The HOV guide recommends a Yield sign to assign right of way or a detector loop that will hold the general-purpose vehicles at the stop bar while the HOVs have a green indication, although this guideline has seldom been applied. No signalization is required for HOV bypasses that are on a separate ramp.

Enforcement Area Design

The dimensions associated with enforcement areas will vary according to the site characteristics, but the design in Figure 5 was included in the HOV guide to illustrate the principles involved. The California DOT (*7,8*) has a similar typical design in its HOV manual.

The area provides a refuge space for enforcement officers to observe driver obedience of the signal and HOV restrictions in a relatively low-speed situation. The area is also easily accessible by patrol officers on the freeway and could be connected to the street system (depending on local site conditions) to provide increased flexibility for patrol strategies. The HOV guide (*2*) mentions that violations increase when there is a clear view of the enforcement area and drivers can observe the presence or absence of patrol officers; some sort of screen may be desirable to reduce the need for continuous enforcement.

CONCLUSIONS

Freeway entrance ramp metering projects are in operation in approximately 1,800 locations in 13 states and one Canadian province (*1*). Whereas ramp metering is not a new concept [the first installation of ramp metering in the United States was in suburban Chicago in 1963 (*14*)], the factors required to make a project successful are present in only a limited number of cities and corridors. The ramp metering projects that have been implemented are on freeways that experience a significant amount of congestion, usually have a limited amount of right-of-way, and are sometimes installed as a stopgap measure because of an inability to widen the freeway.

As the fiscal and physical difficulties associated with widening freeways have increased, state departments of transportation have relied on transportation management techniques such as ramp metering to provide more vehicle movement capacity in an existing corridor. An addition to some projects that expands the role of ramp metering in increasing the person movement in a corridor has been a bypass lane for high-occupancy vehicles. This lane allows buses and carpools to achieve a time advantage relative to single-occupant vehicles and encourages the use of HOVs.

The implementation of intelligent vehicle/highway system technologies, which have as a basic goal the increased efficiency of the transportation system, may substantially increase the use of ramp meters and HOV bypass lanes to improve operation and provide for increased person movement capability.

One or both of these concepts, properly implemented and enforced, can improve the operation of a freeway corridor.

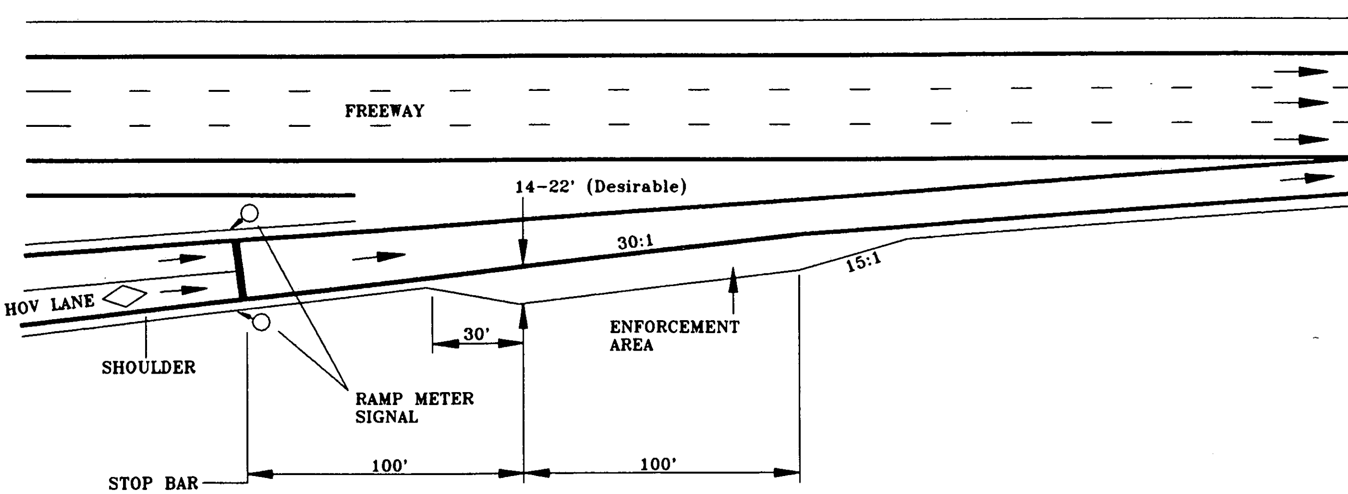

FIGURE 5 Enforcement area for HOV bypass lane at ramp meter (*2*).

Many states have constructed ramp meters and HOV bypasses in very constrained conditions, and they have worked well. This retrofit characteristic is frequently a balance between a less-than-desirable level of improvement and no improvement at all.

This paper presented a variety of designs that have been operated for some time by state DOTs that are convinced they provide a benefit to freeway operations. Some state DOTs have established rather stringent freeway operation policies that rely heavily on such metering concepts. These policies have been instrumental in widespread application of metering treatments in selected areas, and where such policies exist, geometric shortcomings are frequently accommodated in some way. Some designs work well because drivers are familiar with them and understand the behavior needed to overcome the inadequacies. A more detailed investigation of the compromises inherent in the implementation of ramp meters and HOV bypasses is needed to identify those approaches that work consistently well and those that, if installed, need more driver information to operate efficiently. That investigation should include such factors as traffic volume; number of lanes; ramp length; merge area; queue storage; signing, signalization, and marking; and ramp grade.

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