1. Report No. FHWA/TX-01/2121-3	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DESIGN CRITERIA FOR RAMP METERING: APPENDIX TO TxDOT ROADWAY DESIGN MANUAL		5. Report Date November 2000
		6. Performing Organization Code
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9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. Project No. 0-2121
12. Sponsoring Agency Name and Address Texas Department of Transportation Construction Division Research and Technology Transfer Section P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Guidelines: September 1999 – August 2000
		14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Project Title: Design and Operations Criteria for Ramp Metering

16. Abstract

This document contains an appendix for inclusion in the Texas Department of Transportation (TxDOT) Roadway Design Manual. The document contains criteria for ramp design with explicit consideration of ramp metering.

17. Key Words Ramp Meters, Texas Ramp Controller, Design Guidelines	18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161		
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 12	22. Price

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DESIGN CRITERIA FOR RAMP METERING: APPENDIX TO TxDOT ROADWAY DESIGN MANUAL

INTRODUCTION

Engineers install ramp meters to address the following three 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 the freeway for short trips detrimental to freeway operations. 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 the 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 length of green plus yellow indications is 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 may be 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 in red would result in a lower meter capacity of 800 VPH.

Single-Lane Multiple Cars per Green

Platoon metering, also know 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 large platoons). 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 because this strategy requires longer 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 analysis illustrates that bulk metering does not double capacity and this finding should be noted.

Dual-Lane Metering

Dual-lane metering requires two lanes be provided on the ramp in the vicinity of the meter which necks down to one lane at the merge. In this strategy, the controller displays the green-yellow-red cycle for each lane. In Texas, synchronized cycles are used such that the green indications never occur 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.

Quality of Metering

Figure 1 shows the metering availability (percent of time the signal is metering) of the three metering strategies for a range of ramp demand volumes. For a ramp meter to produce the desired benefits, the engineer should select a metering strategy appropriate for the current or projected ramp demand. The ramp width will depend on this selection. Figure 1 provides the following information about the quality of single- and dual-lane metering strategies:

- single lane ramps can be used to provide good quality metering (metering availability of 80 percent or higher) when the ramp demand is less than 1200 vph,
- the quality of metering for single-lane ramps is fair for demand levels between 1200 and 1400 vph,
- single-lane metering should not be used for demands higher than 1400 vph, and
- dual-lane metering provides good quality metering for demand up to 1650 vph.

Thus, it is desirable to select the width of a freeway entrance ramp as follows:

- If ramp demand is less than 1200 vph, design a single-lane ramp.
- If ramp demand is more than 1200 vph, design a dual-lane ramp.
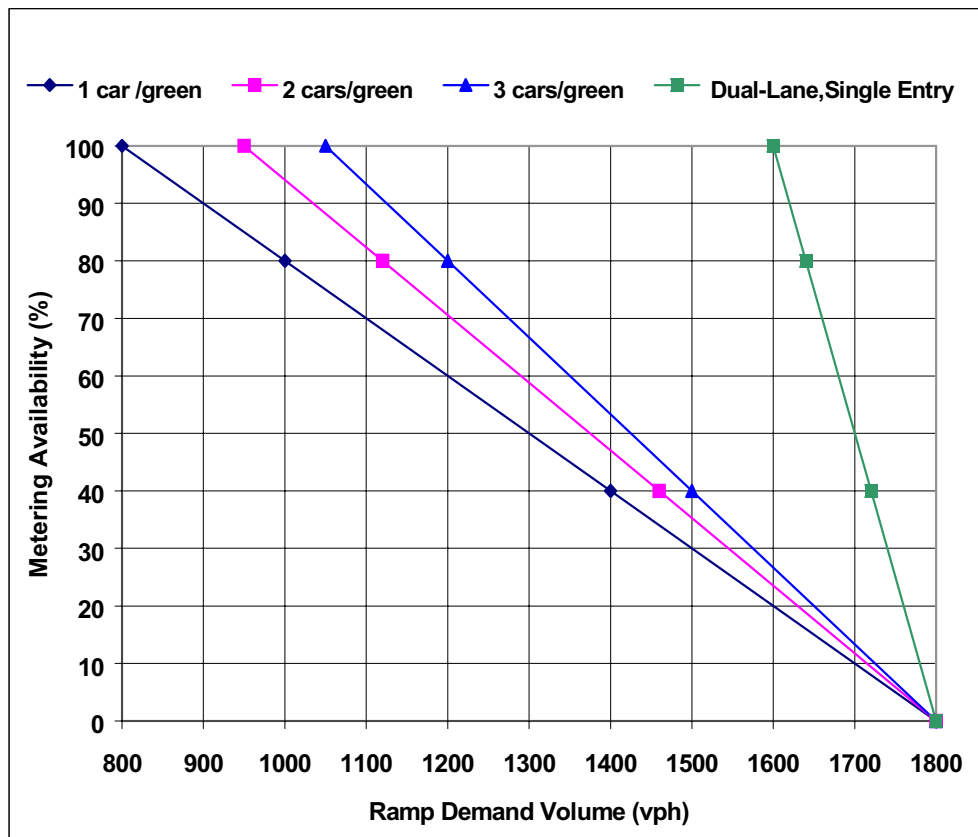
Metering Quality

Good

Fair

Fail

Figure 1. Quality of Metering Strategies.

Design Considerations

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. Sufficient space must be provided to store the resulting cyclic queue of vehicles without blocking an upstream signalized intersection.
3. Sufficient room must be provided for vehicles discharged from the upstream signal to safely stop behind the queue of vehicles being metered.

As illustrated in Figures 2 and 3, both single-lane and dual-lane meters in Texas usually use signal heads on each side of the metered ramp. The ability to provide sufficient storage space for ramp metering depends on the length of the ramp and the location of ramp signals.

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Figure 2. Single-Lane Meter.

Figure 3. Dual-Lane Meter.

Figure 4 illustrates distance requirements for ramp meters. In this figure, the dotted line shows the ramp length. The queue detector controls the maximum queue length in real-time. Thus, the distance between the meter and the queue detector defines the storage space. For dual-lane ramps, the ramp storage area (lower part of Figure 4) should also consider the transition from one lane to two lanes and dual-lane storage space. The transition zone should be at least 23 meters long, and the length of dual-lane storage should be sufficient to store a minimum of four cars per lane (approximately 31 meters). In addition, the placement of signal poles must take into consideration the following:

- minimum setback to prevent 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 gore-to-gore length of a ramp depends on two geometric 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. The top part of Figure 5 provides a cross section view of the freeway, a 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 0.91 meters from the shoulder or, in case of a curb, from the edge of the travel lane. The bottom part of Figure 5 illustrates the desired and minimum dimensions for ramps. Using trigonometry, 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 for given geometrics. Research shows that an outer separation of less than 50 feet will not provide sufficient storage and acceleration distances on a straight ramp. 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.
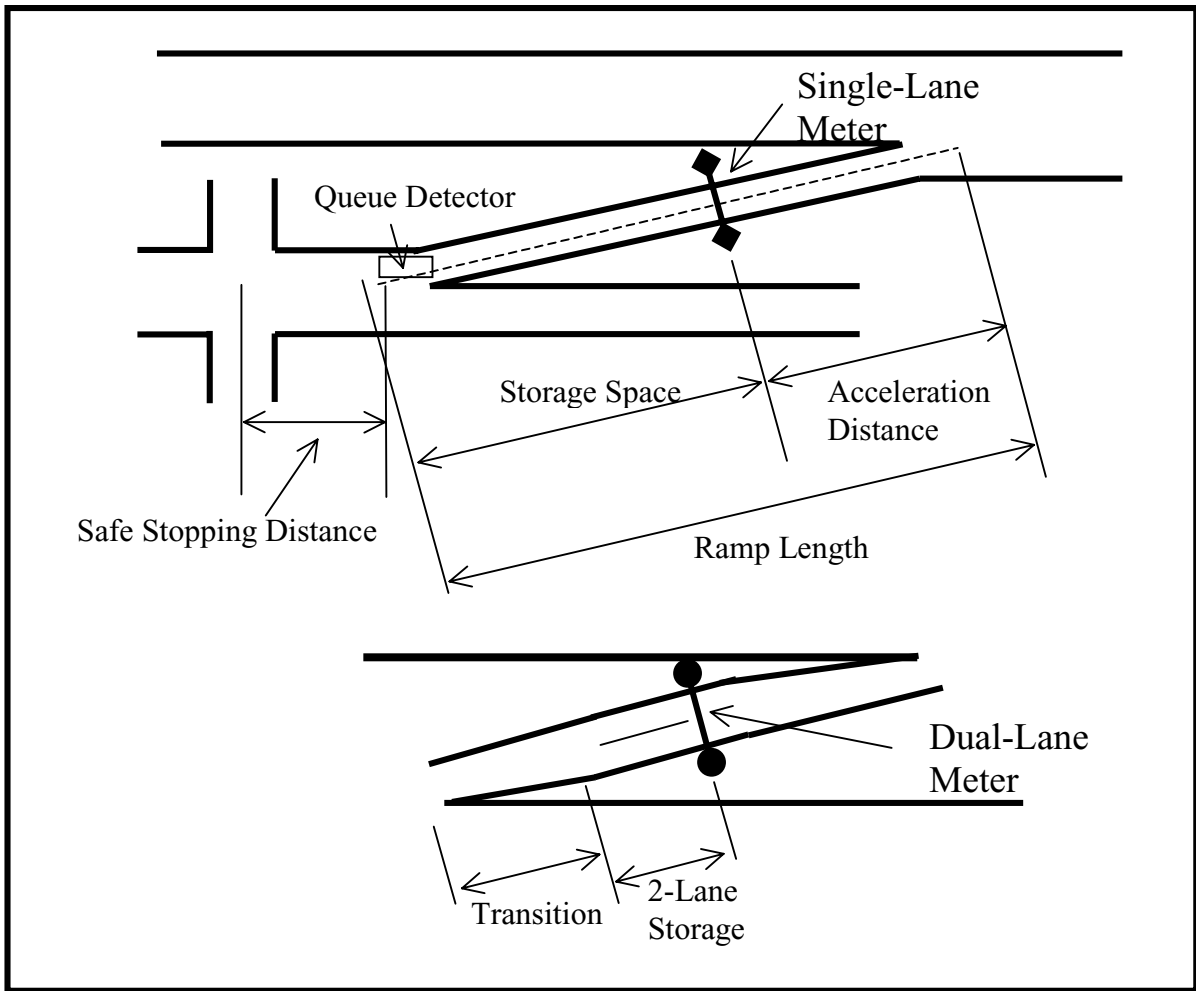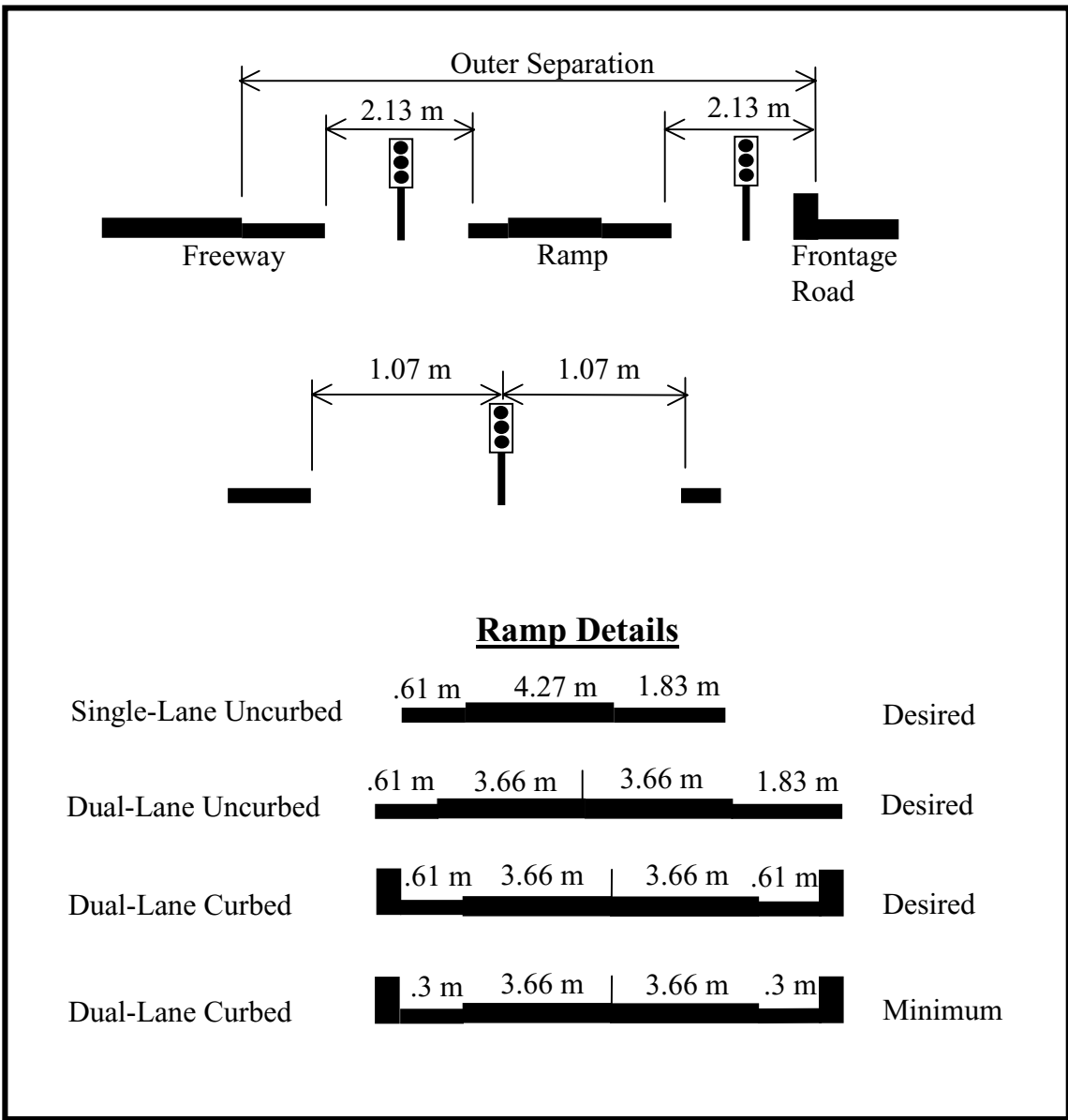
Figure 4. Design Issues Related to Ramp Meters.

Figure 5. Clearances for Placement of Ramp Signal Posts.

RAMP DESIGN CRITERIA

Minimum Stopping Distance to the 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 55 km/h or higher. Left turn speeds are usually no higher than 40 km/h, and right turn speeds are usually no higher than 30 km/h. Right-turn vehicles, in particular, should be able to make lane changes to the metered queue, presumably located downstream on the left side of the frontage road.

For a 55 km/h frontage road design speed, the minimum separation distance is calculated to be 73 meters from the basic AASHTO stopping sight distance equation:

$$X = 0.278vT + \frac{v^2}{254f_v} = 0.278 \times 55 \times 2.5 + \frac{55^2}{254 \times 0.34} = 73 \; meters$$

where:

X	=	Stopping sight distance, meters;
v	=	Traffic speed, km/h;
T	=	Perception-reaction time (2.5 sec), seconds; and
f_v	=	Coefficient of deceleration braking friction as related to speed.

Here, the stopping sight distance (X) is measured from the centerline of the cross street in the interchange. For a 40 km/h left-turn speed, the AASHTO stopping distance is 44.4 meters 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 two- or three-lane frontage road. For right-turn speeds of 30 km/h, a lane-change distance of 25 meters is assumed plus an added stopping distance of 29.6 meters. Adding a street half-width of 14 meters produces a distance from the centerline of the cross street of 68.6 meters. The distance to the back of the queue should also be some distance downstream of any turnaround lane entrance, which may be nearly 30 meters from the cross street curb line.

Thus, the minimum desired distance from the centerline of the cross street to the back of the design queue should be about 75 meters. A more desirable distance would be about 100 meters permitting two lane changes for right-turn vehicles from the cross street and higher ramp approach speeds.

Storage Distance

Figure 6 provides the maximum queue length distribution for locating the excessive queue detector based on 95 percentile criteria. This figure shows the requirements for three metering strategies: (1) single-lane with single vehicle release per cycle, (2) single-lane with bulk metering (three vehicles per green), and (3) dual-lane metering assuming single-line storage. For each strategy, the graph terminates when demand volume exceeds its meter capacity. From Figure 6, one can see that the minimum single-lane storage length is approximately 170 meters. If the storage length of design vehicles is 7.72 meters, this distance will be sufficient for storing 22 vehicles. The actual storage distance for a dual-lane meter will depend on the dual-lane storage distance provided in the design. For instance, if half of the 22 vehicles are stored in a dual-lane storage area, the total storage distance will be reduced to 126 (84 plus 42) meters.

The following generalized spacing model can be used to determine the single-lane storage distance:

$$L = 0.250V - 0.00007422V^2 \qquad V \le 1600vph$$

In this equation, L (in meters) is the required single-lane storage distance on the ramp when the expected peak-hour ramp demand volume is V vph.
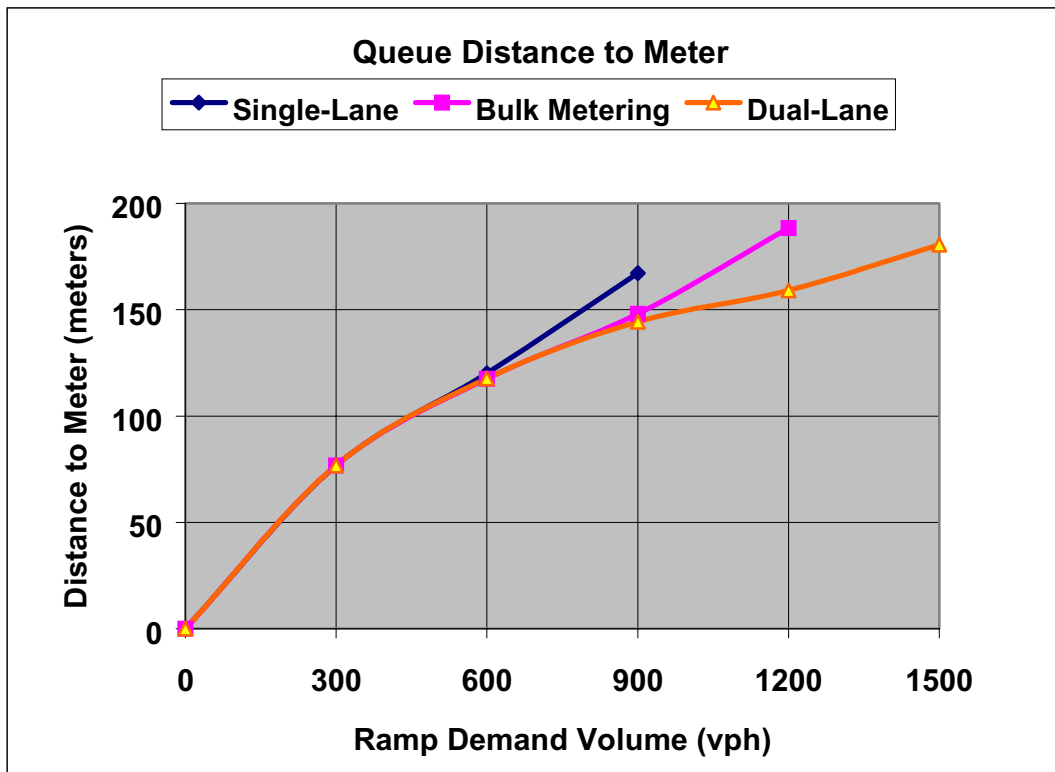

Figure 6. Ramp Single-Lane Storage Distance Requirements.

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. Figure 7 provides similar acceleration distances needed to attain various freeway merging speeds based on AASHTO design criteria. The desired distance to merge increases with increasing freeway merge speed and ramp grade. Table 1 provides numerical values for Figure 7.
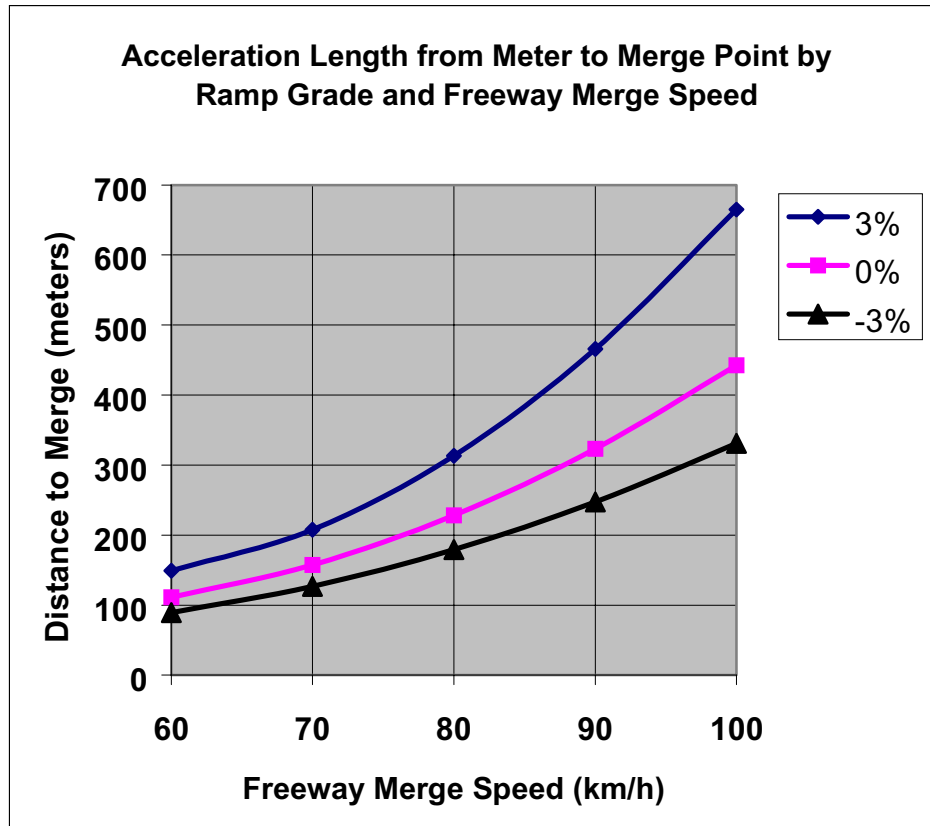

Figure 7. Distance from Ramp Meter to Freeway Merge for Three Ramp Grades Based on AASHTO Passenger Car Acceleration Criteria.

Table 1. Travel Distance from Ramp Meter to Freeway Merge Point for Various Freeway Entry Speeds (meters).

Merge Speed (km/h)	Ramp Grade (percent)		
	-3	0	+3
60	90	112	150
70	127	158	208
80	180	228	313
90	248	323	466
100	331	442	665