Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-95/1392-5		

4. Title and Subtitle	5. Report Date
DISTANCE REQUIREMENTS FOR RAMP METERING	November 1994
	6. Performing Organization Code
7. Author(s) Sameer Sharma and Carroll J. Messer	8. Performing Organization Report No. Research Report 1392-5
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. Study No. 0-1392
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Interim: September 1, 1993 - August 31, 1994 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 Study Title: Effective Detector Placement for Computerized Traffic Management

16. Abstract

Freeway ramp metering systems are being used to alleviate urban freeway congestion. This report presents a methodology for determining the distance requirements for ramp metering for a wide range of traffic volume and freeway geometric conditions. The distance requirement for ramp metering consists of distance required for queue storage and distance required for the freeway merging operation. A queue storage model has been developed to determine distance required for queue storage. The constant acceleration models of linear motion have been used to determine distance required for the freeway merging operation.

A methodology for determining the optimal placement of the ramp meter signal has been presented. Guidelines for effecting a trade-off between queue storage and freeway merging distance requirements have also been presented. A sample problem demonstrates the use of the presented methodology.

17. Key Words	18. Distribution Statement
Ramp Metering, Entrance Ramp, Queue Storage, Freeway Merging, Ramp Meter Signal.	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)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	38	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISTANCE REQUIREMENTS FOR RAMP METERING

by

Sameer Sharma
Graduate Research Assistant
Texas Transportation Institute

and

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

Research Report Number 1392-5
Research Study Number 0-1392
Research Study Title: Effective Detector Placement
for Computerized Traffic Management

Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

November 1994

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

IMPLEMENTATION STATEMENT

The guidelines presented in this report may be used for immediate implementation in ramp metering projects around the state. These guidelines may be used in the design and implementation of ramp metering systems. Designers and engineers may use these guidelines for checking on the adequacy of a given entrance ramp and freeway merge area for ramp metering. Distance requirements for freeway merging, and for queue spillback may be determined by using this report.

The research in this report may be used to determine the optimal location of the ramp meter signal. The guidelines included in this research report may also be used in the formulation of highway design policy in the design of entrance ramps.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration, or the Texas Department of Transportation. This report does not constitute a standard, specification or a permit regulation. Additionally, this report is not intended for construction, bidding, or permit purposes. Carroll J. Messer, P.E. #31409, was the engineer in charge of this work.

ACKNOWLEDGMENT

This research report was performed as a part of study 0-1392, entitled "Effective Detector Placement for Computerized Traffic Management," conducted by the Texas Transportation Institute (TTI) and sponsored by the Texas Department Of Transportation (TxDOT) in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

Many people contributed significantly to this work. These include Dr. Don Woods, who served as the overall project 1392 principal investigator for the Texas Transportation Institute. Dr. Tim Lomax provided literature concerning ramp metering systems in use in other states. Thanks are also extended to Mr. George Wier for his assistance with graphics.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

Ramp metering systems are being installed in several cities in Texas as a means of solving the freeway congestion problem. This research report describes the distance criteria involved in implementing ramp metering systems on entrance ramps for urban freeways. It outlines a methodology for determining the distance requirements for ramp metering for a wide range of traffic volume and freeway geometric conditions. Guidelines for optimally placing the ramp meter traffic signals for specific geometric conditions are also presented along with a description of the trade-offs involved.

Operational design criteria have been developed by presenting procedures to determine distance requirements for a wide range of freeway merging operations and queue storage conditions. Distance requirements for freeway merging have been developed by using constant acceleration models of linear motion. Queue storage requirements have been determined by developing a queue storage model. An illustrative example describes the use of the design criteria and how the design criteria may be used for various traffic volume and freeway geometric considerations.

1.0 INTRODUCTION

Traffic demand on Texas urban freeways continues to grow at about three percent per year even with all the freeway construction completed in recent years [1]. On congested urban freeways, average operating speeds are often less than 48 km/h (30 mph) in stop-and-go traffic, resulting in unacceptably high levels of delay, fuel consumption and emissions.

Freeway Traffic Management (FTM) systems are being implemented in several cities in Texas as a means of alleviating the freeway congestion problem without having to increase the physical capacity of the existing facility. Ramp metering is one of the components of FTM systems. Heavy ramp volumes and congestion on urban freeways have necessitated planning the installation of ramp metering systems on entrance ramps. Proposals for ramp metering systems for several additional urban freeways are being considered for congestion mitigation and air quality enhancements.

Ramp metering, as part of FTM systems, offers several operational features that improve freeway flow, traffic safety, and air quality by optimally regulating the input traffic to the freeway. Ramp metering involves placement of traffic signals on freeway entrance ramps so that cycling the signal regulates the ramp traffic [see Figure 1]. When in use, ramp meters discharge traffic at a measured rate based on real-time traffic conditions, thus maintaining the demand-capacity balance and thereby minimizing congestion.

After installing ramp metering systems, several operational problems, as well as non-compliance of the ramp meter signal, occurred because of inadequate queue storage space on the entrance ramp and the resulting acceleration distance to the merge area. This report presents a methodology for determining the distance requirements for ramp metering for a wide range of traffic volume and freeway geometric conditions. Guidelines for optimally placing the traffic signals for specific geometric conditions are also presented along with a description of the trade-offs involved. The purpose of this report is to provide engineers with a means to decide on the location of the ramp meter signal, to check the adequacy of a given location, and to decide upon specific geometric elements.

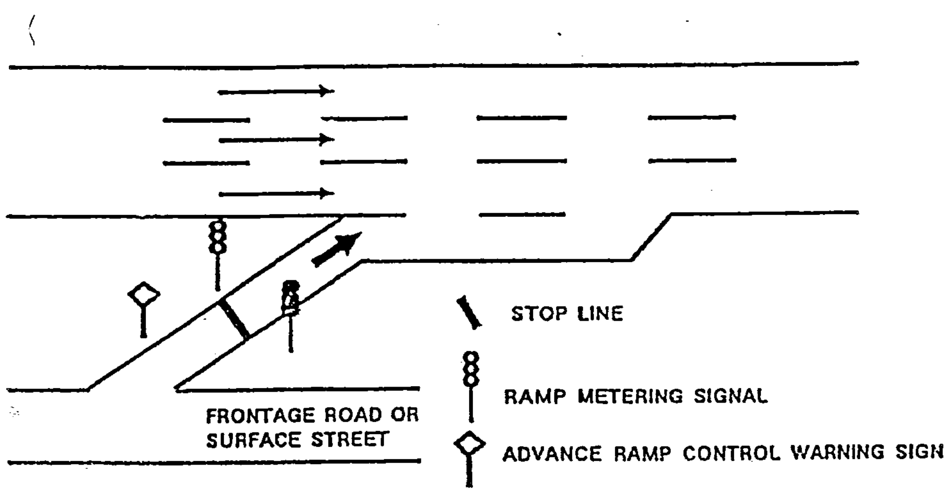

Figure 1. Typical Ramp Metering System Layout.

2.0 OPERATIONAL DESIGN CRITERIA

The three distance components of interest for the selection of the location of a metered entrance ramp together with the downstream freeway and upstream frontage road are:

1) Distance required to accelerate to freeway speed from the ramp meter stop line.
2) Distance required to find a gap in the freeway traffic stream.
3) Distance required for queue storage, behind the stop line.

Distances 1 and 2 together comprise the total freeway merging operation.

2.1 THE FREEWAY MERGING OPERATION

A vehicle from an initial stopped position that is entering a freeway from a metered entrance ramp will need adequate distance to accelerate to the freeway speed and then find an acceptable gap in the freeway traffic stream. The critical assumption in accomplishing this transfer is that the ramp vehicle will need to continue accelerating and achieve an adequate time headway over an adjacent freeway vehicle.

The following analysis shows that an acceleration rate of 3 mpsps (10 fpsps) assumes uniform acceleration [2]. This is a rapid but usable acceleration rate for low speeds. Once the ramp vehicle reaches freeway speed, the vehicle needs to find an acceptable gap and transfer from the acceleration lane to the freeway. A headway of 1.5 seconds over an adjacent freeway vehicle was considered acceptable because it translates to a gap of 3 seconds in the freeway traffic stream [3]. Constant acceleration models for linear motion were used to conduct this section of the analysis.

The distance required for the freeway merge operation includes the distance along the entrance ramp after the ramp meter stop line, and the travel distance along the acceleration lane. Figure 2 shows the distance required to achieve freeway speed, to achieve a 1.5 second headway, and the combined required distance for conditions of freeway speeds ranging from 48 to 97 km/h (30 mph to 60 mph). This range includes the speeds most frequently observed on urban freeways during ramp metering. The freeway speed is defined as the speed of main lane freeway traffic, and is presented along the X-axis in Figure 2. Distance required to merge is presented along the Y-axis and is defined as the distance from the ramp meter stop line to the final merge point on the freeway. The distance required for metering an entrance ramp for a given freeway speed can be obtained from Figure 2.

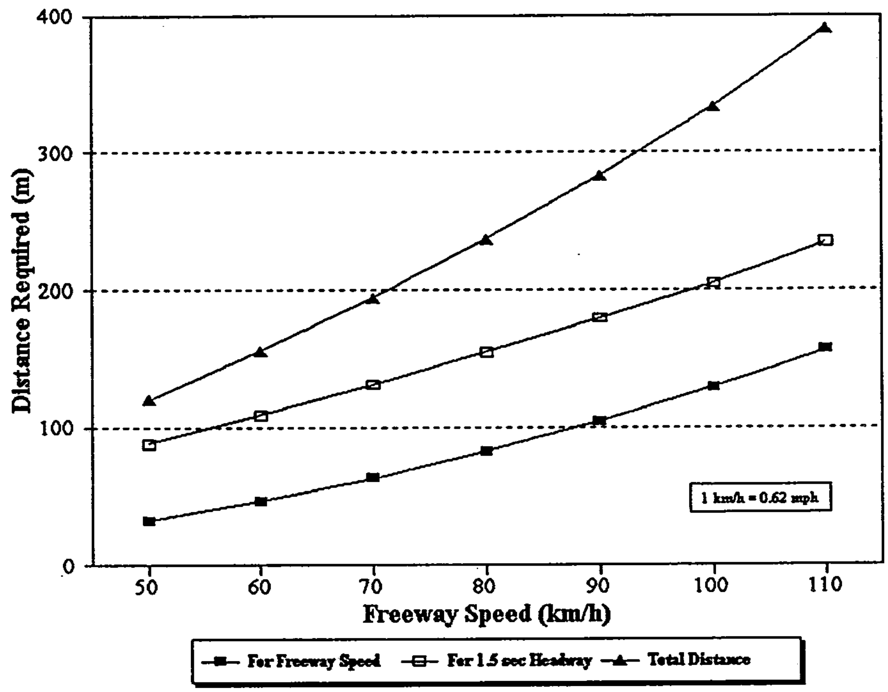

Figure 2. Distance Requirements for the Freeway Merging Operation.

2.2 QUEUE STORAGE REQUIREMENTS

A queue forms behind a ramp meter signal when the vehicle arrival rate exceeds the ramp metering rate. This queue may be stored upstream of the ramp meter signal, and it may spill back for a certain distance on the left most lane of the frontage road (as often exists in Texas). If the storage distance is inadequate, the queue might even reach the upstream intersection and pose operational problems. Therefore, it is imperative that adequate distance be provided for queue storage behind the ramp meter signal.

A storage requirement of 7.6 meters (25 feet) per vehicle was assumed because it adequately takes into account the presence of a normal proportion of trucks in the entrance ramp traffic mix. A storage model was developed assuming 95% Poisson arrivals. This model relates the storage distance to the ramp vehicle arrival rate, time period under consideration, and acceptable delay. Arrival rates ranging from 200 vph to 800 vph (in increments of 100 vph) were assumed, as was a minimum ramp metering rate of 200 vph. Acceptable ramp delay is the maximum delay for a vehicle in queue which in the designer's opinion would be accepted by the driver before major ramp signal violations begin to occur. Acceptable ramp delay has been presented in minutes, from 1 minute to 5 minutes, in increments of 1 minute. A ramp delay of more than 5 minutes is considered unreasonable and can be expected to lead to frequent violations of the ramp meter signal. Analysis time periods of 2 minutes and 4 minutes were used because they represent approximate durations of 1 and 2 signal cycles of possible demand overload from a traffic signal, assuming a cycle length of 120 seconds.

The queue length model was developed based on the assumptions described above. These assumptions were considered to be the most realistic for storage distance purposes. The queue length model is represented by the following equation:

$$L_Q = 0.122\,(\alpha VT)/(1 + T/D)$$

L_Q = Length of queue in meters
V = Vehicle arrival rate in vehicles per hour
T = Analysis time period under consideration in minutes
D = Acceptable ramp delay in minutes
α = A constant corresponding to 95% Poisson arrivals, = 2

The 0.122 is a constant that takes into account unit conversions and the set of analysis assumptions previously described.

Table 1 is based on the above queue length model, giving the queue storage requirements for 2-minute and 4-minute analysis time periods for a range of acceptable vehicle delay values ranging from 1 minute to 5 minutes. Figures 3 and 4 illustrate the information provided in Table 1. A designer can use these values to determine the storage distance for conditions presenting a specific arrival rate assuming both an acceptable delay value and either the 2-minute or 4-minute analysis time periods. For arrival rates between the 100 vph increment values, engineering judgement may be used and the queue storage requirement may be determined by either interpolating between the distance values presented in the table, or by solving the model given the design inputs. Table 1 thus gives the distance requirement for the upstream part of a metered entrance ramp. Part of this distance requirement may be accommodated on the frontage road if the left most lane is exclusively used for ramp operation and turns onto the freeway.

Table 1. Distance Requirements for Queue Storage (m)

Entrance Ramp Analysis		Acceptable Delay (min)				
Arrival Rate (vph)	Time Period (min)	1	2	3	4	5
200	2	33	49	59	65	70
	4	39	65	84	98	108
300	2	49	73	88	98	105
	4	59	98	125	146	163
400	2	65	98	117	130	139
	4	78	130	167	195	217
500	2	81	122	146	163	174
	4	98	163	209	244	271
600	2	98	146	176	195	209
	4	117	195	251	293	325
700	2	114	171	205	228	244
	4	137	228	293	342	380
800	2	130	195	234	260	279
	4	156	260	335	390	434

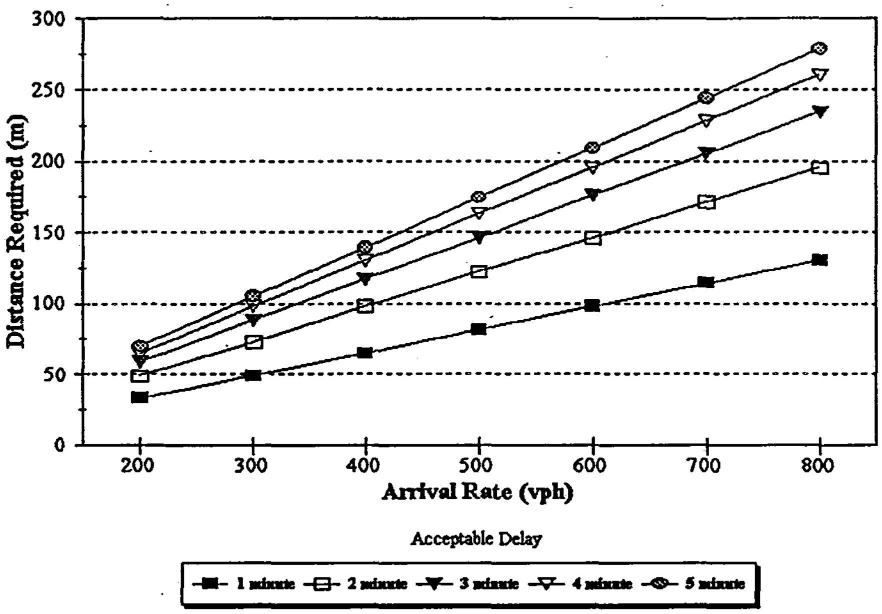

Figure 3. Distance Required for Queue Storage Assuming Two Minute Time Period.

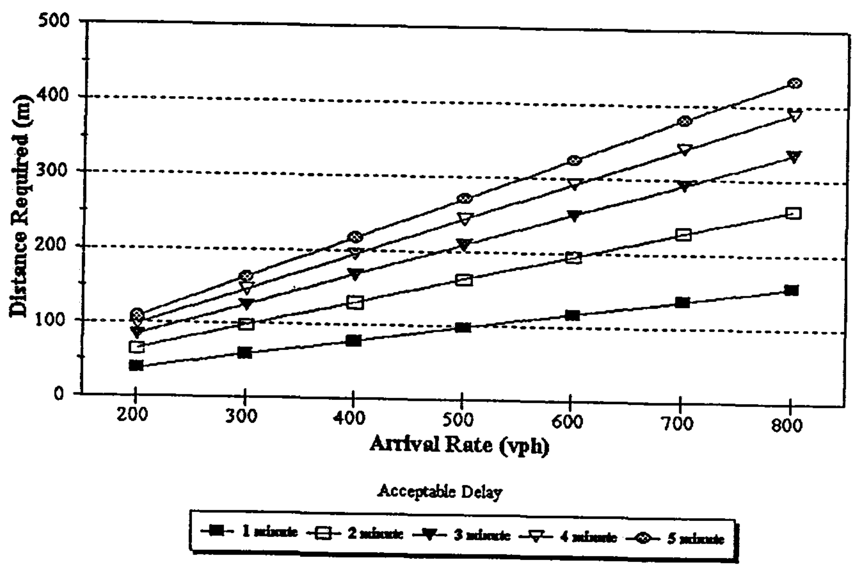

Figure 4. Distance Required for Queue Storage Assuming Four Minute Time Period

3.0 GEOMETRIC CONSIDERATIONS

The satisfactory operation of a metered entrance ramp depends to a large extent on the location of the ramp meter signal. The location of the ramp meter signal is determined by the geometry of the merge area length requirements and the frontage road separation, and should satisfy both safety and operational needs. The ramp meter signal should be located so as to leave adequate distance downstream of the ramp to achieve a safe freeway merge and provide adequate distance upstream of the ramp for queue storage.

An examination of freeway design plans shows that most urban freeway entrance ramps merge at an angle of 3, 4 or 5 degrees. In addition, good roadside safety design practice requires a 9 meter (30 foot) clear zone adjacent to the outside freeway travel lane. The ramp meter signal is presumed to be placed 1.2 meters (4 feet) away from the edge of the entrance ramp travel lane, which is assumed to be 4.9 m (16 feet) wide. The following analysis has been conducted in view of these conditions.

For a given entrance ramp merge angle and distance between the freeway and the frontage road, the length of the entrance ramp can be determined using simple trigonometric principles. Now, given a freeway mainlane speed, one needs to determine how far back from the final merge point the ramp meter signal needs to be located so as to provide adequate distance for a vehicle entering the freeway to merge safely. Determining how far back the ramp meter signal needs to be placed also effectively defines the signal offset. The signal offset is defined as the offset distance from the edge of the freeway travel lane to the ramp meter signal post nearest to the freeway.

Figure 5 relates ramp signal offset to the ramp distance available downstream of the ramp meter signal to achieve freeway transfer. Figure 5 was developed using trigonometric principles to determine the distance available on the entrance ramp, beyond the ramp meter signal, for a given ramp meter signal offset. Figure 6 relates ramp signal offset to maximum speed attainable by the ramp vehicle upon discharge at green. Figure 6 was developed using laws of constant linear acceleration to determine the speed a ramp vehicle will be able to reach, after discharge at the ramp meter signal green, for a given ramp meter signal offset and a given distance available on the ramp. Information in these figures can be used for entrance ramp merge angles of 3, 4 and 5 degrees.

Having decided upon storage requirements, the ramp distance available for freeway merging can be determined. The signal offset can be determined from Figure 5 by relating the ramp distance available. Figure 6 may now be used to determine the speed that can be achieved for the specific signal offset. By adding the length of the acceleration lane to the available ramp distance and checking this total available distance with Figure 2, it can be determined whether the distance requirements for safe freeway merging are satisfied.

From Figure 6, it is apparent that a design choice to add lane(s) on the outside of the freeway cross section results in reduced speed that can be attained on the ramp, given a ramp signal location. This means that the ramp signal must be relocated to meet the minimum requirements of a 90 km/h (55 mph) speed at the beginning of the merge area.

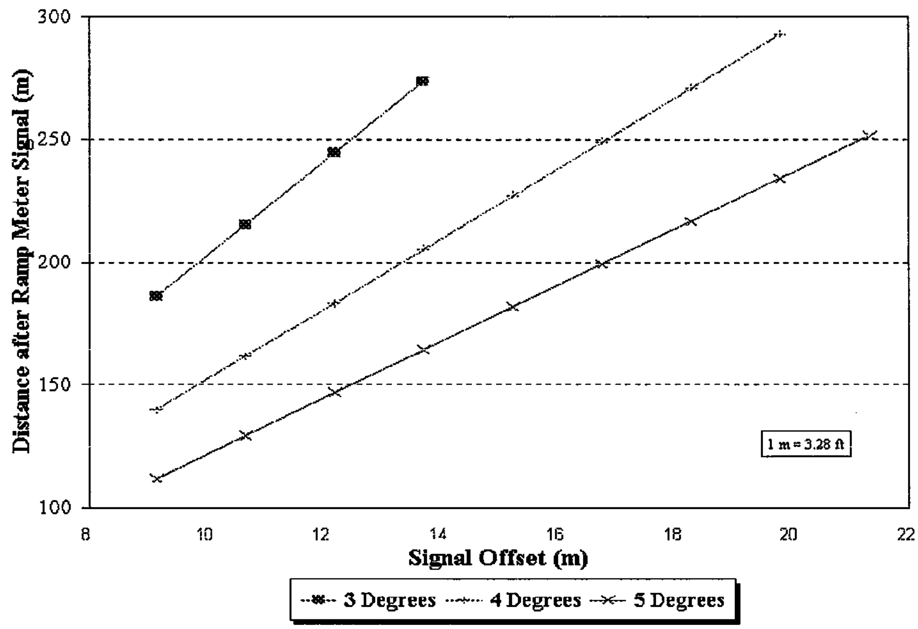

Figure 5. Ramp distance available for a ramp signal offset for different merge angl

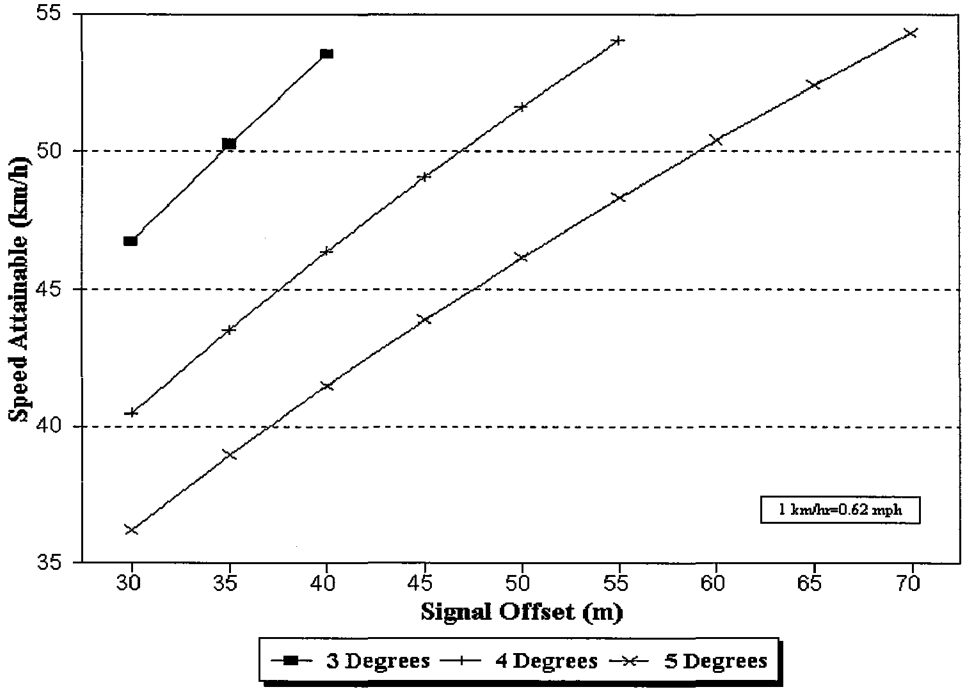

Figure 6. Speed attainable for a ramp signal offset for different merge angles

4.0 SAMPLE ANALYSIS FORM

Goal: To determine the best placement of a ramp metering system to optimize acceleration and storage distance.

Assumptions:

- Peak hour traffic conditions.
- 3-lane frontage road leaving the diamond interchange.
- Far left lane of the frontage road becomes the entrance ramp.
- Direct entry type entrance ramp.
- Entrance lane width = 4.9 m (16 feet).
- Ramp meter signal placed 1.2 m (4 feet) away from the edge of the entrance ramp travel lane.
- Roadside safety clear zone requirements stipulate at least a 9 m (30 feet) clear zone from the edge of the freeway travel lane.

I. Geometric Conditions:

A. Freeway Speed = ___90___km/h.

B. Angle of Merge = _3____4____5___degrees.

C. Separation between travel lane and left frontage lane (edge-to-edge) = ____________m.

D. Length of Entrance Ramp = ____________m.

E. Merging Distance Available = ____________m.

F. Storage space available beyond diamond interchange to the start of the entrance ramp = ____________m.

G. Roadside safety clear zone requirements stipulate at least a 9 m (30 ft) clear zone from the edge of the freeway travel lane.

II. Operational Conditions:

A. Peak Hour Arrival Rate = ____________vph.

B. Minimum Metering Rate = ____________ (200 vph).

C. Select cycle length of upstream diamond interchange to be considered:
2 Minute Time Period ____________.
4 Minute Time Period ____________ (To account for overflow queue).

D. Choose acceptable delay in minutes for queued vehicles which will not lead to frequent violations of the ramp meter signal:

1____2____3____4____5____ Minutes.

III. Procedure For Placing the Ramp Metering System

A. Ample merging distance must be allocated so that the vehicle may achieve a 1.5 second headway after reaching freeway speed and before merging with the freeway travel lane. This required merging distance may be found from Figure 2. For a freeway design speed of 90 km/h (55 mph), the minimum merging distance required to achieve this headway before entering the through freeway travel lane is 179 m (587 feet).

Merging Distance Required Before Entering the Through Freeway Travel Lane ____________**(i.).**

If the merging distance required (i.) is greater than the merging distance available (I.E.), the merging lane pavement markings must be extended to provide more distance to achieve a 1.5 second headway. If geometric considerations limit this manipulation of the lane lengths, or if the resulting extension ends too close to the next ramp entrance, the current ramp configuration may need to be relocated further downstream.

B. Based on the freeway speed, determine the minimum **ramp distance** required for acceleration purposes. This value can be calculated by considering an acceleration rate of 3 mpsps (10 fpsps). For a freeway design speed of 90 km/h (55 mph), the minimum ramp distance required to accelerate to freeway speed before entering the merging area is 104 m (340 feet).

Ramp Distance Which Must be Allocated for Acceleration Purposes __________**(ii.).**

C. Measure 9 m (30 feet) from the edge of the freeway travel lane to the left edge of the ramp lane and mark the corresponding point on the ramp. This point gives the available ramp distance for acceleration purposes. If this distance is greater than the minimum required distance for acceleration as found in III.B. (ii.)., select this point for the ramp metering signal, otherwise continue to allocate (i.) meters of the ramp length for acceleration purposes.

D. The distance from the downstream intersection to the ramp metering signal is available for queue storage. This distance is referred to as the queue storage distance available (I.F.). Determine the queue storage length required for the given peak hour traffic conditions, metering rate, and the analysis time period by analyzing Figures 3 and 4. If the queue storage length required is less than the queue storage distance available (I.F.), the design for the ramp metering system holds well. Otherwise, the location of the ramp metering signal should be shifted to a point such that it still meets the minimum required ramp distance for acceleration purposes (104 m for freeway speed of 90 km/h (55 mph)).

E. The compromise between the queue storage distance and the roadside safety clear zone requirements (9 m or 30 feet) depends on the engineer-in-charge of the project and the flexibility of the system to shift the pavement markings on the ramp in order to adjust the clear zone distance.

5.0 ILLUSTRATIVE EXAMPLE

Goal: To determine the best placement of a ramp metering system to optimize acceleration and storage distance.

Assumptions:

- Peak hour traffic conditions.
- 3-lane frontage road leaving the diamond interchange.
- Far left lane of the frontage road becomes the entrance ramp.
- Direct entry type entrance ramp.
- Entrance lane width = 4.9 m (16 feet).
- Ramp meter signal placed 1.2 m (4 feet) away from the edge of the entrance ramp travel lane.
- Roadside safety clear zone requirements stipulate at least a 9 m (30 feet) clear zone from the edge of the freeway travel lane.
- See figure 7 for a graphical display.

I. Geometric Conditions:

A. Freeway Speed = ___90___ km/h.
B. Angle of Merge = _3___4 X___5_ degrees.
C. Separation between travel lane and left frontage lane (edge-to-edge) = ___18___ m.
D. Length of Entrance Ramp = ___260___ m.
E. Merging Distance Available = ___150___ m.
F. Storage space available beyond diamond interchange to the start of the entrance ramp = ___245___ m.
G. Roadside safety clear zone requirements stipulate at least a 9 m (30 ft) clear zone from the edge of the freeway travel lane.

II. Operational Conditions:

A. Peak Hour Arrival Rate = ___650___ vph.
B. Minimum Metering Rate = ___200___ (200 vph).
C. Select cycle length of upstream diamond interchange to be considered:
2 Minute Time Period ____________.
4 Minute Time Period _____X_____ (To account for overflow queue).
D. Choose acceptable delay in minutes for queued vehicles which will not lead to frequent violations of the ramp meter signal

1___2___**3 X**___4___5___ Minutes.

III. Procedure For Placing the Ramp Metering System

A. Ample merging distance must be allocated so that the vehicle may achieve a 1.5 second headway after reaching freeway speed and before merging with the freeway travel lane. This required merging distance may be found from Figure 2. For a freeway design speed of 90 km/h (55 mph), the minimum merging distance required to achieve this headway before entering the through freeway travel lane is 179 m (587 feet).

Merging Distance Required Before Entering the Through Freeway Travel Lane ___ 179 m ___ **(I.)**.

If the merging distance required (I.) is greater than the merging distance available (I.E.), the merging lane pavement markings must be extended to provide more distance to achieve a 1.5 second headway. If geometric considerations limit this manipulation of the lane lengths or if the resulting extension ends too close to the next ramp entrance, the current ramp configuration may need to be relocated further downstream.

B. Based on the freeway speed, determine the minimum **ramp distance** required for acceleration purposes. This value can be calculated by considering an acceleration rate of 3 mpsps (10 fpsps). For a freeway design speed of 90 km/h (55 mph), the minimum ramp distance required to accelerate to freeway speed before entering the merging area is 104 m (340 feet).

Ramp Distance Which Must be Allocated for Acceleration Purposes
___ 104 m ___ (ii.).

C. Measure 9 m (30 feet) from the edge of the freeway travel lane to the left edge of the ramp lane and mark the corresponding point on the ramp. This point gives the available ramp distance for acceleration purposes. If this distance is greater than the minimum required distance for acceleration as found in III.B. (ii.)., select this point for the ramp metering signal, otherwise continue to allocate (I.) meters of the ramp length for acceleration purposes.

D. The distance from the downstream intersection to the ramp metering signal is available for queue storage. This distance is referred to as the queue storage distance available (I.F.). Determine the queue storage length required for the given peak hour traffic conditions, metering rate, and the analysis time period by analyzing Figures 3 and 4. If the queue storage length required is less than the queue storage distance available (I.F.), the design for the ramp metering system holds good. Otherwise, the location of the ramp metering signal should be shifted to a point such that it still meets the minimum required ramp distance for acceleration purposes (104 m for freeway speed of 90 km/h (55 mph)).

E. The compromise between the queue storage distance and the roadside safety clear zone requirements (9 m or 30 feet) depends on the engineer-in-charge of the project and the flexibility of the system to shift the pavement markings on the ramp in order to adjust the clear zone distance.

F. Figure 8 displays the results of the example problem.

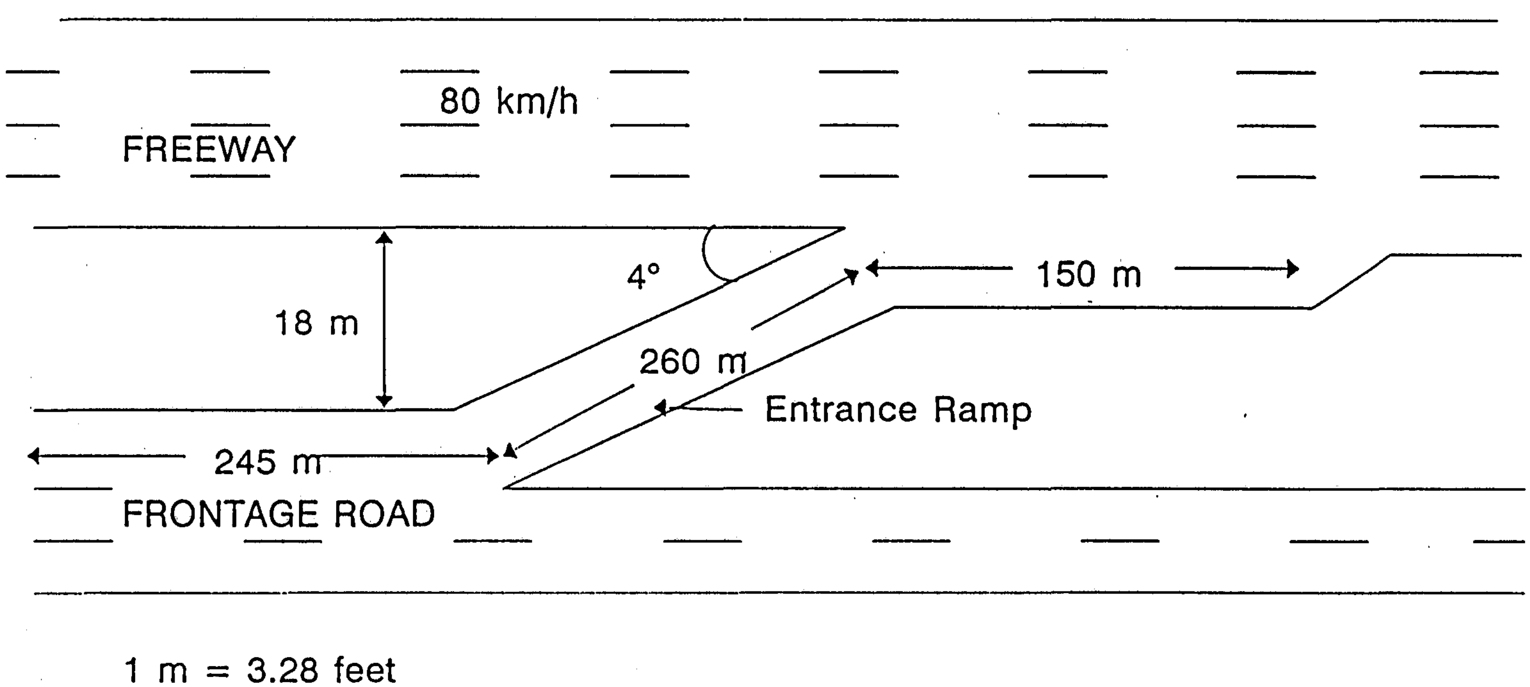

Figure 7. Illustration of Sample Problem

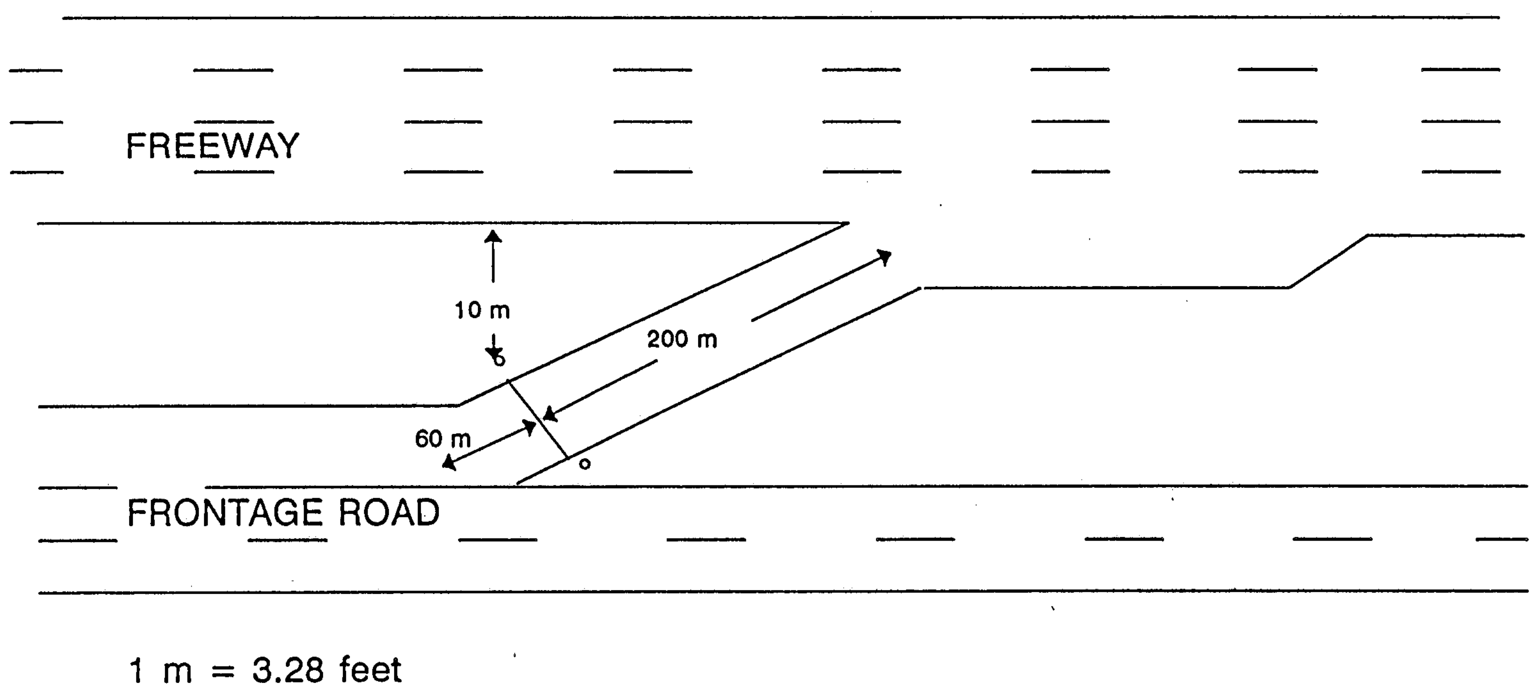

Figure 8. Ramp Meter Signal Location

6.0 FINDINGS

The analysis procedure presented in this report is intended to provide engineers and designers guidelines for the planning, design, and installation of ramp metering systems. Some solutions to providing proper distances for ramp metering have been presented in the illustrative example. Alternative solutions might be found in changing the design assumptions of time, in increasing the length of the acceleration lane, reducing the merge angle of the entrance ramp, or converting the left frontage road lane for ramp only use. The feasibility of these solutions is determined by local conditions and needs to be considered by the designer.

7.0 REFERENCES

1. G.C. Herrick. *Strategies for Improving Traffic Operations at Oversaturated Signalized Diamond Interchanges.* A thesis in Civil Engineering, Texas A&M University, May 1992.

2. J.H. Buhr, R.H. Whitson, K.A. Brewer, and D.R. Drew, "Traffic Characteristics for Implementation and Calibration of Freeway Merging Control Systems," Highway Research Record 279, p.87-106, 1969.

3. K.A. Brewer, J.H. Buhr, D.R. Drew, and C.J. Messer, "Ramp Capacity and Service Volume As Related to Freeway Control," Highway Research Record 279, p.70-86, 1969.