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16. Abstract The primary objective of this project was to develop improved ramp metering design and implementation guidelines for use by Texas Department of Transportation (TxDOT). These guidelines will provide for more effective design and implementation of ramp-metering systems at existing as well as proposed freeway entrance ramps. This report contains the documentation of research conducted by TTI during a one-year project funded by TxDOT. It includes: a review of current ramp metering practice in the United States, a review of current ramp metering practice in Texas, a review of design criteria, and the development of ramp-design guidelines.					
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**RAMP-METERING DESIGN AND OPERATIONS
GUIDELINES FOR TEXAS**

by

Nadeem A. Chaudhary, P.E.
Research Engineer
Texas Transportation Institute

and

Carroll J. Messer, P.E.
Research Engineer
Texas Transportation Institute

Report 2121-2

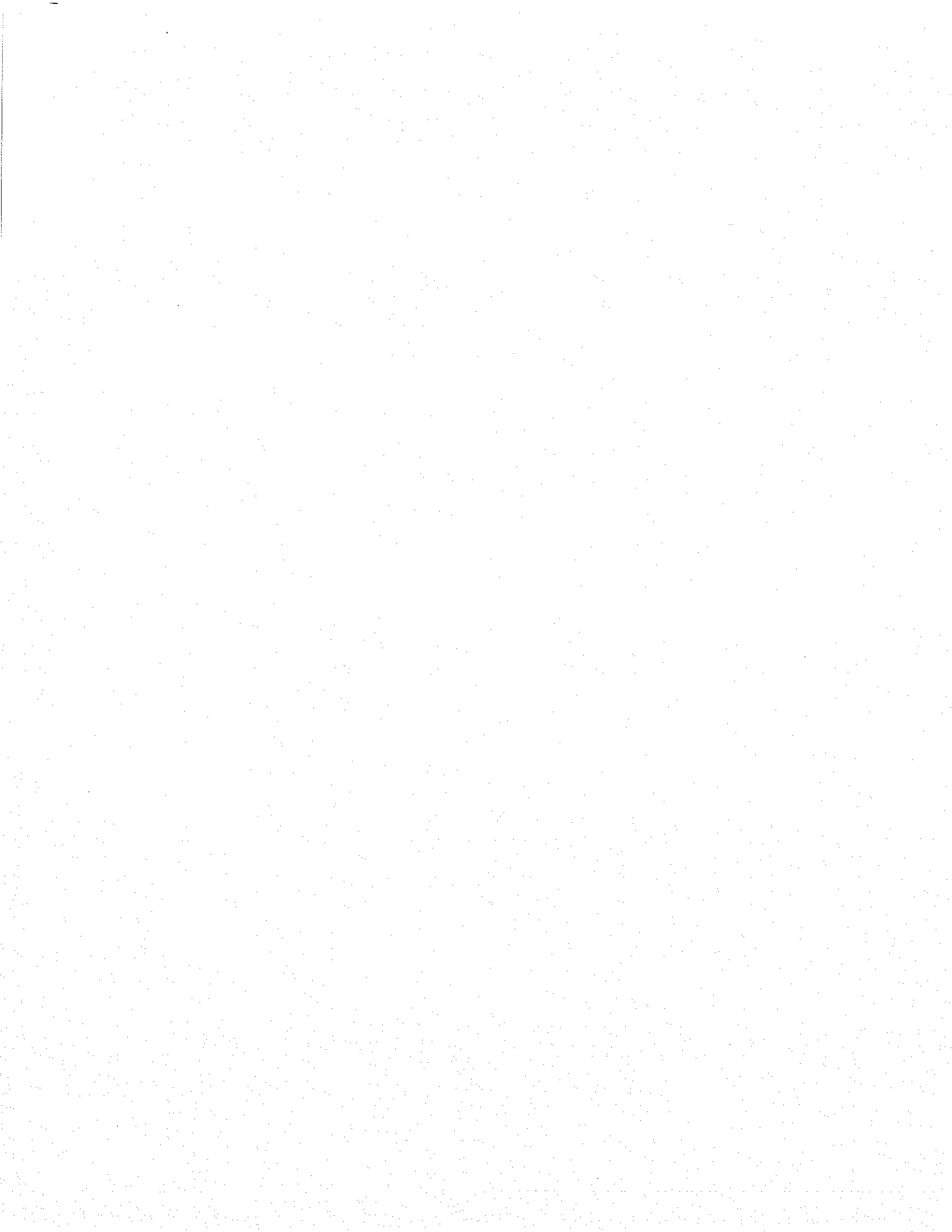
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The Texas A&M University System
College Station, Texas 77843-3135



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1. INTRODUCTION

By design, freeways are free-flowing facilities that are expected to provide a desired level of service to the motorists. In the past decade, however, urban growth and development patterns have placed tremendous burden on freeways in most metropolitan areas of the country. In many cases, it is not uncommon for the traffic to reach a stop-and-go state, especially during the peak periods. More frequent than not, these conditions persist for hours and may compromise motorist safety in addition to the tremendous cost in terms of lost time, delays, and increased fuel consumption and emissions. For a number of reasons, it is becoming more difficult to build out of this situation. In light of these factors, several State Departments of Transportation (DOTs) have implemented measures to mitigate freeway traffic congestion. Ramp metering is one such measure.

The initial use of ramp meters in Texas began in the mid 1960's. During the following years, ramp meters were installed in Austin, Dallas, Fort Worth, Houston, and San Antonio. However, most of these meters were later removed due to extensive reconstruction projects. All of these early ramp-meter installations were single-lane and allowed one car to enter the freeway per signal cycle. In most, if not all cases, on-ramp demands in Texas were well below the capacity (900 vehicles per hour [VPH]) of these meters. Furthermore, most ramp demands fell in the 300 to 600 VPH range (*I*). By the early 1990s, the reconstructed freeways in large metropolitan areas of Texas were again facing severe freeway congestion. Thus began the second era of ramp-meter installations. However, this time around, ramp demands were significantly higher than the capacity of the traditional single-lane one car per green meters. In fact, it is not uncommon for many ramps to experience demands in the range of 1200 to 1400 VPH. In a significant number of cases, the demand is even higher. However, engineers did not design the existing ramps in Texas with ramp-metering applications in mind, especially for the level of demands being experienced now. Furthermore, TxDOT does not have any guidelines for designing the ramp with explicit consideration of ramp-metering systems. TxDOT initiated this project to address this need.

OBJECTIVES OF RAMP METERING

Ramp meters are traffic signals that control traffic at entrances to freeways. Ramp meters are installed to address three primary operational objectives:

1. control the number of vehicles that are allowed to enter the freeway,
2. reduce freeway demand; and
3. break up the platoons of vehicles released from an upstream traffic signal.

The purposes of the first and second objectives are to ensure that the total traffic entering a freeway section remains below its operational capacity. The purpose of the third objective is to provide a safe merge operation at the freeway entrance. A secondary objective of ramp metering is to introduce controlled delay (cost) to vehicles wishing to enter the freeway, and as a result, reduce the incentive to use freeway for short trips.

Most urban freeways are multi-lane facilities that carry heavy traffic during peak periods. Furthermore, traffic demand at a single on-ramp is usually a small component of the total freeway demand. Therefore, metering a few ramps is usually not sufficient to achieve the first objective. In addition, drivers affected by a small ramp-metering system perceive such a system to be unduly taxing them, favoring those who have entered the freeway at uncontrolled ramps at upstream freeway sections. Thus, ramp-metering should be installed on a sufficiently wide section of a freeway if it is to achieve its expected benefits and keep the motorists happy. When properly installed, ramp metering has the potential to achieve the following benefits:

- increased freeway productivity,
- increased speeds,
- safer operation on a freeway and its entrances, and
- decreased fuel consumption and vehicular emissions.

TYPES OF RAMP METERING

When merge area of the freeway is not a bottleneck, an uncontrolled single-lane freeway entrance ramp may have a throughput capacity of 1800 to 2200 vehicles per hour (VPH). The same ramp will have lower capacity when metered. The maximum theoretical metering capacity depends on the type of strategy used. There are three ramp-metering strategies. These strategies are described in the following sub-sections.

Single-Lane One Car per Green

This strategy allows one car to enter the freeway during each signal cycle. Each signal cycle in Texas has green, yellow, and red signal indications. The lengths of green plus yellow indications are set to ensure sufficient time for one vehicle to cross the stop line. The length of red interval should be sufficient to ensure that the following vehicle completely stops before proceeding. From a practical point of view, the smallest possible cycle is 4 seconds with 1 second green, 1 second yellow, and 2 seconds red. This produces a meter capacity of 900 VPH. However, field observations have shown that a 4-second cycle is too short to achieve the requirement that each vehicle must stop before proceeding. Also, any hesitation on the part of a passenger-car driver may cause the consumption of two cycles per vehicle. A more reasonable cycle is around 4.5 seconds, obtained by increasing the red time to 2.5 seconds. This increase results in a meter capacity of 800 VPH.

Single-Lane Multiple Cars per Green

This strategy, also known as bulk metering, allows for two or more vehicles to enter the freeway during each green indication. The most common form of this strategy is to allow two cars per green. Three or more cars can be allowed; however, this will sacrifice the third objective (breaking up platoon). Furthermore, contrary to what one might think, bulk metering does not produce a drastic increase in capacity over a single-lane one car per green operation. This is due to the fact that this strategy requires more green and yellow times as ramp speed increases, resulting in a longer cycle length. Consequently, there are fewer cycles in one hour. For instance, two cars per green strategy requires cycle lengths between 6 and 6.5 seconds and

results in metering capacity of 1100 to 1200 VPH. This finding illustrates that bulk metering does not double the benefits and this fact should be noted.

Dual-Lane Metering

Dual-lane metering implementation requires two lanes on a ramp in the vicinity of the meter. In this strategy, the controller operates by alternating the green-yellow-red cycle for each lane. Depending on the controller being used, the cycle may or may not be synchronized. In Texas, a synchronized cycle is used, and the green indication never occurs simultaneously in both lanes. Furthermore, the green indications are timed to allow a constant headway between vehicles from both lanes. Dual-lane metering can provide metering capacity of 1600 to 1700 VPH. In addition, dual-lane ramps provide more storage space for queued vehicles. The only problem is that most existing ramps, such as those in Texas, were not designed to provide dual-lane operation.

DESIGN CONSIDERATIONS FOR RAMP METERING

Installation of a ramp meter to achieve the desired objectives requires sufficient room at the entrance ramp. The determination of minimum ramp length to provide safe, efficient, and desirable operation requires careful consideration of several elements described below:

1. Sufficient room must be provided for a stopped vehicle at the meter to accelerate and attain safe merge speeds.
2. Even when the overall ramp demand is less than the capacity of a meter, portions of a signal cycle at the upstream signal may be releasing vehicles at flow rates that are significantly higher than metering capacity. Thus, sufficient space must be provided to store the resulting cyclic queue of vehicles without blocking the upstream intersection.
3. Sufficient room must be provided for vehicles discharged from the upstream signal to safely stop at the meter and/or behind a stopped vehicle.

In addition to above design issues, the ramp controller parameters must be carefully selected to achieve the desired objectives. However, no guidelines are currently available to TxDOT for designing efficient ramp metering system.

RESEARCH OBJECTIVES

The primary objective of this project is to develop ramp-metering design and implementation guidelines for use by TxDOT. These guidelines should provide for effective design (geometric and control devices), implementation, operation, and maintenance of ramp metering system at existing as well as proposed ramps. The specific objectives of this project are to:

1. Develop guidelines for selecting the geometric design of new ramp facilities for providing optimum ramp-metering operation. These guidelines will include the entrance ramp and the freeway merge area.

2. Develop guidelines for improving existing facilities for allowing the implementation of the best possible ramp metering system.
3. Develop guidelines for selecting the best possible ramp metering strategy.
4. Develop guidelines for installing traffic control devices at existing and new metered ramps.

SCOPE

The scope of this one-year project is limited to freeway entrance ramps. The primary objective of the project is to develop guidelines for the design, implementation, and maintenance of ramps and ramp-metering systems. The impacts of adjacent roadway facilities is to be included in the analysis only to account for their impact on the entrance ramp operation and to account for the impact of ramp design/operation on them. These facilities include freeway mainline section immediately before and after the entrance ramp and upstream traffic signals.

RESEARCH APPROACH

The approach used in this research project included several systematic steps. These included:

1. A study of ramp metering practices in the United States. This step consisted of a review of literature to assess current practices related to the design and operations of ramp-metering systems.
2. An assessment of ramp metering in Texas. This step included acquiring an understanding of existing policies and practices as they related to the design and operations of ramp meters, several field studies, and a detailed study of the ramp controller used in Texas.
3. Development of analytical models to analyze the effects of all pertinent variables related to ramp design and ramp-metering operation. Also, computerized spreadsheets were developed for facilitating the use of these models.
4. Use of hardware-in-loop simulation throughout this research project as a means to study various strategies in a controlled environment.

Hardware-in-Loop Testbed

A hardware-in-loop setup provides the capability to study the behavior of a real traffic controller using simulated traffic data (Figure 1). The testbed consisted of a Texas ramp-metering controller connected to the TexSim model running on a personal computer. TexSim is a microscopic simulation model developed by TTI staff for analyzing real-time systems using actual hardware.



Figure 1. Hardware-in-Loop Testbed.

ORGANIZATION OF THIS REPORT

This report consists of several chapters. Chapter 2 provides an overview of the ramp-metering status in the United States. Chapter 3 provides a description of the key elements of ramp-metering systems in Texas. Chapter 4 provides the current status of ramp metering in Texas. This chapter also includes the results of several field studies. Chapter 5 presents an overview of issues related to the design and operation of ramp meters. Finally, Chapter 6 presents research results dealing with the design of effective ramp meters.



2. RAMP METERING STATUS IN THE U.S.

Freeway ramp metering as a control strategy has been used since the early sixties (2, 3). The first comprehensive assessment — a project funded by the Federal Highway Administration — of ramp metering in the U.S. was published in 1989 (4). An updated version of this report was published again in 1995 (5). According to this report, in 1995 there were 10 metropolitan areas with more than 50 operational ramp meters. In addition, there were 13 other metropolitan areas with less than 50 ramps being metered. Table 1 provides more information about these areas. Since then, many metropolitan areas (e.g. Houston, Texas) have expanded their ramp metering systems, and numerous more (e.g. Arlington, Texas) have started using ramp metering. Yet others, like El Paso, are just getting started.

Table 1. Ramp-Metering Systems in Operation as of 1995.

Metropolitan Areas with More than 50 Meters	Metropolitan Areas with less than 50 Meters
Chicago, IL	Columbus, OH
Los Angeles, CA	Denver, CO
Minneapolis/St. Paul, MN	Detroit, MI
New York, NY	Fresno, CA
Orange County, CA	Houston, TX
Phoenix, AZ	Milwaukee, WI
Portland, OR	Northern Virginia, VA
San Diego, CA	Riverside, CA
San Jose/San Francisco, CA	Sacramento, CA
Seattle, WA	San Antonio, TX
	San Bernardino, CA
	Tacoma, WA
	Toronto, ON

Source: (5)

At this time, a single comprehensive report describing the current status of metering in the nation is not available. Furthermore, most states in the U.S. use some recommended guidelines for installing and operating ramp meters, but there are no nationally accepted standards. Despite this, there is a consensus that ramp metering can be successfully implemented by careful selection of some design features. These include, but are not limited to:

- adequate storage space on the entrance ramp, and
- adequate acceleration distance from the meter to the merge location.

In addition, there is consensus that all means to inform/educate the motorists and politicians must be utilized before ramp metering is initiated. These efforts include media campaigns, press releases, and information dissemination through web sites.

Within the framework of the stated objectives of ramp metering, an agency can adopt a policy that lies somewhere within the following two extreme cases:

1. give highest priority to vehicles on the freeway, or
2. give highest priority to vehicles on the ramp.

The objective of the first policy is to keep the freeway traffic moving at all times, including times when there is an incident on the freeway. This policy is implemented by operating the controller in a traffic responsive mode. In this mode, freeway detectors are used to assess traffic conditions on the freeway, and metering rates are adjusted to accommodate only that amount of traffic that can be handled while keeping the freeway level of service below a specified value. Traffic responsive metering can be implemented in an isolated mode or a system mode. In the isolated mode, the controller takes into account freeway conditions in the vicinity of a specific ramp only. In the systems mode, sophisticated algorithms and a central computer are used to take into account traffic conditions on a freeway section consisting of many metered on-ramps.

The objective of the second policy is to ensure that the upstream signal is kept free of any queues at all cost. Engineers implement this policy by using queue detectors at the ramp entrance and suspending the metering operations when a queue is detected and as long as it is present. Sometimes this policy is based on a maximum allowable delay value for the ramp traffic. Like the traffic responsive mode, this policy can be implemented in an isolated or system mode using a central computer. Regardless, queue clearance at the ramp always overrides the isolated or central operation.

The ramp-metering operations in Minnesota and Texas, respectively, are examples of these two extremes. All other states in the U.S. utilize policies resulting from a compromise between the above two extremes and, in many cases, are closer to the first extreme.

Currently, Minnesota is metering approximately 430 on-ramps (6). When installing meters, engineers ensure that adequate acceleration distance and the maximum possible storage space are provided at each ramp. In most cases, Minnesota uses dual-lane operation. The meters are operated in a traffic responsive mode without permitting any flushing due to queues. It is not uncommon for ramp vehicles to experience 5 to 10 minutes of delay (6).

In Houston, Texas, TxDOT selected a policy that ensures no vehicle experiences a delay exceeding two minutes on the ramp. This objective is achieved by flushing large queues as soon as they are detected. The Fort Worth District adopted the same policy in its implementation of ramp meters in Arlington, Texas.

RAMP-METERING DESIGN AND OPERATIONAL GUIDELINES

As discussed earlier, over a dozen states are currently using ramp metering as a component of freeway traffic management strategies. Most states use basic implementation guidelines provided in the *Manual on Uniform Traffic Control Devices* (MUTCD) (7). Some states provide further guidelines in their design manuals. These states include Arizona and Washington. Only a handful of states have specific guidelines readily available for use in designing and operating ramp-metering systems. Even in these cases, a number of design issues

are not addressed. The guidelines suggest that these issues be resolved using engineering judgement. This subsection presents three sources that contain useful design-related information.

In 1979, the Illinois DOT published a document dealing with the issue of freeway surveillance and control (8). This document contains a chapter discussing various issues related to single-lane, one vehicle per green ramp-metering operation. Issues discussed include:

- location and number of signal heads,
- signs,
- storage space,
- lane and shoulder widths,
- types and locations of detectors, and
- control strategies (including metering rates).

More recently, the Division of Traffic Operations at California DOT (Caltrans) put together specific design guidelines for ramp meters (9). This document was published in 1989 and contains guidelines for single-, dual-, and three-lane (two regular lanes plus one high occupancy [HOV] lane) metering. Specifically, this document contains the following information.

- Design criteria for:
 - lane and shoulder widths,
 - storage space,
 - acceleration lane and location of stop bar,
 - location of HOV lane, and
 - meter location.
- Enforcement issues
- Hardware criteria for:
 - signal heads,
 - loop detectors (mainline, entrance ramps, and exit ramps), and
 - controller and cabinet.
- Signing and pavement markings
 - advance warning sign,
 - HOV signing and pavement marking,
 - vehicles per green, and
 - other pavement markings.

The Washington DOT *Design Manual* dated August 1997 also includes some specific, but very basic, guidelines for ramp metering (10). Topics discussed include:

- types of signal heads;
- storage space and alternates when adequate storage cannot be provided;
- selection of ramp metering rates, including discussion of bulk metering;
- location of ramp meter; and
- driver compliance.

SUMMARY

In summary, most DOTs using ramp metering have minimal ramp-metering guidelines, if any. The only exception is Caltrans, which has detailed guidelines about most aspects of ramp metering. Furthermore, all states currently using ramp metering recognize the importance of on-ramp storage space for a successful ramp-metering system. However, the determination of storage space in a specific instance is not dealt with in a clear and concise manner. Almost all states leave this decision for the engineer in charge.

3. TEXAS RAMP-METER SYSTEM

In this chapter, we present key features of ramp-metering systems in Texas. Figures 1 and 2 illustrate various components of single-lane and dual-lane ramp meters, respectively, currently used in Texas. These include detectors, signs, and signals. The following subsections provide descriptions of these components.

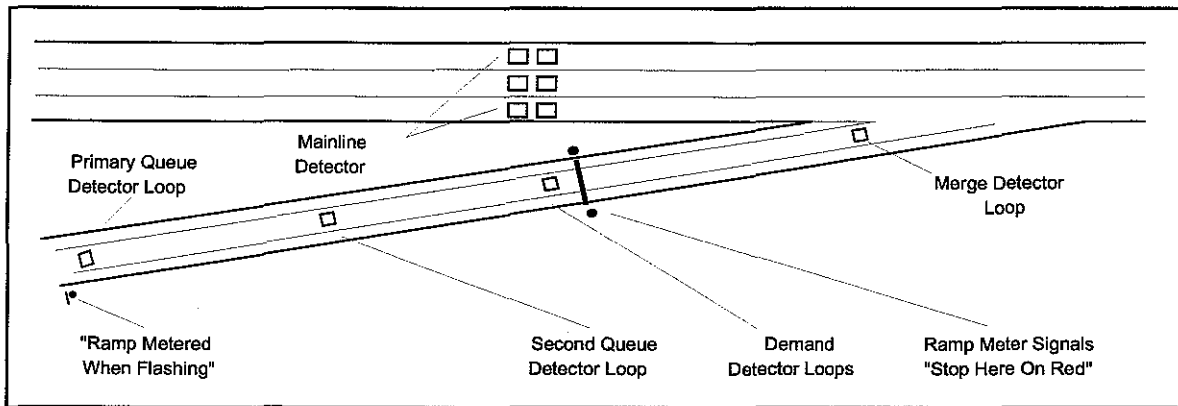


Figure 2. Single-Lane Ramp-Meter System.

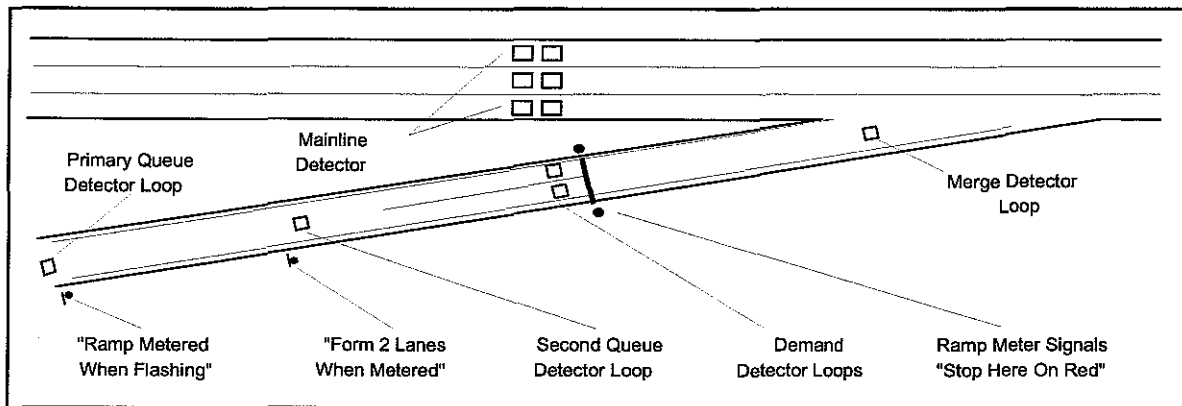


Figure 3. Dual-Lane Ramp Meter System.

LOOP DETECTORS

Texas ramp-metering operation requires a mandatory set of detectors. In addition, optional detectors can be installed to provide a wide range of operations. This section provides information about these detectors. Table 2 provides a summary of various loop detectors that can be used in a ramp-metering system.

Table 2. Placement and Application of Ramp-Meter Detectors.

Type of Detector	Location/Size	Application
Mainline (Optional)	Located in the freeway upstream and/or downstream of the on-ramp ingress point to the freeway.	Provides freeway occupancy, speed, or volume information that is used to select the local metering rate. These detectors also provide incident detection measurement devices for traffic management centers. Used by nearly all agencies.
Merge (Optional)	Placed upstream of the merge area and downstream of the stop-bar along the on-ramp.	Used primarily to provide on-ramp count data. Minnesota uses it to determine the appropriate time to terminate metering based on the differential between the current on-ramp volume and the fixed-time metering rate.
Passage (Optional)	Positioned immediately downstream of the stop-bar.	Used in California and Washington to determine the duration of the green signal display on the specified lane.
Demand (Required)	Placed immediately upstream of the stop-bar in both specified lanes.	Senses vehicle presence at the stop-bar and initiates the green traffic signal display for that specific lane under the selected metering strategy.
Second Queue (Optional)	Placed approximately half-way between the stop-bar and the on-ramp entrance point in both lanes.	Incrementally increases the metering rate to control growing queues within the queue storage reservoir.
Primary Queue (Required)	Positioned near the on-ramp entrance area (typically within 30 meters)	Monitors excessive queues that cannot be contained within the queue storage reservoir. Maximizes the metering discharge rate to clear excessive queues.

Demand Detector

The purpose of the demand detector is to ensure that the meter displays green only in the presence of a vehicle at the meter. This detector is a required component of the ramp-meter installations in Texas.

Primary Queue Detector

The purpose of the primary queue detector is to monitor excessive queues that cannot be contained in the storage space provided.

Second Queue Detector

Second queue detector, installed between the demand detector and the primary queue detector, is optional and provides for adapting to traffic demand at the ramp.

Mainline Detectors

Optional mainline detectors consist of a pair of detectors in each freeway lane. These optional detectors are placed upstream of the entrance ramp gore and are used to obtain volume and occupancy data for implementing traffic-responsive metering.

Merge Detector

A merge detector is optional and is installed to ensure that a previously released vehicle enters the freeway before the meter releases the next vehicle.

WARNING AND REGULATORY SIGNS

In addition to the detectors, a series of warning and regulatory signs are used to convey the intent of the freeway management system. Table 3 provides an illustration of the various ramp-meter signs used under single-lane and dual-lane configurations.

Control Devices

The final element of the single-lane or multiple-lane traffic control devices is the traffic signal display. As the motorist nears the ramp-meter stop-bar, one of two standard signing and traffic signal display conventions is used to inform the driver of the regulatory requirements of the ramp meter and to indicate when the motorist is allowed to enter the freeway. Figures 4 and 5 illustrate the typical post mounted signal used for single- and dual-lane metering. It should be noted that signal heads are installed on both sides of the entrance ramp. Also, these three-section signal heads are installed on breakaway posts because they are within the thirty feet clear zone. Furthermore, the signal- and dual-lane meters utilize a different number of signal-heads on each pole.

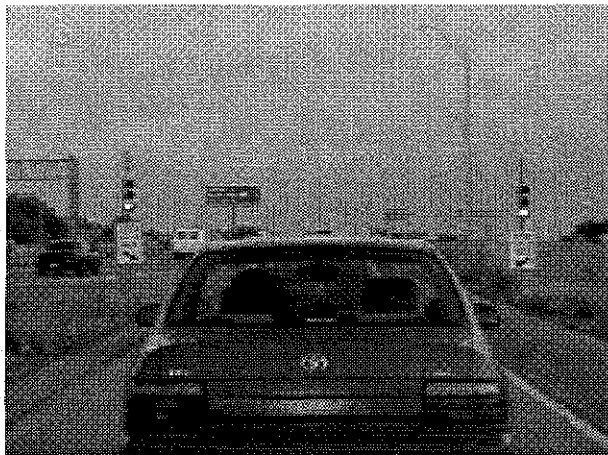
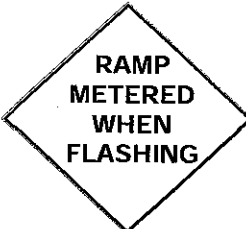
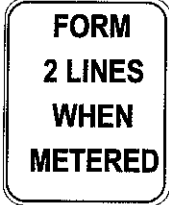





Figure 4. Single-Lane Meter.



Figure 5. Dual-Lane Meter.

Table 3. Ramp Metering Signing Locations and Applications.

Sign	Location	Application
	<p>Placed on the left-side of the frontage road approximately 200 feet (60 meters) upstream of the slip-ramp entrance point and downstream of any signalized intersections or off-ramps.</p>	<p>This warning sign is accompanied by a yellow flashing beacon that is activated during metered periods to alert motorists of the upcoming controlled ramp.</p>
	<p>Positioned near the beginning of the dual-lane queue storage reservoir on the right-side of the on-ramp.</p>	<p>This regulatory sign is used to convert the single-lane on-ramp into a dual-lane queue storage reservoir during flow signal operations.</p>
	<p>Placed on both sides of the on-ramp at the flow signal stop-bar. This sign is placed on the signal pole under the post-mounted configuration.</p>	<p>This regulatory sign identifies the flow signal stop-bar location and is used to align drivers over the demand detectors placed upstream of the stop-bar.</p>
	<p>Can be optionally placed either on the signal pole or with the "Stop Here on Red" regulatory sign under a mast-arm configuration.</p>	<p>This regulatory sign is used to inform motorists of the intended traffic control under flow signal operations.</p>
	<p>Placed with the corresponding signal head under the mast-arm design.</p>	<p>This regulatory sign is used to identify the proper lane control and inform motorists of the traffic control requirements during metered periods.</p>

As illustrated in Figure 4, single-lane meters use one signal-head on each side of the meter. One of these signals is installed at an angle where vehicles stopped at the meter can clearly see the lights. The other is installed at an angle that allows lights to be seen from the ramp entrance. Additionally, a "Stop Here On Red" sign is posted below each signal-head.

For dual-lane meters (Figure 5), two three-section heads are installed on each pole. The top signal head points to vehicles entering the ramp, while the bottom signal head points to vehicles stopped at the meter. Signals on the left side pole are for the left-lane and signals on the right-side pole are for the right-lane. A "Stop Here On Red" sign is mounted on each pole

between the two signal heads. Additionally, a "Left Lane Left Signal" sign is placed below the bottom signal head on the left pole, and a "Right Lane Right Signal" is similarly placed on the right pole.

TEXAS RAMP CONTROLLERS

Unlike most other states in the nation, Texas uses controllers specifically manufactured for ramp-metering operation by Eagle TCS of Austin, Texas. Two versions of Eagle RMC 300 controllers are currently being used in Texas. The older controller runs software version 1.01, dated July 1992. The newer RMC 300 98 version 2.00a (dated February 1998) controller provides several enhancements over its predecessor, and is functionally compliant with the draft National Transportation Communication Interface Protocol (NTCIP) standard (11). This version of the controller is being used on all five ramps in Arlington and some ramps in Houston. Both versions of this controller operate in the following basic manner:

1. When the metering operation begins, the controller activates the flashing beacon accompanying the "Ramp Metered When Flashing" sign. The beacon flashes throughout the metering duration.
2. The controller activates the metering operation consisting of a startup cycle followed by regular metering cycles. Each metering cycle begins only when the demand detector detects a vehicle. These cycles continue until the metering operation terminates or gets suspended.

The newer version of the controller provides several additional features and enhancements over those provided by the old controller. These differences between the two controller versions are described below:

1. The old controller simultaneously activates the flashing beacon and the startup cycle at the signal. In contrast, the new controller provides the user the capability to enter the duration for which the beacon will flash before activating the startup cycle. In selecting this duration, the engineer should take into consideration the time it takes for a vehicle just crossing the beacon to go past the meter before it is activated.
2. In the old controller, the green time for the startup cycle is 15 seconds long and cannot be changed by the user. In addition, the startup cycle uses the same values for yellow and red times programmed by the user for the metering cycle. Therefore, the user must carefully select these common values, especially the yellow time, to suit the driver expectancy at the end of both these cycles. In contrast, the new controller provides the user flexibility to enter different durations for green, yellow, and red signal indications for each of the startup and regular cycles, thereby giving a better control to fine-tune the operation.
3. The old controller can meter only one lane, whereas the new controller is capable of metering up to four lanes, including one lane for high priority vehicles.
4. The new controller provides a capability to automatically adjust metering rates using data from an intermediate queue detector.

5. The new controller provides a wider range of responsiveness in detecting and responding to a queue.

As mentioned previously, Texas adopted a policy of preventing a ramp queue from blocking an upstream traffic signal. Additionally, this policy also prevents installation of a ramp meter if it would result in more than two minutes of delay to any ramp vehicle. The primary queue detector is used as a means of implementing this policy, and therefore, is a required component of ramp-meter installations in Texas. During the metering operation, if the occupancy of this detector exceeds a user-specified threshold (i.e., 50 percent) value for a specified length of time (i.e., 20 seconds), the controller suspends the ramp-metering operation and provides time for the queue to flush. The controller resumes metering operation when the occupancy decreases to a value below the specified threshold value. When in the flush mode, the new controller is capable of turning off all signal lights (flush-in-dark mode) or displaying a green signal (flush-in-green mode). Current draft specification of Texas ramp metering controller (12) permits both types of operation. The following paragraphs provide further detail about the current version of ramp metering controller.

Depending on the availability of various types of detectors, the ramp meter controller can be programmed to operate in either traffic-responsive or pretimed mode. Within each of these modes, the controller can be programmed to operate under a pattern or a plan. The controller provides for four timing plans. Each timing plan consists of eight patterns (levels A through H). In any plan, level A corresponds to the non-metering state. In other words, selection of level A directs the controller to shut-off metering. The remaining levels – B through H – provide a range of metering rates, where level A corresponds to the highest programmed metering rate and level H corresponds to the lowest programmed metering rate in that plan. In the “Pattern” mode, the controller always uses a specific user-selected metering rate. In the “Plan” mode, the controller varies the metering rate within a user-specified range depending on traffic conditions.

An optional second queue detector can be installed at the ramp between the demand and primary queue detectors. When installed, the second queue detector senses the onset and dissipation of congestion. Based on this information, the controller either increases or decreases the metering rate within a user-specified range of metering levels. The second queue detector, however, cannot trigger the flush mode. Furthermore, the occupancy of this detector must be below its threshold value for the controller to terminate the flush mode and resume metering.

4. STATUS OF RAMP METERING IN TEXAS

In Texas, ramp meters are currently operational in Houston and Arlington. Furthermore, El Paso has installed meters at the Paisano and Trowbridge on-ramps on westbound (WB) I10 and plans to turn on these meters shortly. This section presents the current status of metering in Houston and Arlington.

RAMP METERS IN HOUSTON

In Houston, ramp meters have been operational for several years. Table 4 provides a summary of operational ramps as of February 2000. All of these ramps operate in an isolated mode on a time-of-day basis. Furthermore, all but two ramps use the single-lane one car per green strategy. One exception is the FM 1960 on-ramp in the inbound direction at SH 290. This ramp has dual-lane metering. The other one is the Kirby ramp in the westbound direction on Highway 59. This is a single-lane ramp with bulk metering.

Table 4. TxDOT Houston District Ramp Metering Locations.

I-10 Katy Freeway – 28 meters installed		
AM Operations -----	15 inbound (eastbound [EB])	
	9 outbound (westbound [WB])	
PM Operations -----	10 inbound (EB)	
	9 outbound (WB)	
I-45 North Freeway – 23 meters installed		
AM Operations -----	10 inbound (southbound [SB])	
PM Operations -----	10 outbound (northbound [NB])	
US 290 Northwest Freeway – 22 meters installed		
AM Operations -----	11 inbound (EB)	
PM Operations -----	10 outbound (WB)	
US 59 Southwest Freeway – 22 meters installed		
AM Operations -----	9 inbound (EB)	
PM Operations -----	4 outbound (WB)	
I-45 Gulf Freeway – 22 meters installed		
AM Operations -----	7 inbound (NB)	
I-610 West Loop Freeway – 15 meters installed		
AM Operations -----	6 clockwise (NB)	
I-610 North Loop Freeway – 14 meters installed		
AM Operations -----	5 counter-clockwise (WB)	
PM Operations -----	4 clockwise (EB)	
SH 225 LaPorte Freeway – 13 meters installed		
Total Meters Installed: 159		Total AM Operations: 72
		Total PM Operations: 47

In general, ramp metering in Houston has been successful, and there are plans to expand the ramp-metering operation. One reason for the success of ramp-metering operations in Houston is the fact that all delay to on-ramp traffic is kept low. The other reason is a successful media campaign during the initial stages of ramp-metering operation. One issue of concern is that many existing and potential ramp-metering sites have volumes higher than the capacity provided by single-lane one car per green operation; however, most existing ramps in Houston do not have the geometric features to implement dual-lane ramp metering. At high-volume ramps with operational ramp meters, a large chunk of time is consumed in the flush mode, and thus the full benefits of metering are not realized. At the Kirby ramp, TxDOT recently implemented bulk metering to assess its usefulness for such situations. Initial observations of this operation showed that this strategy improved operations and is working reasonably well. A later section presents the results of a field study to assess the bulk metering operation at the Kirby on-ramp. Another problem in Houston has been a significant number of incidents in which vehicles have hit the signal poles. However, data are not available to assess the causes of these incidents.

ARLINGTON RAMP METERING

In Arlington, Texas, a small ramp-metering system was turned on about nine months ago. This system, located on a northbound section of SH 360, has five on-ramps. All five meters are currently operating in a time-of-day mode during the morning rush period. This section of freeway experiences heavy congestion starting as early as 6:30 a.m. and lasting for about two hours. Congestion occurs due to heavy through traffic originating at upstream sections of SH 360 coupled with heavy uncontrolled traffic entering from I-20, located about one mile upstream of the first on-ramp (Mayfield) in the system. Another feature of this system is that the frontage road discontinues a few blocks downstream of the last on-ramp (Abrams) in the system.

The Fort Worth/Arlington traffic management system has the infrastructure (video surveillance, fiber-optic cable, etc.) to provide for system metering from a central location. However, traffic management software to be delivered by Eagle Traffic Control Systems (Eagle TCS) is not yet ready. Once complete, this software will enable the operation of the ramp-metering system in real-time using TTI's RAMBO II optimization software. At this time, the ramps are being operated in an isolated mode with the fastest metering rates possible. However, the current system provides a crude capability for uploading/downloading data to/from all five controllers from a central location using a program provided by Eagle TCS. Eagle TCS modified this program, originally designed to upload/download data to/from the controller through a serial or telephone connection, to use a controller's address to communicate with it on a party line.

Experience during the initial phase of ramp metering operation in Arlington has generally been good. However, due to some minor operational problems, the system has been fine-tuned on several occasions. During the first months of operation, the metering operation used the "flush-on-dark" mode for clearing queues. However, this operation caused noticeable confusion for the first few vehicles in the queue because the drivers of these vehicles did not immediately realize the course of action when the signal turned off. As an alternate, the signal operation was recently changed to provide "flush on green." This was done without informing the drivers, who did not seem to have any difficulty adapting to this change. The use of this feature is a major

departure from the way meters operate in Houston. The pros and cons of this operation are currently being investigated.

FIELD STUDIES OF OPERATIONS IN TEXAS

In order to get a better understanding of the various types of ramp-metering operations in Texas, several ramp meters were videotaped and analyzed. These included five ramps from Houston and two ramps from Arlington. This section presents a summary of the findings.

Houston Data

I-10 WB Blalock Ramp

- Study duration: 4:00 p.m. to 4:30 p.m.
- Number of metered cycles: 435
- Number of flush cycles: 0
- Estimated demand: 897 VPH
- Red violations: 20 times (4.6 percent)

US 290 EB Fairbanks N Ramp

- Study duration: 7:45 a.m. to 8:15 a.m.
- Number of metered cycles: 375
- Number of flush cycles: 1
 - This occurred about 13 minutes into the study period.
 - Approximate duration: 31 seconds
 - Hesitation delay: 8 seconds
 - Number of vehicles flushed: 7
- Red violations: 9 times (2.4 percent)

US 290 EB Fairbanks N Ramp

- Study duration: 4:30 p.m. to 5:00 p.m.
- Number of metered cycles: 438
- Number of vehicles: 422
- Estimated demand: 844 VPH
- Red violations: 10 times (2.4 percent)

US 290 EB FM 1960 Ramp (Dual-Lane Operation)

- Study duration: 7:30 a.m. to 8:00 a.m.
- Number of metered cycles: 585
 - Left-lane: 298
 - Right-lane: 287

- Number of Vehicles: 578
 - Left-lane: 301
 - Right-lane: 277
- Estimated demand: 1156 VPH
 - Left-lane: 602 VPH
 - Right-lane: 554 VPH
- Red violations: 21 times (3.6 percent)
 - Left-lane: 12 times (4 percent)
 - Right-lane: 9 times (3.2 percent)

US 59 WB Kirby Ramp (Bulk Metering)

- Study duration: 4:50 p.m. to 5:10 p.m. (some incomplete cycles dropped)
- Number of metered cycles: 53
 - Each cycle: 8.7 seconds (green, 5 seconds; yellow, 1.7 seconds; and red, 2 seconds)
 - In seven different time periods
 - Smallest period: 1 cycle (duration: 8.7 seconds)
 - Largest period: 16 cycles (duration: 2 minutes, 22 seconds)
 - Total duration of metered cycles: 477 seconds (7 minutes, 57 seconds)
- Number of flush cycles: 7
 - Followed by a startup cycle with 15 seconds green, 1.7 seconds yellow, and 2 seconds red
 - Smallest flush cycle: 14 seconds
 - Largest flush cycle: 148 seconds (2.5 minutes)
 - Total duration: 736 seconds (12 minutes, 16 seconds)
 - Total vehicles flushed: 381
 - Most startup cycles had one vehicle violating the red signal.
 - Vehicle delay at start of flush mode: range, 0 to 8 seconds; mode, 5 seconds; and average delay, 3.3 seconds.
- Meter availability: 39 percent
- Estimated demand for first 15 minutes: 1484 VPH
- Estimated demand for 20 minutes, 21 seconds: 1527 VPH

Arlington Data

Abrams Ramp (Flush-on-Green)

- Study duration: 7:33 a.m. to 8:33 a.m.
- Number of metered periods: 9
 - Minimum number of cycles in a period: 1
 - Maximum number of cycles in a period: 8
 - Average number of cycles per period: 4.6
 - Total vehicles metered: 49
 - Total duration: 282 seconds (4 minutes, 42 seconds)

- Number of complete flush plus startup cycles: 8
 - Total duration: 2738 seconds (45 minutes, 36 seconds)
 - Total vehicles flushed: 1003
 - One flush cycle: 1722 seconds long and flushed 646 vehicles
- Meter availability: 9.3 percent
- Estimated total demand: 1242 VPH
- Delay at the beginning of flush period: 0-8 seconds with an average of 4.1 seconds. This was mostly from the second and third vehicles in the queue.
- Total red violations: 7

Park Row Ramp (Flush-on-Green)

- Study duration: 6:14 a.m. to 7:10 a.m.
- Number of metered periods: 15
 - Minimum number of cycles in a period: 1 (2 times)
 - Maximum number of cycles in a period: 41
 - Average number of cycles per period: 16
 - Total vehicles metered: 206
 - Total duration: 1158 seconds (19 minutes, 18 seconds)
- Number of complete flush plus startup cycles: 14
 - Total duration: 2146 seconds (35 minutes, 46 seconds)
 - Total vehicles flushed: 712
 - Largest flush cycle: 432 seconds long and flushed 143 vehicles
- Meter availability: 35 percent
- Estimated demand: 1016 VPH
- Delay at the beginning of flush period: 2-5 seconds with an average of 3.3 seconds. This was mostly from the second and third vehicles in the queue.
- Total red violations: 6

Summary

Field studies show that single-lane, one car per green operation works well when the ramp demand is less than 900 VPH. When ramp demand exceeds 1000 VPH, the effectiveness of this strategy, as indicated by meter availability, is reduced. In such cases, other metering strategies must be considered. The best strategy for high-demand ramps is to implement dual-lane metering. However, most existing ramps are not wide enough to provide two lanes. In addition, it may not be feasible to widen an existing ramp due to other constraints. When such constraints exist, bulk metering should be considered, since this strategy provides more capacity than the one car per green operations. It should also be noted that bulk metering does not significantly increase meter capacity and is only suitable for cases when demand is marginally above meter capacity. Researchers verified this fact using hardware-in-simulation described earlier. Bulk metering also compromises the objective of breaking up the platoon of vehicles desiring to enter the freeway.

Furthermore, a comparison between the flush-on-dark and the flush-on-green operations indicates that both modes result in some startup delay at the beginning of the flush period, but the

onset of delayed response occurs at different times. In the case of flush-on-dark operation, the delay is generally due to hesitation of the first vehicle; whereas, in flush-on-green operation, the delay results from the second and third vehicles in the queue. Also, researchers observed that, at times, the flush cycle for the Abrams ramp continued for up to 19 seconds in the absence of any vehicle, resulting in an unproductive period at the end of the flush cycle. The controller parameters should be adjusted to minimize the frequency and duration of these unproductive periods.

5. OPERATIONS AND DESIGN ISSUES

This chapter presents an overview of design and operations issues as they relate to current Texas practice. The objective is to identify and describe the basic elements that need to be considered in designing ramp-metering systems in Texas. This chapter begins by describing operational criteria, followed by an identification of design features to ensure safe and efficient operation.

REVIEW OF RAMP-METERING OPERATION IN TEXAS

As described earlier, the primary queue detector is a required component of ramp meters in Texas. As such, it affects the meter operation more than any other component of the system. This section explains why and provides some insight into the importance of detector location on meter operation. For clarity, this section is further divided into several subsections.

Ramp Demand Less than Meter Capacity

Consider a hypothetical case for ramp-metering operation when ramp demand is less than the meter capacity. It is assumed that there is sufficient room on the ramp to store queued vehicles. It is further assumed that ramp demand is composed of vehicles released during three signal phases at an upstream interchange. Each major signal phase will release vehicles at the saturation flow rate (i.e., 1800 vehicles per hour, or higher) during its initial period, which could be as long as the effective length of that phase during peak periods. Therefore, during portions of each cycle at the upstream signal, ramp vehicles will be arriving at a rate that is faster than the meter capacity. Thus, a queue will form at the ramp. However, since the overall ramp demand is assumed to be less than the meter capacity, the queue of vehicles at the ramp will eventually clear, probably within one signal cycle. Figure 6 illustrates this hypothetical scenario.

Figure 6 shows the ramp meter operation for a time duration during which the upstream signal goes through four cycles. This time duration is divided into three distinct periods at the meter: metering, red dwell, and metering. During the first period (polygon at the bottom), a queue forms at the meter and then dissipates. This time is followed by a short nonproductive period during which there is no demand at the meter, and thus the ramp signal dwells in red. It should be noted that the meter capacity is lost during this time period. The third period begins as vehicles released during the second signal cycle begin to arrive at the meter. Since the second signal cycle releases more vehicles, it results in a longer queue, requiring more time to clear. Such cycles may occasionally occur due to time-varying demand at the upstream traffic signal. The ramp queue has not cleared when vehicles from the third (average) signal cycle begin to arrive. The result is another long queue which clears as vehicles from the fourth signal cycle begin to arrive, and so on.

The ramp-metering operation described above will operate well as long as the traffic signal happens to be located upstream of the maximum back of the queue. In such cases, the upstream signal will never get blocked. However, if the upstream signal in this example were located at point A, the signal would get blocked twice during the illustrated period.

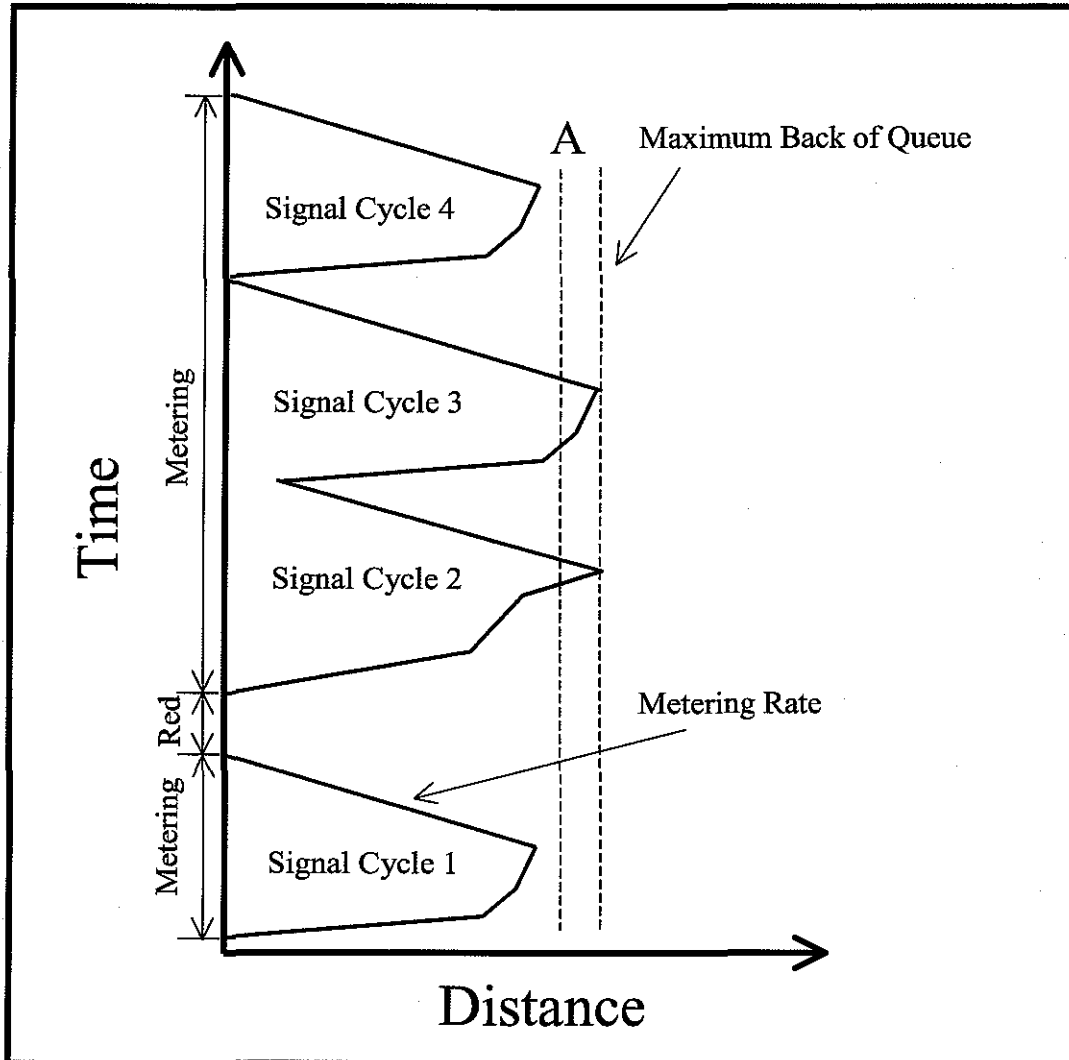


Figure 6. Time-Space Diagram of a Hypothetical Ramp-Metering System.

Optimal placement of the primary queue detector downstream of the traffic signal can prevent blocking of the signal by temporarily switching the meter operation to a flush operation. Figure 7 illustrates the meter operation in the presence of a primary queue detector. Here, the detector was placed some distance downstream of the traffic signal to provide a buffer for additional queue growth during detection/reaction time. As can be seen in Figure 7, the meter flushed once and cleared the queue before vehicles released from the third signal cycle started to arrive at the meter. Thus, the third signal cycle never threatened to block the signal. It should also be noted that several short periods of dwell time were introduced. The reader may also wish to verify that any other location of primary queue detector closer to the ramp meter will increase the frequency and duration of flush cycles, thereby reducing metering efficiency. Thus, the location of the primary queue detector also affects the operational efficiency of the meter.

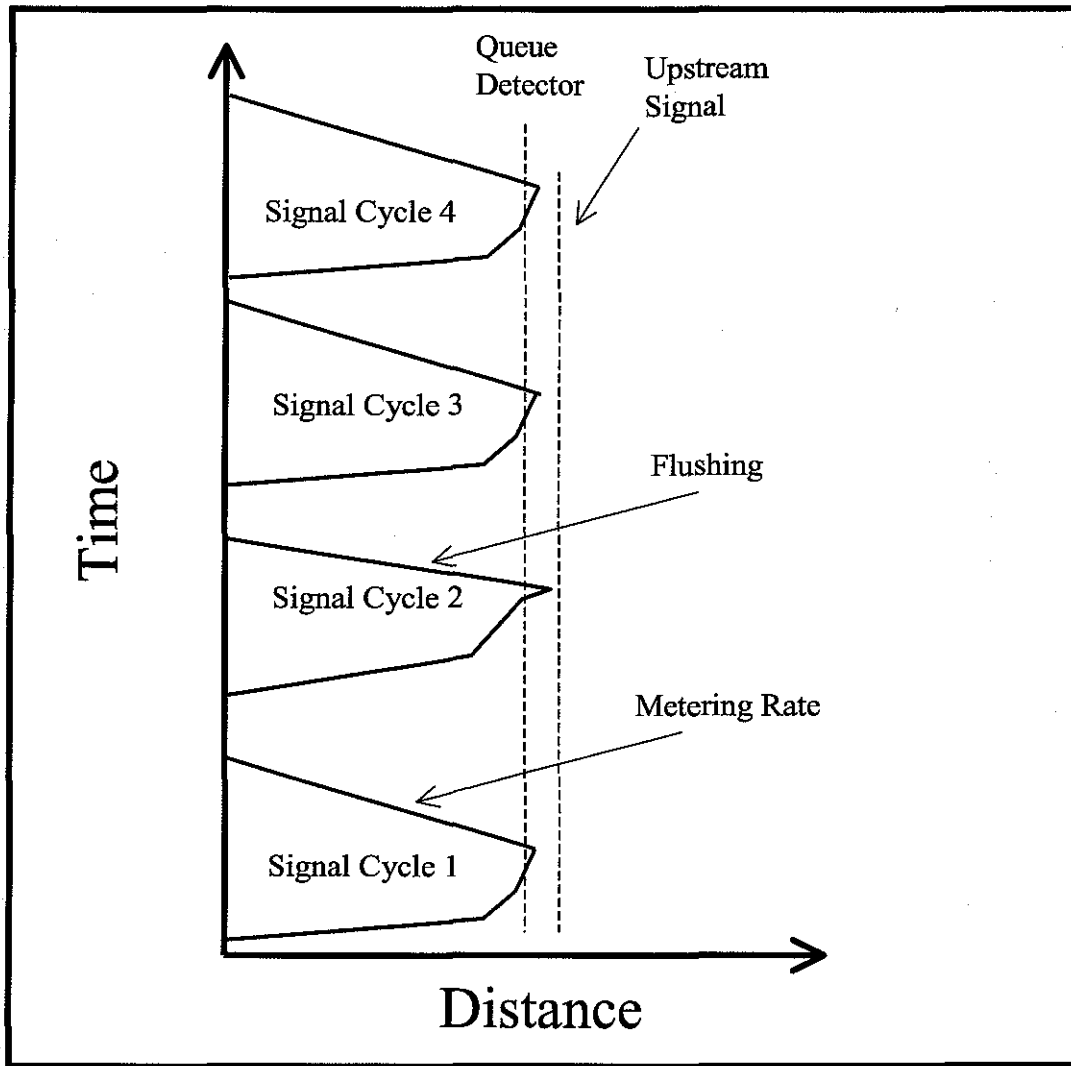


Figure 7. Effects of Primary Queue Detector on Metering Operation.

The reader may also wish to verify that if the upstream signal in the above scenario was closer to the ramp meter (resulting in less storage space), the signal would be blocked more often. In such a case, the primary queue detector will prevent blocking, but may not be able to result in an acceptable ramp metering operation. Under such circumstances, the following three feasible options could be pursued:

- meter traffic at the upstream signal,
- increase ramp meter capacity, and
- do not install ramp meter.

A study of the first of these options was beyond the scope of this research project. The second option will be addressed in the next chapter. The third option should be considered if an acceptable ramp-metering operation cannot be provided.

As the above discussion has showed, in addition to preventing a ramp queue from blocking the upstream signal, the location of the primary queue detector also affects the efficiency of a ramp-metering system. In fact, the detector location also controls the maximum delay a queued vehicle may experience while waiting at the meter. This fact can be verified by comparing various queue profiles in Figures 6 and 7. As an example, the last vehicle from the second signal cycle will experience less delay in the system when a queue detector is used. In fact, the closer the queue detector is to the ramp meter, the lower this maximum delay will be. Thus, the Texas practice of ensuring that the maximum delay to a vehicle is not more than two minutes would usually require the placement of a primary queue detector even when there is sufficient storage space, and there is no danger of queue spillback into the upstream signal.

Ramp Demand More than Meter Capacity

The previous section illustrated that the availability of sufficient storage space is critical for effective ramp metering. Given that sufficient storage space exists, and the ramp demand is not too much higher than the metering capacity for a significant period of time, it may be possible to provide an acceptable ramp-metering system. However, the best option would be to increase metering capacity if possible.

Summary

This section used simplified scenarios to provide some insight into the importance of storage space and queue-detector location for implementing effective ramp metering in Texas. Whether sufficient queue storage can be provided on a freeway on-ramp, however, depends on several factors related to the geometric design of the facility. The next section is devoted to a discussion of these issues.

GEOMETRIC DESIGN CONTROLS

The ability to provide sufficient storage space for ramp metering depends on the length of the ramp and the location of ramp signals. Figure 8 illustrates distance requirements for ramps meters. In this figure, the dotted line indicates the ramp length. The placement of signal poles must take into consideration:

- minimum clearances to prevent the drivers from reaching the signal head,
- storage space between the upstream signal and the meter, and
- distance from meter to merge point on the freeway to provide room for vehicles stopped at the signal to attain merge speed.

The storage space includes the safe stopping distance for vehicles departing from the upstream signal or the U-turn bay. As explained in the next chapter, this distance should be at least 250 feet. For dual-lane ramps, the ramp storage area (lower part of Figure 8) should also consider the transition from one lane to two lanes and dual-lane storage space. The transition zone should be at least 75 feet long and the length of dual-lane storage should be sufficient to store a minimum of four cars per lane (100 feet).

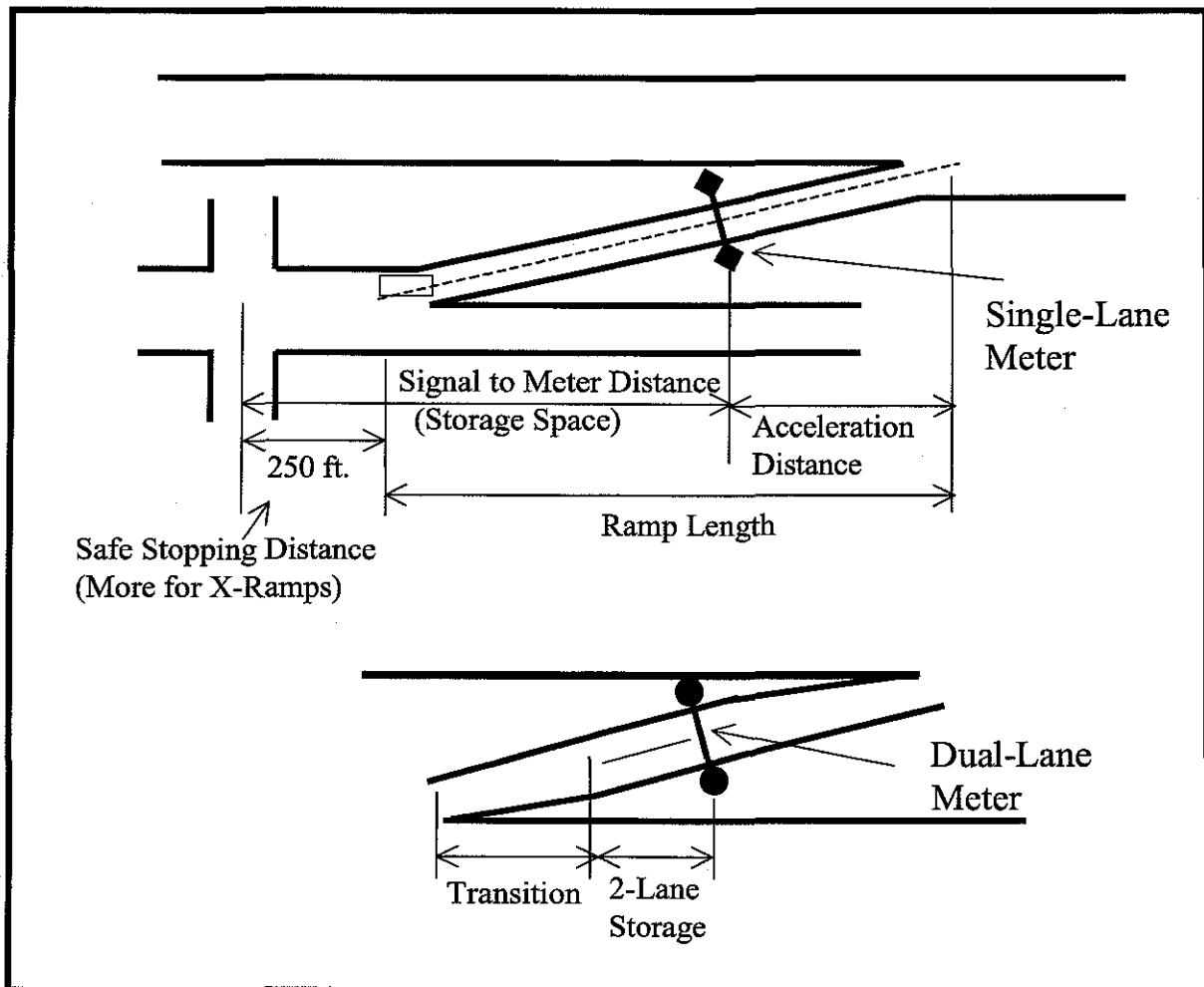


Figure 8. Design Issues Related to Ramp Meters.

The gore-to-gore length of a ramp depends on two factors: outer separation and ramp angle. Outer separation is the distance from the outside edge of the right most freeway lane to the inside edge of the frontage road. Figure 9 illustrates the mathematical relationship between ramp length, ramp angle, and outer separation. The figure also illustrates how clear zone requirements and ramp width affect the placement of signal poles. The top part of Figure 10 provides a cross section view of the freeway, single-lane ramp, and the frontage road. In this figure, thick lines represent travel lanes and thin lines represent shoulders. As shown, the offset to the signal head (setback) should be a minimum of three feet from the shoulder or, in case of a curb, from the edge of the travel lane. The bottom part of Figure 10 illustrates the desired and minimum dimensions for ramps. Using these mathematical relationships, one can determine the ranges of storage and acceleration distances for a given outer separation and ramp angle. The engineer can use these results to determine if an acceptable ramp metering operation can be provided.

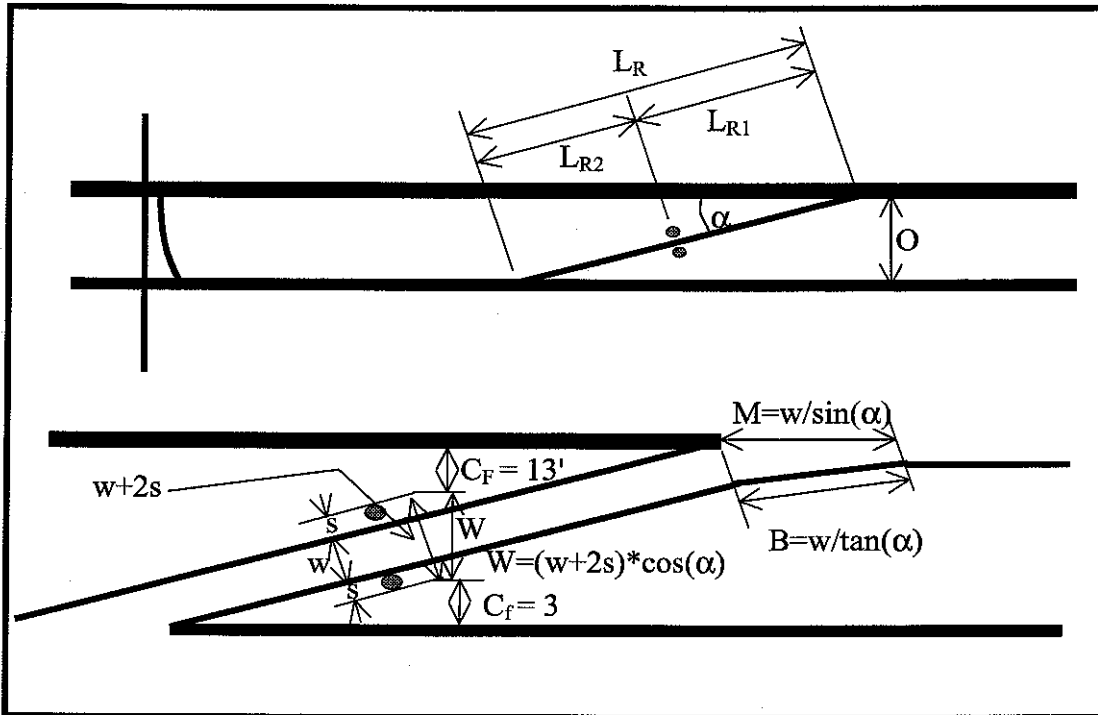


Figure 9. Mathematical Representation of Ramp Geometric Design.

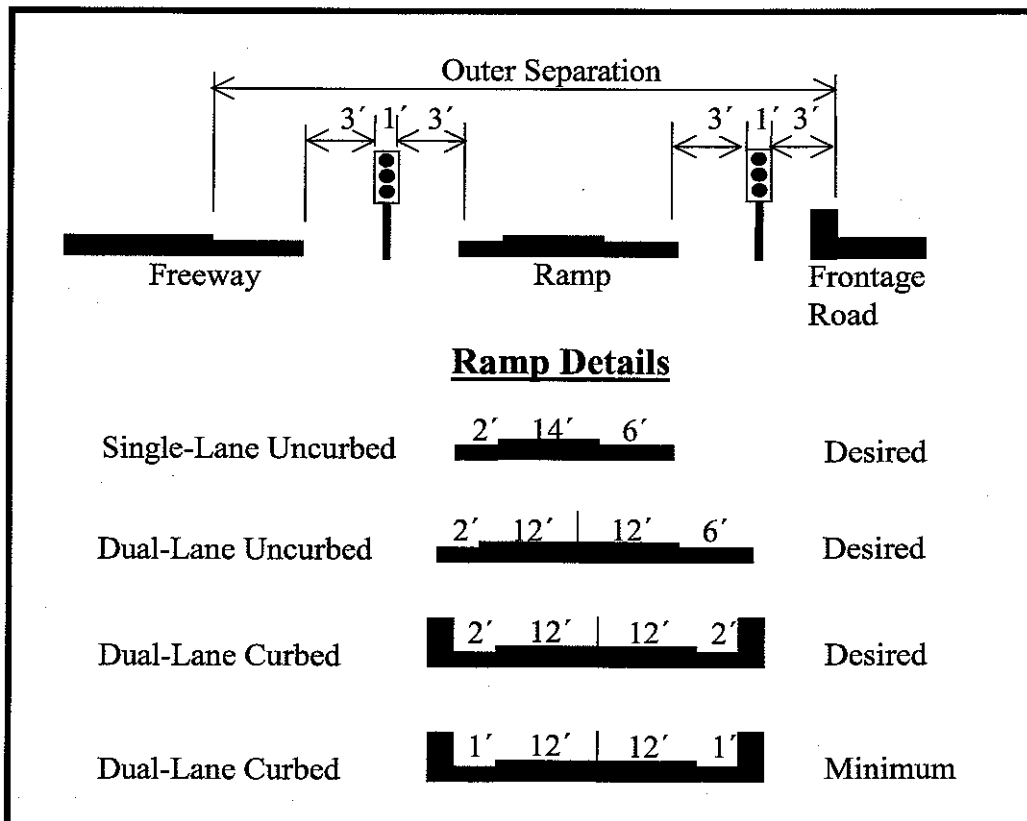


Figure 10. Clearances for Placement of Ramp Signal Posts.

We performed calculations for a range of outer separation, ramp angles, and merge speeds. From these calculations for a straight ramp, we found that outer separation of less than fifty feet does not result in any feasible solution for selected signal clearance distance and for merge speeds of forty miles per hour or higher. Tables 5 through 8 provide a sample of feasible calculations for single-lane and dual-lane ramps using the clearances shown in Figure 10.

Table 5. Twenty-Two Foot Wide Direct-Entry Ramp for Single-Lane Metering.

1	2	3	4	5	6	7	8	9	10	11	12
O (feet)	Speed (mph)	Grade (%)	Angle (α)	Min. L _{RI}	L _R (feet)	L _{RI} (1) (feet)	L _{R2} (1) (feet)	L _{RI} (2) (feet)	L _{R2} (2) (feet)	Extra Dist.	Max. Speed
50	40	-3	4	339	717	401	316	459	258	62	43
50	40	-3	5	339	574	339	234	368	206	0	40
50	40	0	4	419	717	419	297	459	258	0	40
50	45	-3	4	455	717	455	261	459	258	0	45

Table 6. Twenty-Six Foot Wide Direct-Entry Ramp for Dual-Lane Metering.

1	2	3	4	5	6	7	8	9	10	11	12
O (feet)	Speed (mph)	Grade (%)	Angle (α)	Min. L _{RI}	L _R (feet)	L _{RI} (1) (feet)	L _{R2} (1) (feet)	L _{RI} (2) (feet)	L _{R2} (2) (feet)	Extra Dist.	Max. Speed
50	40	-3	4	339	717	429	287	431	286	90	44
50	40	-3	5	339	574	343	230	345	229	4	40
50	40	0	4	419	717	429	287	431	286	10	40

Table 7. Twenty-Two Foot Wide Single-Lane Ramp with 443 Feet Merge Taper Distance.

1	2	3	4	5	6	7	8	9	10	11	12
O (feet)	Speed (mph)	Grade (%)	Angle (α)	Min. L _{RI}	L _R (feet)	L _{RI} (1) (feet)	L _{R2} (1) (feet)	L _{RI} (2) (feet)	L _{R2} (2) (feet)	Extra Dist.	Max. Speed
50	40	-3	4	339	1002	686	316	745	258	347	53
50	40	-3	5	339	891	638	253	685	206	299	51
50	40	0	4	419	1002	686	316	745	258	267	48
50	40	0	5	419	891	638	253	685	206	219	47
50	40	3	4	548	1002	686	316	745	258	138	43
50	40	3	5	548	891	638	253	685	206	90	42
50	45	-3	4	455	1002	686	316	745	258	231	53
50	45	-3	5	455	891	638	253	685	206	183	51
50	45	0	4	571	1002	686	316	745	258	115	48
50	45	0	5	571	891	638	253	685	206	67	47
50	50	-3	4	598	1002	686	316	745	258	88	53
50	50	-3	5	598	891	638	253	685	206	40	51

Table 8. Twenty-Six Feet Wide Dual-Lane Ramp with 443 Feet Merge Taper Distance.

1	2	3	4	5	6	7	8	9	10	11	12
O (feet)	Speed (mph)	Grade (%)	Angle (α)	Min. L _{RI}	L _R (feet)	L _{RI} (1) (feet)	L _{RI} (2) (feet)	L _{RI} (2) (feet)	L _{RI} (2) (feet)	Extra Dist.	Max. Speed
50	40	-3	4	339	974	686	287	688	286	347	53
50	40	-3	5	339	868	638	230	639	229	299	51
50	40	-3	6	339	798	605	192	607	190	266	50
50	40	0	4	419	974	686	287	688	286	267	48
50	40	0	5	419	868	638	230	639	229	219	47
50	40	0	6	419	798	605	192	607	190	186	46
50	40	3	4	548	974	686	287	688	286	138	43
50	40	3	5	548	868	638	230	639	229	90	42
50	40	3	6	548	798	605	192	607	190	57	41
50	45	-3	4	455	974	686	287	688	286	231	53
50	45	-3	5	455	868	638	230	639	229	183	51
50	45	-3	6	455	798	605	192	607	190	150	50
50	45	0	4	571	974	686	287	688	286	115	48
50	45	0	5	571	868	638	230	639	229	67	47
50	45	0	6	571	798	605	192	607	190	34	46
50	50	-3	4	598	974	686	287	688	286	88	53
50	50	-3	5	598	868	638	230	639	229	40	51
50	50	-3	6	598	798	605	192	607	190	7	50

The following is a description of entries in these tables:

- Column 1: Outer separation, feet;
- Column 2: Desired merge speed, mph;
- Column 3: Ramp grade, percent;
- Column 4: Ramp angle, degrees;
- Column 5: Minimum acceleration distance downstream of meter to achieve desired merge speed, feet;
- Column 6: Ramp length, feet, including 443 feet of taper distance when applicable;
- Column 7: Acceleration distance on the ramp, feet. This value is larger of the distance in column 5 and the distance calculated when meter is pushed maximum downstream;
- Column 8: Storage space upstream of the meter, feet. This value is equal to the length of ramp minus entry in column 7;
- Column 9: Acceleration distance on the ramp when meter is pushed maximum upstream, feet. In this case, clearance of ramp signal from the frontage road becomes a constraint;
- Column 10: Storage space upstream of meter (length of meter minus entry in column 9), feet;
- Column 11: Additional acceleration distance available, feet; and
- Column 12: Maximum speed that can be achieved when additional acceleration distance is available, mph.

These calculations show that an outer separation of 50 feet is required to get any feasible solutions. Furthermore, the calculations suggest the need to design ramps with additional acceleration distance parallel to the freeway. Additional storage area may also be needed on the frontage road to provide an effective ramp metering-system.

6. GEOMETRIC DESIGN CRITERIA FOR RAMP METERING

INTRODUCTION

For ramp metering to operate effectively, adequate ramp spacing between the cross street interchange and the downstream merge point to the freeway should be provided to satisfy operational objectives. This chapter develops design criteria and controls for identifying the ramp spacing needed where metering is envisioned.

Single-Lane Ramp Configuration

Figure 11 presents a nominal layout of single-lane ramp metering in Texas where one-way frontage roads are common. The meter is located along the entrance ramp between the frontage road and freeway. The generic term "ramp" will be used herein, although some "ramp" distance may actually be located upstream along the connecting frontage road. The generic ramp meter design depicted in Figure 11 could have a single-lane design (as shown), a dual-lane design, or a single-lane design with an added HOV/AVL by-pass lane. Traffic detectors may be placed upstream of the meter along the ramp to provide various responsive controls to serve changing traffic demands and to maintain the entry time to the freeway within desirable target levels. These meter detection functions are demand, intermediate queue, and excessive queue.

Space is needed along the ramp for vehicles to queue behind the meter while awaiting entry onto the freeway. Sufficient "freeboard" is needed behind the average queue for handling cyclic flow variations arriving from upstream interchange traffic signals. Additional distance is needed upstream of the queuing area to provide necessary traffic maneuvering and safe stopping distances. The queuing distance upstream of the meter depends on ramp volumes, metering strategy, and the number of queuing lanes provided. Additional distance is required downstream of the meter to permit metered vehicles to accelerate from a stop back to the running speed of the freeway traffic.

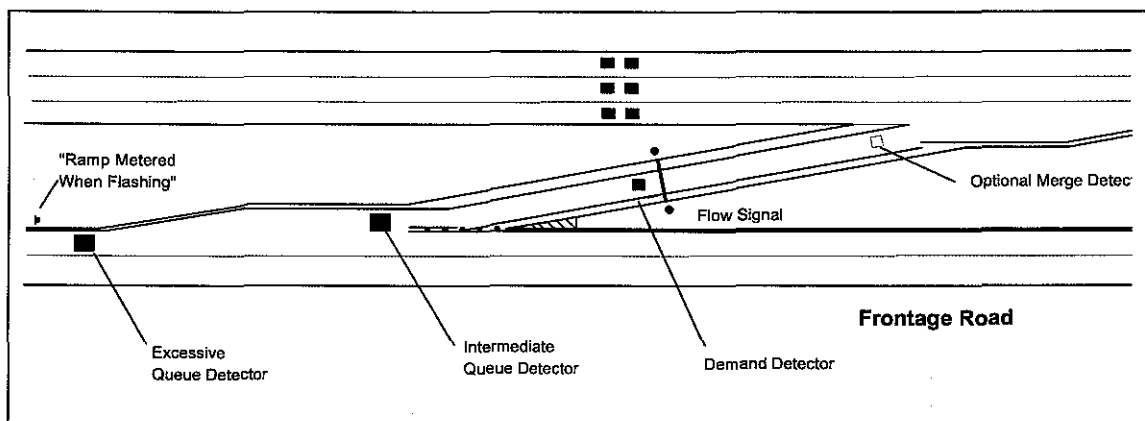


Figure 11. Typical Single-Lane Ramp Meter Layout in Texas.

METERING DESIGN CONTROLS AND CRITERIA

Minimum Distance to Back of Queue

Motorists leaving an upstream signalized interchange will likely encounter the rear end of a queue as they proceed toward the meter. Adequate maneuvering and stopping distances should be provided for both turning and frontage road traffic. Frontage road (ramp) speeds are usually higher than left- or right-turn speeds leaving the upstream traffic signal. Frontage road traffic speeds may be 35 mph, or higher. Left-turn speeds are usually no higher than 25 mph, and right turn speeds are usually no higher than 20 mph. Right-turn vehicles, in particular, should be able to make lane changes to the metered queue, presumably on the left side of the frontage road.

For a 35 mph frontage road design speed, the minimum separation distance is calculated to be 249 feet from the basic AASHTO (13) stopping sight distance equation:

$$X(\text{feet}) = 1.47vT + \frac{v^2}{30f_v} = 1.47 \times 35 \times 2.5 + \frac{35^2}{30 \times 0.34} = 249 \text{ feet}$$

where:

X	=	stopping sight distance, feet;
v	=	traffic speed, mph;
T	=	perception-reaction time, seconds; and
f_v	=	coefficient of deceleration braking friction as related to speed.

which is assumed to be measured from the center line of the cross street in the interchange. For a 25 mph-left turn speed, the AASHTO stopping distance is 147 feet as measured from the center line of the cross street.

Right-turn vehicles must also weave or lane-change across one or more frontage road lanes before stopping at the back of the queue, assuming that the queue being metered is positioned along the inside lane(s) of a 2- or 3-lane frontage road. For right-turn speeds of 20 mph, a lane-change distance of 80 feet is assumed plus an added stopping distance of 107 feet. Adding a street half-width of 45 feet produces a distance from the center line of the cross street of 232 feet. The distance to the back of the queue should also be some distance downstream of any turnaround lane entrance, which may be nearly 100 feet from the cross street curb line.

Thus, the minimum distance desired from the center line of the cross street to the back of the design queue should be about 250 feet. A more desirable distance would be about 310 feet permitting two lane changes for right-turn vehicles from the cross street, and higher ramp approach speeds.

Feasible Metering Rates

Motorist behavior and physical capabilities place limits on ramp-metering operation. When a driver stops at the meter on red (and becomes the next to go), motorists usually will not wait more than 20 seconds before running the red signal. Urban drivers' patience has its limits.

Moreover, drivers in a single lane cannot reliably perform the stop-go-stop metering cycle any faster than about 4.5 seconds or reliably respond to the red-green-yellow signal displays any shorter than 2+1.5+1 seconds of R+G+Y display time. Thus, the meter cycle should be between 4.5-20 seconds per cycle, producing feasible minimum-to-maximum ramp-metering volumes per lane of between about 200-800 vphpl in the one-vehicle-per-cycle single release mode of ramp metering. The practical capacity of single lane ramp metering is about 800 vphpl without flushing the queue (meter dwells until the excessive queue clears the meter).

Ramp Spacing Related to Service Time

Ramps should be sufficiently long to permit a reasonable service time charge for using the freeway during peak traffic conditions (to encourage diversion) while still metering at a relatively high flow rate. The time a vehicle spends in queue at the meter, S , depends on the queue length on arrival and the mean time of service per vehicle, T_s , or the cycle time of the meter (with one vehicle being released per cycle per lane). Thus,

$$S = E(n) * T_s = \frac{L(ft)}{25(ft/veh)} * \frac{60(min/hr)}{M(vphpl)} = 2.4 \frac{L(ft)}{M(vphpl)}$$

where:

- S = service time (delay) at the meter per lane, minutes;
- $E(n)$ = expected number of vehicles in queue when length is L , vehicles;
- L = length of queue being stored, feet; and
- M = ramp metering rate, vphpl.

Thus, a vehicle arriving when the queue is a length $L = 667$ feet with vehicles storing at 25 feet per vehicle, and which is being metered at the maximum rate of $M = 800$ vphpl, would experience a delay to service of $S(\text{min}) = 2.4 * 667 / 800 = 2$ minutes. Since many urban freeway ramps in Texas have traffic demand volumes exceeding 800 vph, single-lane meters will often be running at their maximum rate of 800 vph. Ramps need to be long enough, not only to store queues, but to delay entry into the freeway (to encourage diversion) when the meter is running full speed. However, if the ramp queue gets too long, excessive ramp delays will result, drivers will complain, and their voluntary compliance of the meter will diminish. Figure 12 illustrates the fundamental metering service time (delay) relationship with queue storage length for single-lane metering equal to the arrival rate.

Metering Process

The adaptive ramp-metering design used in Texas processes platooned ramp arrivals into the freeway as smooth-flowing, uniformly-spaced merging traffic. Over the period of one hour, the ramp entry volume will nearly equal the current ramp demand volume (less any change in queue storage, which is usually relatively small). This fact results from examining the equation of mass balance of traffic flow for one hour:

$$Q = Q_o + V - M$$

$$V = M + (Q - Q_o) \leq M + 0.04X$$

$$V \cong M$$

where:

- M = metered ramp volume, vph;
- V = hourly ramp demand volume, vph;
- Q = queue at end of hour, vehicles;
- Q_o = queue at start of hour, vehicles; and
- X = ramp queue storage distance, feet.

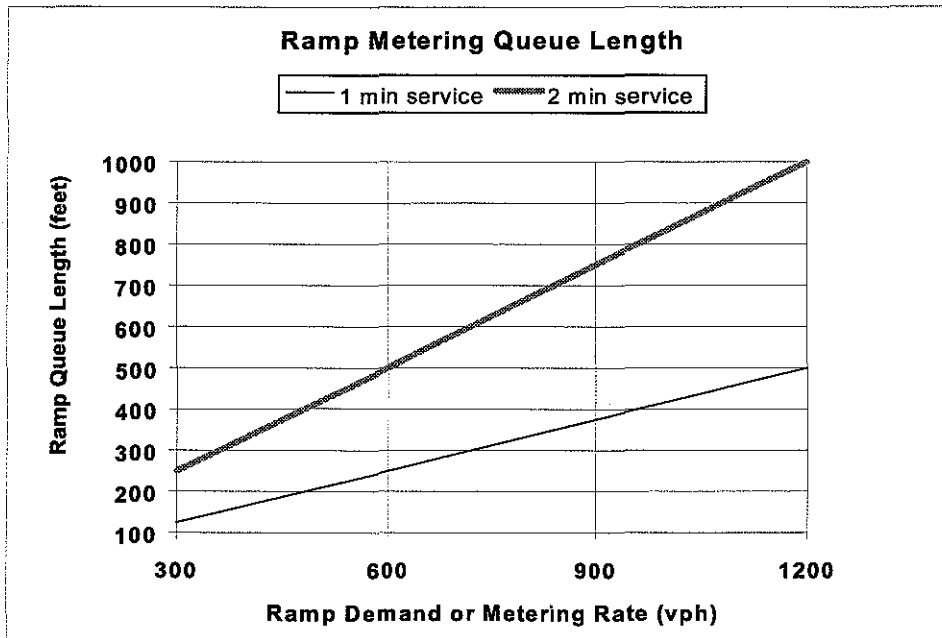


Figure 12. Relationship Between Ramp Queue Length and Ramp Demand Equal Metering Rate to Produce Ramp Service Times of One and Two Minutes.

A ramp 1000 feet long would only allow ramp demand to exceed the metering rate by 40 vph under the most ideal assumption (queue being empty at the start of the metering). Thus, ramp length does not significantly affect the ramp volume metered for a given hour; however, ramp spacing does affect the quality of ramp metering provided which may be used to reduce the ramp demand somewhat in the long term.

Metering Analysis

Adaptive ramp metering, like that used in Texas, adjusts its metering rate until queue equilibrium is established (over a time period longer than the upstream intersection signal cycle, for example at least for five minutes, but probably less than one hour, since demand changes would be expected). Essentially, the meter's flow states produce an expected flow of

$$aM + e0 + wF + zV = M \Rightarrow V$$

where the new terms are:

- a = ramp availability, or the fraction of time the ramp meters normally;
- e = fraction of time the ramp meter is empty (no ramp queue);
- w = fraction of time the ramp meter is “flushing” the queue;
- F = ramp flush rate when an excessive queue is detected and the meter is turned off (either goes dark, or green), $F \cong 1800$ vph; and
- z = fraction of time the meter is in the “dwell” state trying to recycle.

When the ramp’s hourly demand volume, V , is less than its nominal metering rate M (or its capacity), no queue growth or flushing (F) occurs. Thus, z and w are zero. Therefore, the fraction of time the ramp nominally meters (its availability, a) is about

$$a = V / M$$

When the ramp demand V is less than the metering rate M , the ramp availability is metering nominally all the time, but a fraction of the time the meter is empty ($e = 1 - V/M$ in this case).

When the ramp demand V is greater than the ramp’s nominal metering rate (and its nominal metering capacity of about $M = 800$ vph), the meter is never empty and e is equal to zero. Thus

$$aM + wF + zV = V$$

Solving this equation, the fraction of time a (a = availability) the ramp is metering nominally (as desired) is

$$a = \frac{V(1-z) - wF}{M}$$

For this case ($V > M$), it is desired to maximize a (the percentage of time the meter is operating nominally) for a given V , F , and M . To maximize a (the availability), z (the dwell state fraction) must be minimized. Since $a + w + z = 1$ in this case, solving for w and substituting in the above equation yields the generalized equation for availability, a , of

$$a = \frac{(1-z)(F-V)}{F-M} = \frac{r(F-V)}{F-M} \quad M < V, \quad V \leq F$$

where the relative ramp efficiency r is $1 - z$.

The fraction of the time the meter is in the dwell state, z , will depend on the ramp spacing, design of the traffic detectors, and upon the traffic volume, which will be different for each ramp and time of day.

A simulation program of this metering problem was written in Microsoft Excel from which ramp metering availability results were obtained. Figure 13 illustrates the results of the simulation program for availability when the ramp volumes are slightly higher than the ramp capacity. The relative efficiency, $r = 1 - z$, increases toward 1.0 in Figure 13 as the ramp queuing distance increases; thus, the meter operates as designed for a higher proportion of the time as the ramp length increases. However, ramp lengths in excess of 800 feet result in little improvement in this measure of performance.

To summarize the results presented, queue storage lengths in Texas probably should be greater than 600 feet, but probably not longer than 800 feet. Further analysis of the need for additional ramp spacing for metering is presented in the following sections.

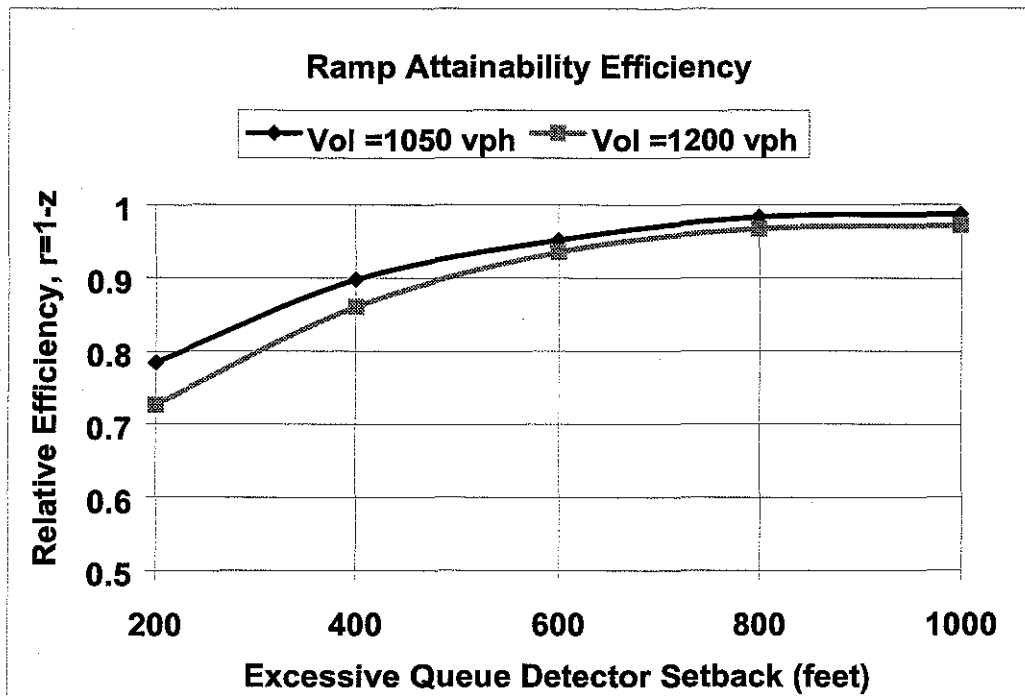


Figure 13. Improvement in Relative Metering Efficiency with Increasing Excessive Queue Storage Length for Two Ramp Volumes.

Excessive Queue Detector Location

Prior studies have already indicated that queue storage lengths of around 600-800 feet would promote reasonable delays and operational efficiency if the meter can reliably serve the average traffic demand. However, traffic flow from an upstream signal is dynamic, pulsating, and variable both within upstream signal cycles and over several cycles, as noted in a previous chapter. Researchers conducted further Excel simulation studies to assess the distribution of maximum queue lengths that various excessive queue detector locations should be able to contain.

The primary function of the excessive queue detector is to protect an upstream intersection from queue spillback. Secondly, its mission is to monitor and control the amount of metering delay being experienced by motorists. When an excessive queue is detected, the usual ramp meter response is to go into a "flush mode" of operation for a prescribed period of time following clearance of the intermediate queue detector. The flush mode essentially returns the ramp to a non-metered state by either going dark, or by the meter displaying green for the duration of the flush period.

The location of the excessive queue detector (or queuing space provided) should be sufficient to avoid "false calls" as cyclic platoon flow is emitted from the upstream signalized interchange. These platoon flow rates may exceed 3500 vph or higher (when two lanes of traffic are arriving from the upstream signal) for 15-20 seconds. These platoons should be stored in queue without falsely triggering the meter to flush.

Design criteria for locating the excessive queue detector were selected to reliably contain the 95-percentile queue expected during a 140 second peak-hour signal cycle, assuming a nominal queue existed at the meter at the start of the upstream signal cycle. The largest platoon was assumed to develop from 55 percent of the cycle's traffic demand to the ramp (determined as the 95 percentile green split, where 1/3 is the average value). Moreover, the 95 percentile traffic demand per cycle was loaded on this cycle approaching the ramp. The arrival flow rate from the peak platoon (P , vph) is assumed to be the saturation flow of the signal phase generating the platoon, or $P = N * S_i$ where N is the number of departure lanes and S_i is the saturation flow per lane (about 1,800 vphpl).

The equation of mass balance is used to determine the ramp queue size at the end of each platoon's arrival to the meter's queue as:

$$q(\text{veh}) = q_o + (P - M) * \rho C / 3600$$

where

- q = design queue size for excessive queue detector (vehicles);
- q_o = average number of vehicles in queue at start of critical phase;
- P = platoon flow rate, NS_i , (vph);
- M = metering rate during period (which will produce a two minute metering delay (vph); and
- ρC = portion of cycle, C , needed to service design platoon, (seconds).

Stochastic queuing theory was used to select the initial queue size, assuming Poisson arrivals and uniform metering rates. The nominal metering rate, M (vph), was selected to produce a two minute ramp delay, D , assuming the average ramp demand volume, V (vph), being simulated. The equation for the metering rate, M , is

$$M = V + \frac{30}{D}$$

Figure 14 provides the simulation modeling results for maximum queue length distribution, and for locating the excessive queue detector based on the 95 percentile criteria

described above. Three metering strategies were analyzed: (1) single-lane with single vehicle release per cycle, (2) single-lane, with bulk metering (3 vehicles per green), and (3) dual-lane metering. Graphs end for ramp demand volumes exceeding meter capacity for the three metering strategies.

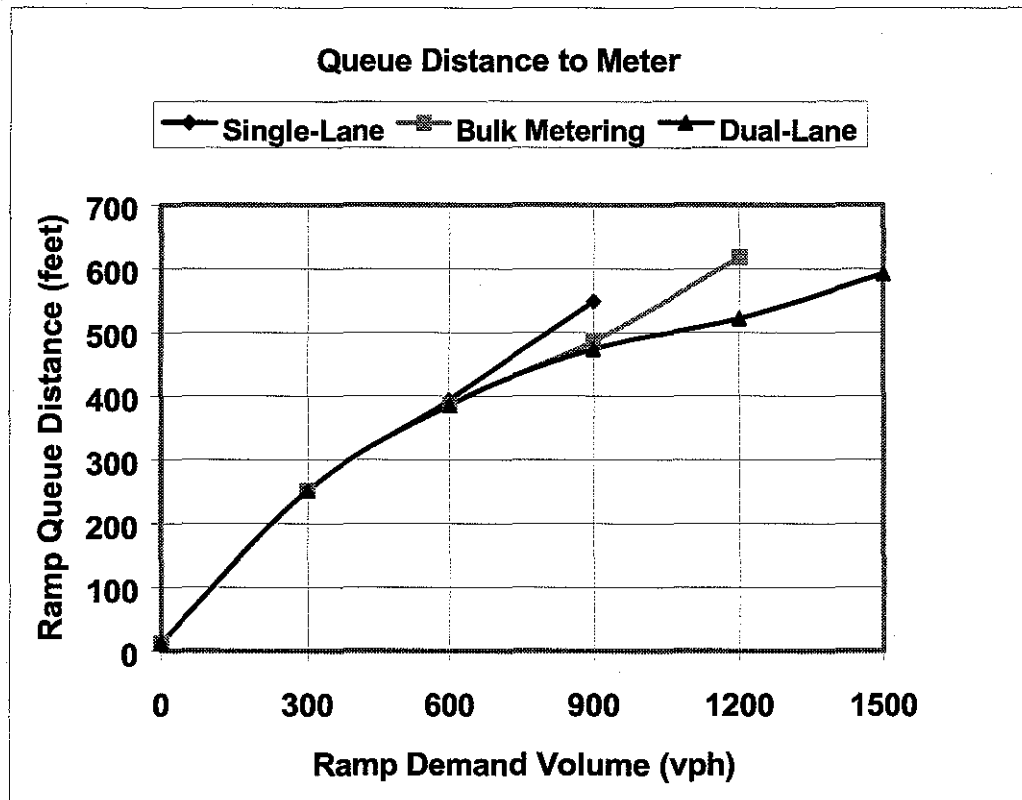


Figure 14. Ninety-Five Percentile Queue Spillback Distance from an Undersaturated Meter.

DISTANCE FROM METER TO MERGE

AASHTO provides speed-distance profiles for various classes of vehicles as they accelerate from a stop to speed for various ramp grades (13). Figure 15 provides similar acceleration distances needed to attain various freeway merging speeds based on the AASHTO design charts. About 419 feet is presumed needed to accelerate from a stop at the meter to a 40 mph merging speed on level grade. Desired distance to merge increases with increasing freeway merge speed and ramp grade.

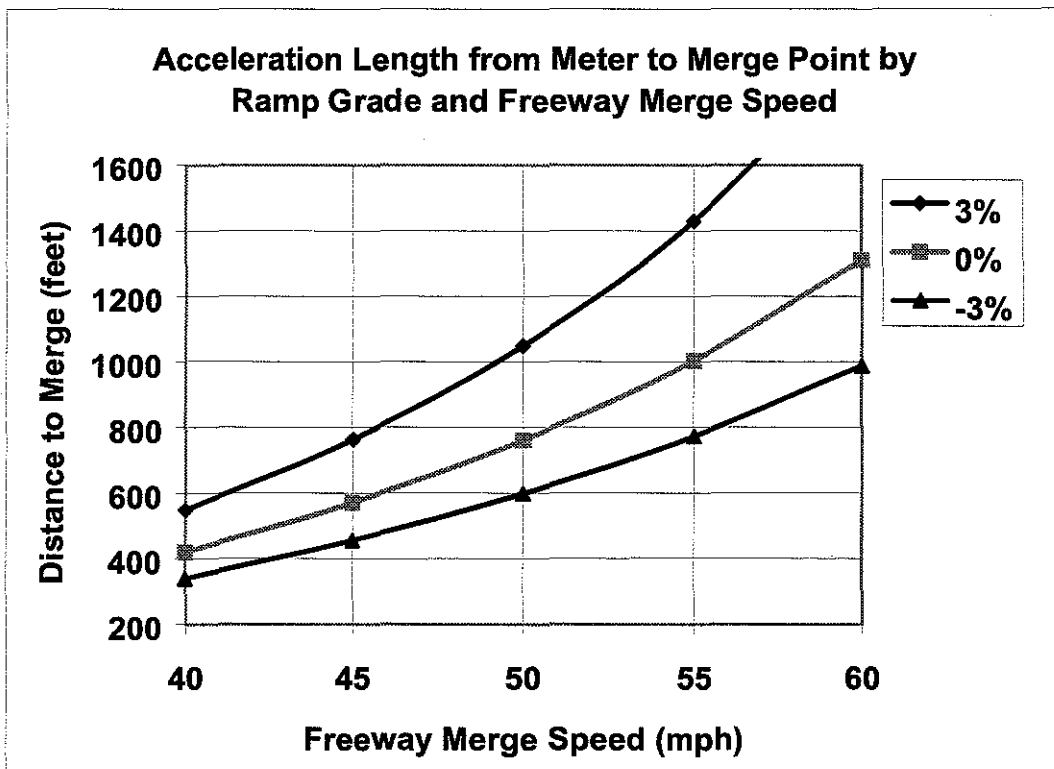


Figure 15. Distance from Ramp Meter to Freeway Merge for Three Ramp Grades Based on AASHTO Passenger Car Acceleration Criteria.

The numerical values for Figure 15 are presented in Table 9 below.

Table 9. Travel Distance from Ramp Meter to Freeway Merge Point for Various Freeway Entry Speeds (feet).

Merge Speed (mph)	-3% Ramp Grade	0% Ramp Grade	+3% Ramp Grade
40	339	419	548
45	455	571	764
50	598	762	1049
55	773	1004	1429
60	988	1311	1946

SUMMARY OF RESULTS

Types of Ramp Metering in Texas

Three types of ramp metering exist in Texas to improve freeway flow, increase safety, and minimize air pollution. These three basic metering strategies are:

1. Single-lane, single vehicle release per cycle. This form is currently the most widely used, but it has a ramp-metering capacity of only 800 vph.
2. Single-lane, bulk (usually platoons of 2 or 3 vehicles per cycle) metering, which provides a reliable ramp-metering capacity of 1100-1200 vph. Only one platoon metering site exists in the state (US 59 @ Kirby in Houston).
3. Dual-lane, single vehicle release per cycle, which may merge back into one lane along the ramp. This form of metering has proved to be very safe and self-enforcing as tested, and it provides a reliable capacity metering rate of 1600 vph. Only one now exists in the state (US 290 @ FM 1960 in Houston), which is a conventional diamond ramp without frontage roads.

Urban Freeway Ramp Volumes

Since ramp metering was first employed in Texas in the late 1960s, ramp volumes observed on urban freeway entrance ramps have steadily grown around 2 percent per year on the average. Where modest volumes of 600-800 vph were common during the rush hour in the 1960s, volumes of 1200-1500 vph, or higher, are now routinely on many entrance ramps for many hours of the day, particularly in Houston.

Ramp Availability

The fraction of the time (for example, over an hour) that a ramp meters nominally, when the ramp demand volume exceeds the capacity of the meter, is called its "availability." Availability is a convenient measure of how reliably the meter is regulating the entry traffic for high volume conditions. The availability is given by the equation

$$a(\%) = \frac{F - V}{F - M} \times 100\% \quad c = M \leq V < F$$

where:

- a = ramp availability, or fraction of time the ramp is metering nominally, percent of time;
- c = capacity (for type) of ramp meter in nominal operation, vph;
- F = flush flow rate of ramp, assumed to be 1800 vph, although the freeway may not be able to absorb such entry flow without breaking down, vph;
- V = ramp demand volume, vph; and
- M = nominal ramp metering rate, which is assumed to be the ramp meter capacity, $M = c$, when $V \geq c$. $M \cong V$ when $V < c$. vph.

As shown in Figure 16, the availability is about 100 percent when the ramp demand volume, V , is less than the meter's capacity for well-designed ramps, assuming that the meter was not restricting flow. Should the ramp demand volume, V , exceed the ramp's flush capacity, of about 1800 vph for a short period of time, then the ramp's availability is 0 percent. In between these two boundary volumes, the ramp availability varies from 100 - 0 percent as the ramp demand volume, V , increases. Figure 16 is a graph of these results for the three types of ramp metering described above. These results show that ramp demand volumes in excess of 1200-1400 vph probably should be designed for dual-lane metering as the fraction of time the meter is working effectively would be less than 50 percent.

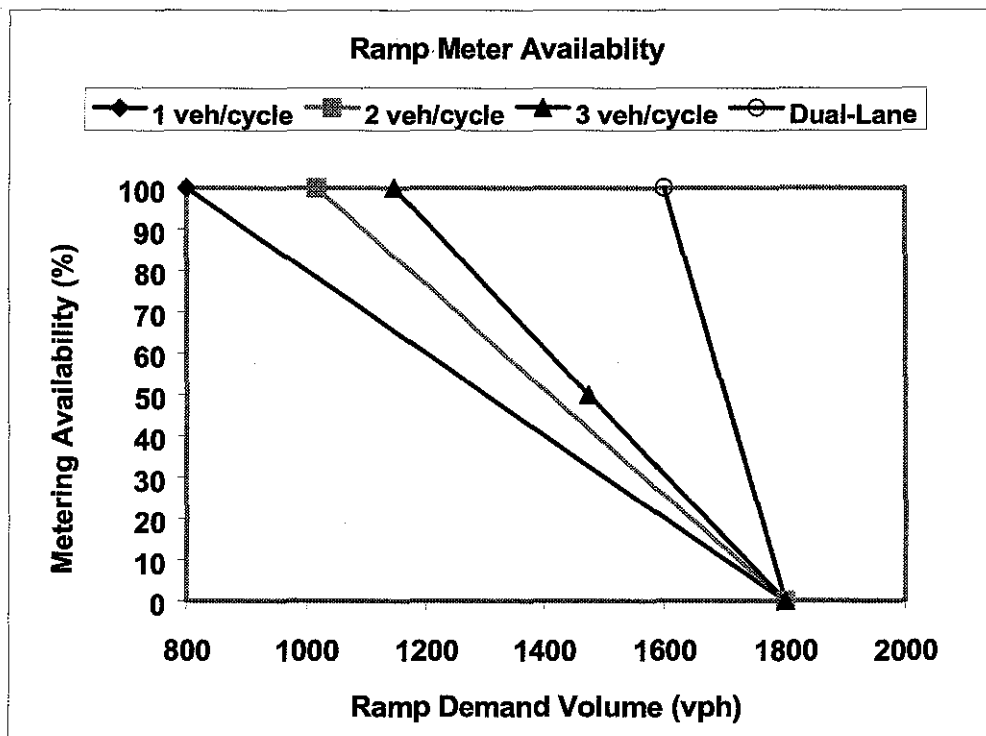


Figure 16. Meter Availability as Related to Ramp Demand and Metering Strategy.

Distance from Cross Street to Meter

The minimum desirable distance from the cross street to the ramp meter can be developed from the previous analyses. The minimum recommended distance from the center line of the cross street to the meter is 250 feet. Operationally, the excessive queue detector is assumed to be placed at this location. To this distance should be added the 95 percentile queue length distribution distance from Figure 14 for a given ramp demand volume. The combined distance from the center line of the cross street to the meter is provided in Figure 17 and in Table 10.

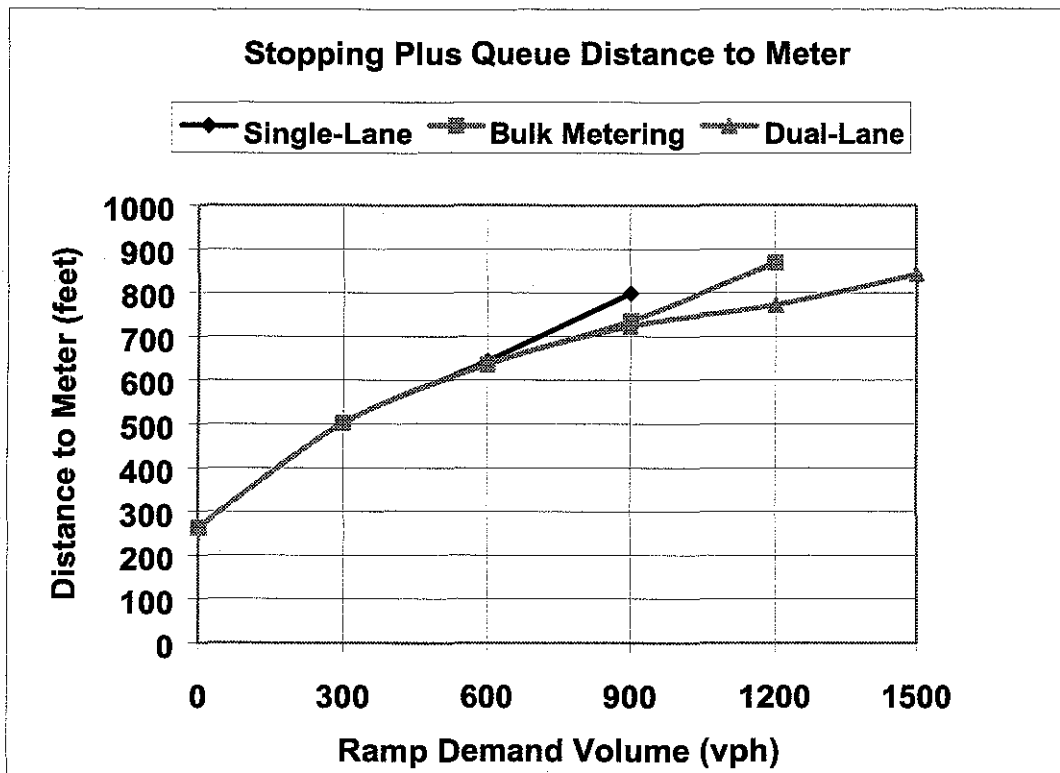


Figure 17. Total Ramp Distance from Cross Street to Meter.

A generalized spacing model was developed from the ramp-metering strategies shown in Figure 17, which can be used to estimate ramp spacing needed when the type of meter is not known with certainty. This equation is:

$$L = 250 + 0.820V - 0.0002435V^2 \quad V \leq 1600vph$$

where L is the total distance needed from the center line of the cross street to the meter (feet), V is the expected peak-hour ramp volume (vph), and the design stopping distance is 250 feet. Other stopping distances could be substituted as desired.

Table 10. Recommended Distance from Cross Street to Meter by Metering Strategy (feet).

Ramp Volume (vph)	Type of Ramp Metering Strategy			
	Single Lane	Bulk Metering	Dual Lane	General Model
0	250	250	250	250
300	502	502	502	474
600	644	636	636	654
900	799	736	724	791
1200	---	868	772	883
1500	---	---	843	932

Distance from Cross Street to Merge

A complete design should provide for the total distance needed from the upstream cross street at the interchange to the meter (Table 10) plus the acceleration distance from the meter to the merge point to the freeway (Table 9). Many design problems and their resulting distances exist, depending upon the metering strategy, ramp volume, ramp grade, and freeway merge speed.

An example problem is used to illustrate the overall ramp distance design requirements for ramp volumes of 0-1500 vph. A level-grade, direct entry ramp is assumed. The stopping distance is the recommended minimum of 250 feet to the back of the queue and the generalized equation described above will be employed. The resulting total distance from the cross street to the merge point for merge speeds of 40, 45, and 50 mph are presented in Figure 18.

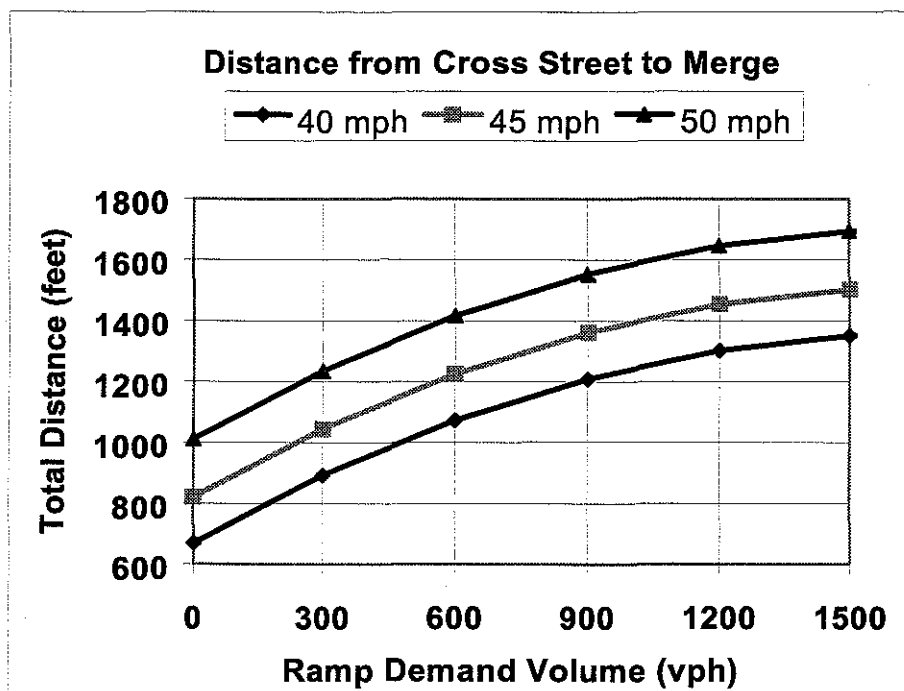


Figure 18. Total Distance Required from Cross Street to Merge for Level Ramp for Three Freeway Merge Speeds.

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