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16. Abstract

The Texas Department of Transportation (TxDOT) uses ramp control signals (also called ramp meters or flow signals) to control the rate at which vehicles enter the freeway. This helps TxDOT (1) promote a more consistent and uniform flow of traffic entering the freeway, and (2) promote a more efficient use of the existing freeway capacity.

The purpose of this project was to develop guidelines and criteria to assist TxDOT decision makers in determining when and where to install new ramp control signals and remove existing ramp control signals when they no longer provide a benefit to freeway traffic. This report documents the process, procedures, and research used to develop those guidelines and criteria. The actual guidelines, criteria, and forms are in Product 0-5294-P1, "Operating Guidelines for TxDOT Ramp Control Signals."

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DEVELOPMENT OF CRITERIA AND GUIDELINES FOR INSTALLING, OPERATING, AND REMOVING TXDOT RAMP CONTROL SIGNALS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Kevin N. Balke, P.E. (Texas #66529).

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- Mr. Steve Connell, TxDOT Fort Worth District;
- Ms. Cindy Smith, TxDOT Houston District;
- Mr. Khoi Tran, TxDOT Houston District;
- Mr. Robert Wheeler, TxDOT Traffic Operations Division;
- Mr. Wade Odell, TxDOT Research and Technology Implementation Office; and
- Ms. Loretta Brown, TxDOT Research and Technology Implementation Office.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

BACKGROUND

Ramp meters (also called flow signals or entrance ramp control signals) are traffic signals that control traffic at freeway entrances (*1, 2*). Ramp meters have been in use since the 1960s as a means of demand control at freeway entrances. They are installed to achieve three operational objectives:

1. to control the number of vehicles entering the freeway,
2. to reduce freeway demand, and
3. to break up the platoons of vehicles released from upstream traffic signals.

All three objectives work toward the same overall goal: to reduce the frequency and severity of freeway capacity problems. The first objective attempts to ensure that the total traffic volume entering a freeway section, plus the entering ramp traffic, remains below the capacity of that section. The second objective uses ramp metering to introduce additional controlled delay (i.e., a cost) to drivers wishing to enter the freeway. As a result of this additional delay, use of the freeway for short trips during peak hours is discouraged. The third objective, breaking up platoons of arriving vehicles on the ramp, provides smoother merging operations, which reduces the likelihood of cyclic breakdowns when platoons arrive. Smoother merging operations also improve safety by reducing rear-end and sideswipe collisions.

When properly installed, ramp metering has the potential to achieve the following benefits (*3*):

- increased freeway throughput,
- increased freeway operating speeds (i.e., reduced delay to drivers on the freeway),
- safer operation on the freeway and its entrances, and
- decreased fuel consumption and vehicular emissions (due to reduced overall delay).

Most ramp metering guidelines also state that one benefit of ramp metering is that it encourages diversion of some ramp demand (especially short trips) to alternate routes, thereby reducing freeway demand. In their well-known report on the status of ramp metering in the United States, Piotrowicz and Robinson (*2*) report that 5 to 10 percent diversion may be possible depending on the location. However, some states in their survey reported no diversion. In a recent study of systems with restricted metering in Wisconsin, Horowitz et al. (*4*) found that diversion did occur, but it was almost always less than 10 percent of total ramp demand.

Because of queuing and the loss of capacity even during recovery, freeway breakdowns and bottlenecks should be avoided wherever possible and mitigated when they occur. Ramp metering has the potential to prevent freeway breakdowns, or delay their onset and reduce their severity, by controlling the rate of vehicle entry onto a freeway, especially by eliminating entering platoons. The result is smoother and safer merging operations and improved overall freeway operation.

Different types of criteria are needed to evaluate all the various reasons as to why the Texas Department of Transportation (TxDOT) may need to install a ramp meter. Just like for a traffic signal, a number of different traffic volumes may exist where operations on the freeway may be improved (or even maintained) as a result of installing a ramp meter. TxDOT may have reasons other than pure traffic volumes to install a ramp meter. For example, TxDOT may have a need to install ramp metering to provide preferential treatment to special classes of users, such as high occupancy vehicles (HOV) or managed lane applications, or to address a known safety hazard. In other cases, TxDOT may have a need to install a ramp meter at individual ramps in order to help improve operations in the corridor, even though the conditions of the isolated ramp may not specifically justify the installation. All these different factors need to be considered in developing warrants for installing ramp meters.

Although agencies have been using ramp meters for decades, very few locations have published "warrants" for installing ramp metering. The *Manual on Uniform Traffic Control Devices (MUTCD)* (5), which calls ramp meters "entrance ramp control signals," suggests that ramp meters may reduce the overall delay to traffic on the freeway and on adjacent streets when the following three conditions are met:

A. Congestion recurs on the freeway because traffic demand is in excess of the capacity, or congestion recurs or a high frequency of crashes exist at the freeway entrance because of inadequate ramp merging area.
B. Controlling traffic entering a freeway assists in meeting local transportation system management objectives identified for freeway traffic flow, such as the following:
    1. Maintenance of a specific freeway level of service.
    2. Priority treatments with higher levels of service for mass transit and carpools.

3. Redistribution of freeway access demand to other on-ramps.

C. Predictable, sporadic congestion occurs on isolated sections of freeway because of short-period peak traffic loads from special events or from severe peak loads of recreational traffic.

During the 1990s, the TxDOT Houston District developed a ramp meter warrant based on the criteria defined in the 1965 *Highway Capacity Manual* (*6*). These warrants required that the following four conditions had to be satisfied before a ramp meter could be installed:

- travel time improvements for the freeway outweigh the delay incurred at the ramp plus the additional travel time incurred to diverted ramp traffic,
- there is sufficient storage space for ramp queues,
- there are suitable alternate routes for diverted traffic, and
- hourly freeway plus ramp demand at a single ramp just upstream of a bottleneck location is above some volume threshold.

The last criterion, volume threshold, was based primarily on engineering judgment at the time. The Houston District found that this criterion was not sufficient to deal with the current operating conditions of many of their freeways. To accommodate their needs, the TxDOT Houston District made the following two significant revisions to the warrants:

- the warrants now require consideration of three consecutive on-ramps upstream of the bottleneck location instead of a single ramp, and
- the volume thresholds for a bottleneck were raised to a demand level of 1800 vehicles per hour per lane (vphpl) to more align with current estimates of freeway lane capacity.

Table 1 shows the revised ramp metering warrants prepared by the Houston District.

Table 1. Existing Ramp Meter Warrants Used by the TxDOT Houston District.

TRAFFIC SURVEY-COUNT ANALYSIS HOUSTON						
RAMP CONTROL WARRANTS DISTRICT NO. 12						
FREEWAY AND RAMP LOCATION:						
CONTROL: SECTION: CITY:						
DATE OF SURVEY: POPULATION (LATEST FEDERAL CENSUS):						
Check applicable characteristics:* ____ (a) The expected reduction in delay to freeway traffic exceeds the expected delay to new users plus added travel time for diverted traffic and traffic on the alternate surface routes; and ____ (b) There is adequate storage space for the vehicles which will be delayed; and ____ (c) There are suitable alternate surface routes available having capacity for traffic diverted from the freeway ramps; and ____ (d) The total volume of traffic on the main lanes and three entrance ramps less any exit ramps prior to the bottleneck location exceeds (or is expected to exceed at the time of installation) the volumes shown in the Table during at least one 15-minute period.						
MINIMUM PEAK HOUR WARRANT VOLUMES (MAIN LANES PLUS RAMP) AT BOTTLENECK LOCATION (COMPLETE APPLICABLE TABLE USING 15 MINUTE PEAK COUNTS) **FOUR-LANE FREEWAY (TWO LANES ONE DIRECTION)**						
OVER 1,000,000	EXISTING					
	MAIN LANES	ENTRY RAMP 1	ENTRY RAMP 2	ENTRY RAMP 3	LESS EXIT RAMPS	DOWNSTREAM TOTAL
SIX-LANE FREEWAY (THREE LANES ONE DIRECTION)						
OVER 1,000,000	EXISTING					
	MAIN LANES	ENTRY RAMP 1	ENTRY RAMP 2	ENTRY RAMP 3	LESS EXIT RAMPS	DOWNSTREAM TOTAL
EIGHT-LANE FREEWAY (FOUR LANES ONE DIRECTION)						
OVER 1,000,000	EXISTING					
	MAIN LANES	ENTRY RAMP 1	ENTRY RAMP 2	ENTRY RAMP 3	LESS EXIT RAMPS	DOWNSTREAM TOTAL
EACH ADDITIONAL LANE ABOVE FOUR IN ONE DIRECTION AND ONE LANE RAMP CONNECTIONS AT INTERCHANGES						
OVER 1,000,000	EXISTING					
	MAIN LANES	ENTRY RAMP 1	ENTRY RAMP 2	ENTRY RAMP 3	LESS EXIT RAMPS	DOWNSTREAM TOTAL
See discussion on pages 4H-1 and 4H-2 of the 2003 Texas Manual on Uniform Traffic Control Devices for determining the location of ramp control under these warrants. * Based on the 2000 Highway Capacity Manual in Chapter 22. Metropolitan area is considered to be the principal city plus adjacent incorporated towns (or cities) and unincorporated communities using current estimated population.						

While these revisions to the warrant form represent significant improvements over the original warrants, problems still exist with the revised form. First, the volume conditions for freeway breakdown are still based on engineering judgment and have not been validated in the field. Furthermore, volume conditions alone are not the only factors that should be considered when assessing whether to install a ramp meter. Other factors, such as merge capacity (i.e., the distribution of available gaps for merging vehicles), capacity reductions due to weaving, demand for downstream exit ramps, and congestion on those ramps, should also be considered but are not on the warrant form.

RESEARCH OBJECTIVES

The specific objectives of this research project are as follows:

1. Develop warrants that TxDOT can use to determine if traffic operations, safety, and system performance can be improved through the installation of a ramp meter.
2. Develop guidelines that TxDOT can use to determine how to operate a ramp meter once its installation has been justified. These guidelines will include the following:
   a. procedures for identifying when conditions in the traffic stream may justify the activation of the ramp meter;
   b. procedures for identifying when conditions in the traffic stream may justify a change in the operations of the ramp meter, including the following:
      i. changing the metering rate at a ramp,
      ii. changing from actuated control to pre-timed control or vice versa,
      iii. changing from single vehicle control to bulk metering or dual-lane metering, and
      iv. changing from isolated control to system control; and
   c. procedures for identifying when conditions in the traffic stream may justify the deactivation of a ramp meter.
3. Develop warrants that TxDOT can use in determining when and how a meter should be removed permanently from a freeway ramp. These procedures will include the following:
   a. criteria for assessing the performance of ramp meters,

   b. procedures for identifying freeway ramps where traffic operations, safety, and/or system performance no longer benefit from a ramp meter, and
   c. recommendations on the steps and processes needed to remove the ramp meter.
4. Produce a series of worksheets that TxDOT could potentially adopt to document the steps, procedures, and rationale used to warrant the installation, operations, and/or removal of a ramp meter.

ORGANIZATION OF REPORT

This report documents the process, procedures, and findings of the research conducted as part of TxDOT Project 0-5294, "Warrants for Installing and Operating Ramp Metering." Chapter 2 documents the findings of a review of ramp metering installation criteria and evaluation literature. Chapter 3 documents three simulation studies we performed as part of this research project: one on establishing traffic volume thresholds for installing ramp control signals, another on analyzing the queue detection settings in a typical TxDOT controller, and a third on alternative strategies for flushing ramp control signals. Also as part of the research effort, we conducted field evaluations of two new ramp meter installations in Houston, Texas. The results and findings from these field studies are contained in Chapter 4. Finally, Chapter 5 discusses the process used to develop the criteria and guidelines for installing, operating, and removing ramp control signals. These criteria and guidelines, which represent the primary product of this research, are contained in TxDOT Product 0-5294-P1, "Operating Guidelines for TxDOT Ramp Control Signals."

CHAPTER 2:
REVIEW OF RAMP METERING WARRANT AND EVALUATION LITERATURE

INTRODUCTION

Ramp metering is the use of traffic signals at freeway on-ramps to control the rate of vehicles entering the freeway. The main purpose is to control traffic flow onto the freeway in order to improve the efficiency of the freeway itself (*1*). Figure 1 depicts a typical TxDOT ramp metering installation.

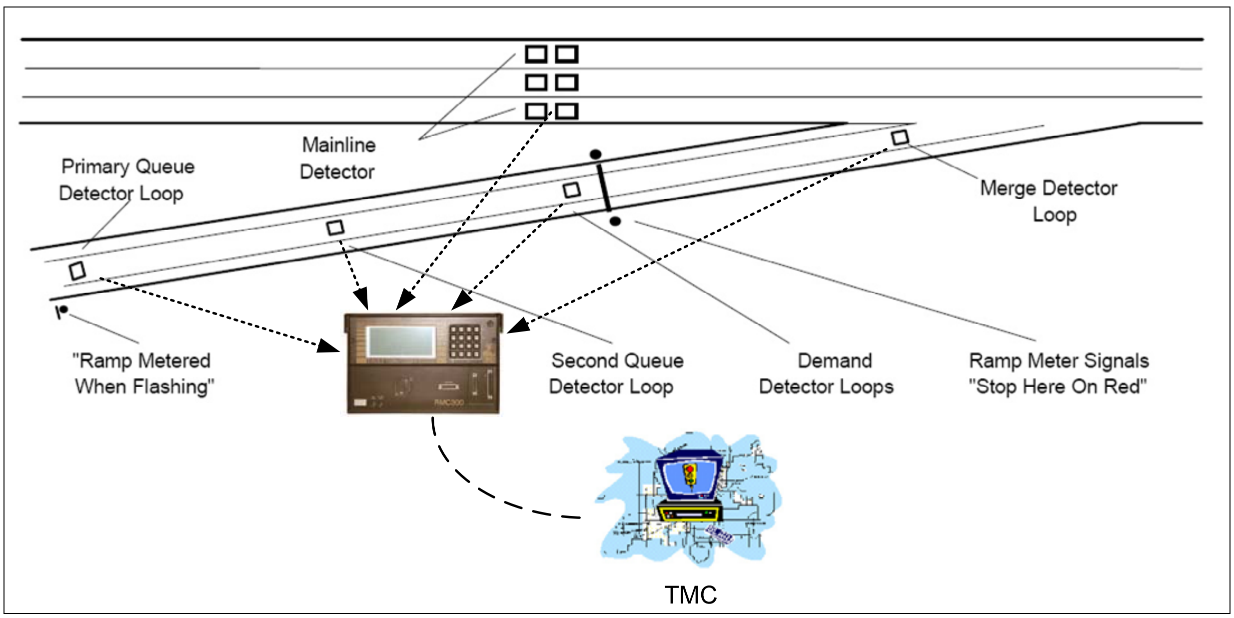


Figure 1. Typical TxDOT Ramp Meter Installation.

Ramp control provides traffic managers with the ability to open and close freeways, roadways, and ramps based on weather, security, or traffic problems. Ramp control gates can be manually, automatically, or remotely controlled from a central location, or from a vehicle at the gate/barrier location (*1*). Figure 2 illustrates an example of a road closure gate.

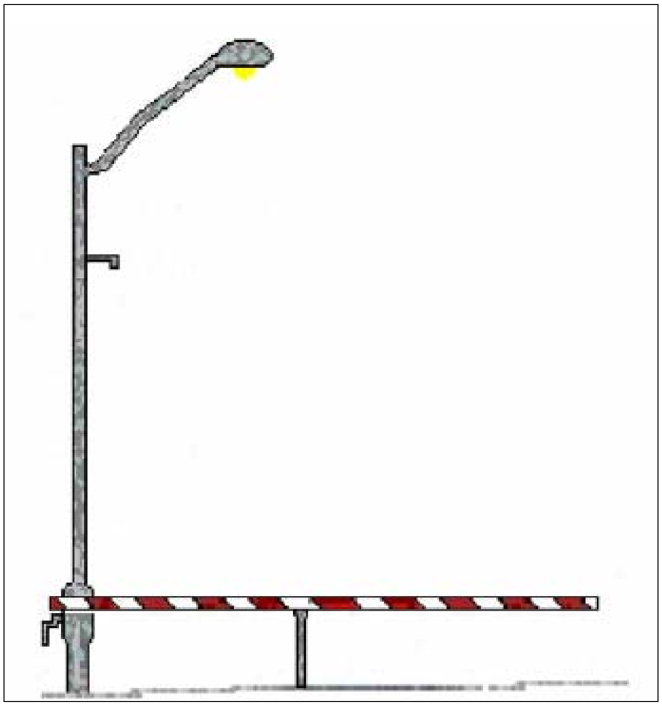


Figure 2. Example of Road Closure Gate (7).

Piotrowicz and Robinson (2) provided an update of ramp metering status in North America as of 1995. Cities included as part of entrance ramp metering case studies include the following:

- Portland, Oregon;
- Minneapolis/St. Paul, Minnesota;
- Seattle, Washington;
- Denver, Colorado;
- Detroit, Michigan;
- Long Island, New York; and
- San Diego, California.

Table 2 highlights the states that have deployed ramp metering, along with their operational status. As of 2005, there are 23 metropolitan areas in North America that have ramp metering systems installed, and approximately 87 percent of these are still operational (7).

Table 2. Summary of Ramp Meter Deployment in the United States in 2005 (*7*).

Metropolitan Area	State	Number of Agencies with Ramp Meters	Number of Ramps		
			Metered	Total	Percent
Allentown, Bethlehem, Easton	PA	1	14	58	24
Atlanta	GA	1	9	980	1
Columbus	OH	1	7	440	2
Dallas, Ft. Worth	TX	1	5	1550	0
Denver, Boulder	CO	1	54	200	27
Detroit, Ann Arbor	MI	1	20	584	3
Fresno	CA	1	37	136	27
Houston, Galveston, Brazoria	TX	1	105	656	16
Las Vegas	NV	1	3	128	2
Los Angeles, Anaheim, Riverside	CA	3	2410	2410	100
Miami, Fort Lauderdale	FL	1	22	560	4
Milwaukee, Racine	WI	1	120	148	81
Minneapolis, St. Paul	MN	1	416	416	100
New York, Northern New Jersey, Southwestern Connecticut	NY	1	1	1850	0
Philadelphia, Wilmington, Trenton	PA	1	16	688	2
Phoenix	AZ	1	132	304	43
Portland, Vancouver	OR	1	106	106	100
Salt Lake City, Ogden	UT	2	32	160	20
San Diego	CA	1	277	670	41
San Francisco, Oakland, San Jose	CA	1	210	794	26
Seattle, Tacoma	WA	2	135	452	30
St. Louis	MO	1	1	400	0
Washington	DC	1	24	746	3

WARRANTS FOR INSTALLING RAMP METERS

There have been a number of attempts to develop "warrants" for ramp metering, but it is difficult to establish a single set of conditions because of the many factors involved. There are few, if any, freeways that experience congestion that cannot be improved by metering. The operation of the freeway, however, is only one of several factors that must be considered in evaluating the appropriateness of metering (*2*). As of now, a formalized procedure to warrant ramp meters does not exist in most states. Historically, freeway sections that warrant ramp metering usually have the following characteristics (*2, 8)*:

- peak-period speeds less than 30 mph,
- vehicle flows between 1200 and 1500 vphpl,
- high accident rates, and/or
- significant merging problems.

In addition, the *MUTCD* (*5*) provides some broad guidelines on when the installation of ramp meters may be appropriate. The *MUTCD* simply states that entrance ramp signals may be justified when the total expected delay to traffic in the freeway corridor, including freeway ramps and local streets, is expected to be reduced.

Other candidates for metering include new and reconstructed facilities that may become overloaded shortly after completion (*8*). Agreement exists among operating agencies that the best time to implement metering is before traffic conditions worsen.

Locations that experience a high number of accidents and freeway operating conditions were the most frequent factors used to identify candidate ramps for metering in Minneapolis/St. Paul. Metering some ramps may also be necessary to complete a system, to prevent undesirable changes in travel patterns, to address the equity issue, and/or to improve the quality of a merge operation (*2*).

Nationwide Status of Ramp Metering Warrants

The following is a summary of the warrants and criteria used by other states to justify the installation of ramp control signals.

Arizona

The Arizona Department of Transportation (ADOT) developed a procedure to determine if ramp metering is warranted for a particular ramp. The data required for the warrant process are:

- current traffic volumes for both the mainline and ramp,
- future traffic volumes for the design year for both the mainline and ramp,
- collision data for both the mainline and ramp, and
- freeway and ramp operating speeds.

It is recommended that current volumes be collected at a maximum of 15-minute time increments (*9*). ADOT ramp meter warrants are summarized in Table 3. The warranting procedure is presented as a flowchart in Figure 3. Individual ramp meter installation should be considered if any of warrants 1 to 6 and either warrant 7 or warrant 8 are satisfied. The only exception is that ramp metering may be warranted based solely upon warrant 2, collision history pattern. In addition, warrant 9, geometric warrant, must be satisfied in all cases to warrant installing a ramp meter.

Table 3. Summary of Warrants for Individual Ramp Meter Used by ADOT (9).

<table>
<tr><th>Warrant Name</th><th colspan="2">Warranting Question</th><th>Responses</th></tr>
<tr><td>Warrant 1 — Recurring Congestion</td><td colspan="2">Does the freeway operate at speeds less than 50 mph for a duration of 30 minutes for 200 or more calendar days per year?</td><td>Yes/No</td></tr>
<tr><td>Warrant 2 — Collision History Pattern</td><td colspan="2">Is there a high frequency of crashes (collision rate along the freeway exceeds mean collision rate in the subject metropolitan area) near the freeway entrance because of inadequate merge area or congestion?</td><td>Yes/No</td></tr>
<tr><td>Warrant 3 — Freeway Level of Service</td><td colspan="2">Will the ramp meter or system of ramp meters contribute to maintaining a higher level of service (LOS) identified in the region's transportation system management (TSM) plan?</td><td>Yes/No</td></tr>
<tr><td>Warrant 4 — Modal Shift</td><td colspan="2">Will the ramp meter or system of ramp meters contribute to maintaining a higher level of vehicle occupancy through the use of HOV preferential treatments as identified in the region's transportation system management (TSM) plan?</td><td>Yes/No</td></tr>
<tr><td>Warrant 5 — Redistribution of Access</td><td colspan="2">Will the ramp meter or system of ramp meters contribute to balancing demand and capacity at a system of adjacent ramps entering the same facility?</td><td>Yes/No</td></tr>
<tr><td>Warrant 6 — Sporadic Congestion</td><td colspan="2">Does the ramp meter or system of ramp meters mitigate predictable sporadic congestion on isolated sections of freeway because of short peak period loads from special events or from severe peak loads of recreational traffic?</td><td>Yes/No</td></tr>
<tr><td rowspan="7">Warrant 7 — Total Volume</td><td colspan="2">Is the ramp plus mainlane volume greater than the tabulated criteria below for the design hour?</td><td rowspan="7">Yes/No</td></tr>
<tr><td>Number of Mainlane Lanes in One Direction including Auxiliary Lanes that Continue at least 1/3 Mile Downstream of Ramp Gore</td><td>Criteria volume Ramp plus Mainlane Volume Downstream of Gore [total vehicles per hour (vph)]</td></tr>
<tr><td>2</td><td>2650</td></tr>
<tr><td>3</td><td>4250</td></tr>
<tr><td>4</td><td>5850</td></tr>
<tr><td>5</td><td>7450</td></tr>
<tr><td>6</td><td>9050</td></tr>
<tr><td>Warrant 8 — Right Lane plus Ramp Volume</td><td colspan="2">Ramp metering is warranted when the ramp plus the mainline right lane exceeds 2100 vph. Is the criterion defined above met, during the design hour?</td><td>Yes/No</td></tr>
<tr><td>Warrant 9 — Geometric</td><td colspan="2">Does the existing or proposed ramp geometry permit safe and effective ramp metering?</td><td>Yes/No</td></tr>
</table>

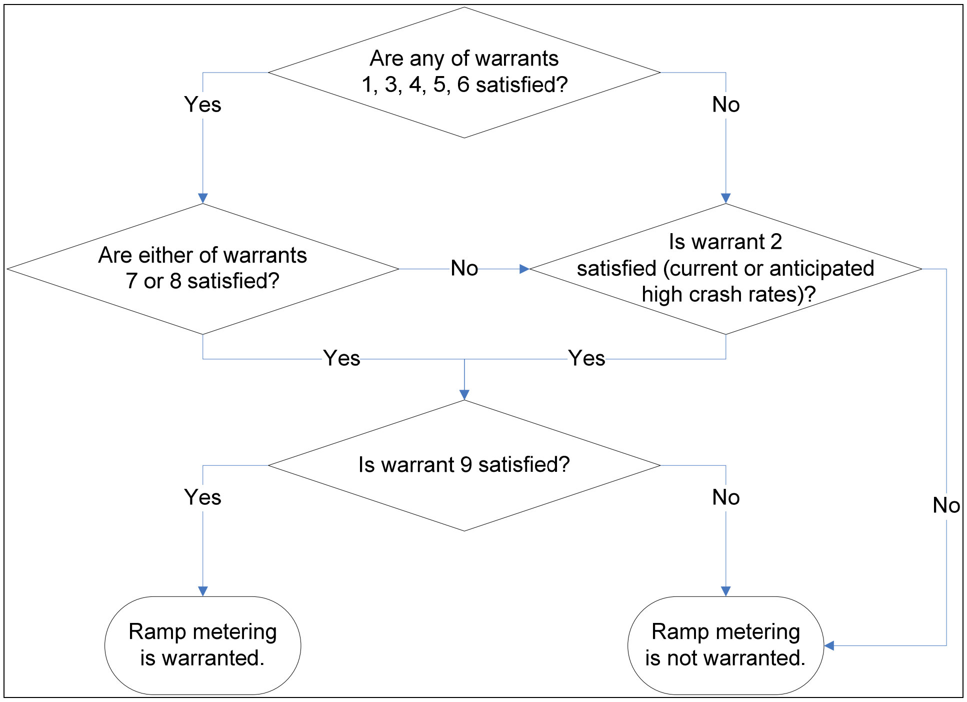


Figure 3. ADOT Ramp Metering Warranting Procedure (9).

California

The California Department of Transportation (Caltrans) does not appear to have a ramp metering warranting procedure that is followed statewide. Each individual district is responsible for determining where and when ramp meter signals should be deployed. According to Caltrans' *Ramp Metering Policy Procedures* (*10*), each district is responsible for their own Ramp Meter Development Plan. In each plan, a district is required to identify the ramps that currently operate with ramp meters or are expected to need ramp meters in the next 10 years. These plans are updated biennially and define the specific policies regarding the planning and implementation of ramp meters, connector meters, and HOV bypass lanes that will be used in each respective district. These plans represent an element of each individual district's Congestion Management Plan.

Caltrans requires that any new interchanges or modifications to existing interchanges, regardless of funding source, contain provisions for ramp meters. These provisions include right-of-way, geometrics to accommodate vehicle storage and HOV bypass lanes, ramp meter equipment, and enforcement areas. These provisions are laid out in detail in Caltrans' *Ramp Meter Design Manual* (*11*). The following criteria list potential design features that might influence operations of ramp meters:

- Geometrics for a single-lane ramp meter should be provided for volumes up to 900 vph.
- Where truck volumes (three axles or more) are 5 percent or greater on ascending entrance ramps to freeways with sustained upgrades exceeding 3 percent (i.e., at least throughout the merge area), a minimum 150 m length of auxiliary lane should be provided beyond the ramp convergence area.
- When entrance ramp volumes exceed 900 vph, and/or when an HOV lane is determined to be necessary, a two- or three-lane ramp segment should be provided.
- Three-lane metered ramps are typically needed to serve peak (i.e., commute) hour traffic along urban and suburban freeway corridors.
- Ramp meters have practical lower and upper output limits of 240 and 900 vehicles per hour per lane, respectively. Ramp meter signals set for flow rates outside this range tend to have high violation rates and cannot effectively control traffic. Therefore, on a ramp with peak-hour volume between 500 and 900 vph, a two-lane ramp meter may be provided to double the vehicle stored in the available storage area. A single-lane ramp meter should be used when rates are below 500 vph and no HOV preferential lane is provided.
- An HOV preferential lane shall be provided at all ramp meter locations. It is the policy of Districts 4, 6, 8, and 11 to meter the HOV preferential lane. Districts 3, 7, and 12 typically do not meter the HOV preferential lane.

Colorado

The Colorado Department of Transportation (CDOT) has used a three-tiered approach to determine when and where to install ramp meters in the Denver area (Region 6) (*12*). Two of the tiers are derived from warrants established by ADOT and Caltrans. The third tier is based on Region 6's field observations and experience with their current ramp meter system. The following lists the criteria that were used in the study:

- Based on the ADOT criteria, a ramp meter may be warranted if the ramp plus mainline volume upstream of the gore exceeds the following thresholds:
  - two mainline lanes: 2650 vph,
  - three mainline lanes: 4250 vph, and

    - four mainline lanes: 5850 vph.
- Use a single-lane metered entrance ramp for volumes up to 900 vph and two-lane metered entrance ramps for volumes above 900 vph (based on Caltrans criteria).

Nevada

The Nevada Department of Transportation (NDOT) outlines policy points that address the consideration for ramp meter deployment in the *HOV/Managed Lanes and Ramp Metering Policy Manual* (*13*). The justifications for ramp meter deployment include:

- Corridors with routine congestion shall be considered for ramp metering.
- Ramp meters shall be considered for deployment on ramps where a safety problem exists either on the ramp or at an allocation on the freeway facility at or near the ramp/freeway merge point.
- For the geographic extent of ramp meter deployment:
    - Ramp meters shall be considered for deployment on a corridor basis if ramp-related problems are observed at multiple locations on a specific corridor and no such problems are observed on any other corridor.
    - Ramp meters shall be considered for deployment at an isolated location if a ramp-related problem is observed at that location and similar problems are not observed at ramps immediately upstream or downstream of the ramp in question.
- Demand thresholds: Pre-metering demand on the ramp shall be used to determine the appropriate ramp metering flow control.

New York State Department of Transportation

The New York State *Highway Design Manual* (*14*) recommends the following factors, adapted from National Cooperative Highway Research Program (NCHRP) Report 155, *Bus Use of Highways: Planning and Design Guidelines*, be considered in determining the applicability of ramp metering:

- Ramp metering should be considered wherever urban freeways operate below level of service "D." Freeway lane density generally should exceed 25 to 30 vehicles per kilometer.

- Adequate parallel surface routes must be available for the traffic diverted from the ramps to improve overall network performance.
- Adequate ramp storage capacity must be available to prevent queues of vehicles waiting to enter the freeway from blocking local street circulation.
- Ramp metering should not be applied where queues exist, e.g., at freeway lane-drops or convergence points, or at freeway-to-freeway connectors.

Referencing a report on the Connecticut Freeway Transportation System, the manual provides the following guidance related to the applicability of ramp metering to available ramp storage:

> *...metering is considered feasible if the available ramp storage exceeds 10 percent of the premetered peak-hour volume. If there is storage for 5 percent to 10 percent of the peak volume, metering may still be feasible; but additional analysis is required and possibly mitigating measures (e.g., additional ramp lane, queue detection, etc.). Ramp metering is not considered feasible if the storage is less than 5 percent of the premetered peak-hour volume.*

Ramp meters have been installed as part of the New York State Department of Transportation's (NYSDOT) Long Island Intelligent Transportation System (LI ITS). The system consists of a computerized traffic management and information system operated by NYSDOT and incorporates the existing INFORM (Information for Motorists) network into its system. The goal of the system is to help improve vehicle travel times, coordinate traffic flow, and limit the amount of congestion occurring on the freeways and limited access facilities in Long Island. NYSDOT's goal in operating the ramp meters is to reduce congestion by staggering the volume of traffic entering the freeway when the main lanes are heavily congested. To be eligible for metering, peak period ramp volumes must satisfy the criteria shown in Table 4.

Table 4. NYSDOT's Region 10 Volume Criteria to Determine Eligibility for Ramp Metering.

Ramp Configuration	Volume Criteria (vph)	
	Minimum	Maximum
One Metered Lane	240 vph	900 vph
Two Metered Lanes	400 vph	1500-1800 vph*

* For merge into single lane

Oregon

The Oregon Department of Transportation's *Traffic Signal Policy and Guidelines* (*15*) states that ramp meters may be provided at any freeway entrance ramp regardless of traffic volumes. Ramp meters are not intended to divert longer distance trips onto the local road system. According to the guidelines, ramp meters may be installed for the following reasons:

- Limit or regulate entering vehicle volume at a merge point.
- Limit or regulate traffic flow through a downstream bottleneck.
- Reduce rear-end and sideswipe crashes associated with high volume freeway ramp merging.
- Limit volume diverted to a specific entrance ramp (ramp meters should be installed as systems rather than at single locations).

It should be noted that all the reasons above are traffic-based criteria except for the third one, which is safety based.

Washington State Department of Transportation

Outreach efforts conducted in a study by Wilbur Smith Associates (*16*) indicated that the Washington State Department of Transportation (WSDOT) uses the four characteristics (peak period speeds, vehicle flows, accident rates, and merging problems) as part of their criteria for determining when to deploy ramp metering. WSDOT also relies on detector data collected from their system to measure lane occupancy, using this information in their decision process to determine when ramp metering could have a beneficial impact on traffic flow. WSDOT prefers to implement ramp metering along a corridor rather than an individual ramp in order to reduce the likelihood of commuters using the adjacent ramps as bypasses for the metered ramp (*16*).

Wisconsin

The Wisconsin Department of Transportation (WisDOT) proposed the following criteria to warrant for ramp metering as part of a statewide ramp control plan (*16*):

- Volume criteria — The ramp should have vehicle flow rates of 1200 vphpl coupled with slow moving traffic along the freeway lanes.
- Ramp volume criteria — The ramp should have volumes of at least 240 vph (400 vph for two lanes).
- Speed criteria — Multiple ramp metering case studies listed 30 mph or less as the common minimum freeway speed to warrant ramp metering.
- Safety criteria — A reduction in accidents at the merge should be expected. Accident rates in the vicinity of the ramp of 80 per hundred million vehicle-miles of travel are used as a starting point for further analysis.
- Ramp geometric criteria — Three primary criteria include storage space, adequate acceleration distance and merge area beyond the meter, and sight distance.
- Funding criteria — An evaluation of potential funding sources should be completed to determine if there is sufficient support for the project.
- Alternate route criteria — The presence of an alternative route for motorists on the arterial network to avoid the delays on entrance ramps created by a ramp meter may be required (*4*).
- Corridor criteria — In most implementations, ramp metering is addressed at the corridor level. It must be determined whether the section under consideration is part of a corridor.

HOV lane criteria are not recommended for WisDOT because HOV treatment is more of an operational consideration and should be addressed within the design process, not during the warrant procedure (*16*).

Criteria for Installing Ramp Meters

According to the literature reviewed, criteria that may warrant ramp meter deployment can be classified into the following categories:

- geometric considerations;
- traffic criteria; and

- safety criteria;

Other factors, such as the availability of alternate routes, the type of corridor where the metering system is being deployed, and non-engineering factors such as equity issues, funding availability, enforcement, public education, and political factors, were cited as playing a part in the decision for deploying ramp metering systems. The first three categories are discussed in more detail.

Geometric Considerations

Three primary geometric considerations exist in order to warrant for ramp metering (*8*):

- availability of storage space,
- adequate acceleration distance and merge area beyond the meter, and
- sight distance.

Ramp storage requirements depend on ramp demand volumes and metered rates, ramp entry flow patterns, and availability of surface street storage. WisDOT guidelines require the ramp to provide storage for a minimum of 10 percent of the current peak-hour volume to ensure that the ramp meter queue does not spill into the surface street (*17*). For meters designed in conjunction with ramp reconstruction, the ramp should accommodate a minimum of 10 percent of the design year projected peak-hour volume. For ramp meters retrofitted to existing conditions, a storage minimum of 5 percent of the current peak-hour volume may possibly be used (*18*).

The distance downstream of the meter must be able to adequately accommodate varying characteristics of vehicle accelerations from stopped conditions to freeway operating speeds.

Because of the curvature of the ramp, advance warning signs are usually used to make drivers aware of the forthcoming stop. In addition to advance signing, INFORM in Long Island, New York, also uses strobe lights in the red lens to help emphasize the stop indication at ramps that have an unusually high number of accidents (*2*).

More recently, the Texas Transportation Institute (TTI) conducted an in-depth study of current ramp metering design and operation practice in Texas as well as in other states (*19, 20*). A spreadsheet based on analytical tools and simulation models for studying all key ramp metering design variables in Texas was developed. Hardware-in-the-loop simulation was used to verify modeling results. This study led to the development of important design criteria for ramp metering in Texas.

Traffic Criteria

Ramp and Mainline Traffic Volumes. The TxDOT Houston District uses the peak sum of the ramp and mainline volumes to determine if ramp metering is warranted. ADOT's warrants, on the other hand, are slightly different in that the rightmost mainline volume is used in the procedure instead of the overall mainline volume. This consideration aims to account for a more realistic representation of gap availability in mainline traffic for merging ramp traffic.

Congestion. Peak period speeds less than 30 mph and a volume/capacity (v/c) ratio of 0.7 or higher have been identified as potential points to consider ramp meter installation in order to prevent or delay the onset of congestion. In addition, areas with a freeway occupancy greater than 18 percent may be considered as potential candidates for ramp metering. It was noted in Wisconsin's study (*16*) that the criteria outlined when an existing ramp meter should be activated may be reasonable for determining when a ramp metering system is warranted as well.

Safety Criteria

None of the literature gave explicit safety thresholds for implementing ramp metering except for the *Wisconsin Statewide Ramp Control Plan* (*16*). Simple accident statistics were compiled in Wisconsin's study to calculate the accident rate per hundred million vehicle-miles (RHMVM) as follows:

$$RHMVM = \frac{\text{Accidents} \times 100,000,000}{AADT \times 365 \times \text{Distance}} \quad (1)$$

where AADT is the average annual daily traffic on the facility.

A threshold of 80 accidents per hundred million vehicle miles was arbitrarily selected for Wisconsin based on a simple comparison with similar statistics compiled for Minnesota and Maryland.

In a more recent attempt to quantify the effects of ramp metering on freeway safety, Lee et al. (*21*) examined the effect of the local traffic-responsive ramp metering strategy on freeway safety. Safety benefits of ramp metering were quantified in terms of the reduced crash potential estimated using the real-time crash prediction model. It was suggested that ramp metering may reduce crash potential by 5 to 37 percent compared to the no-control case. The validity of this study is, however, limited by the accuracy of the calibration in microscopic simulation models used for safety evaluation. In addition, it is difficult to reflect driver behaviors in the real world through a simulation model.

GUIDELINES FOR OPERATING RAMP METERS

Ramp meters with controllers other than fixed time may turn on or off, depending on the traffic volumes or occurrence of accidents/incidents. However, most agencies use standard hours to turn on/off their ramp meters, except in emergencies, for reasons of stability and reliability in the public eye (*8*).

In general, most ramp meters across the country operate during the a.m. and p.m. peak periods. However, several exceptions exist. In a busy, freeway-dependent city like Los Angeles, 32 ramp meters are operated at all times. As a result of a compromise between WSDOT and local neighborhood groups, a ramp meter in Seattle is only turned on during the p.m. peak. Due to equity issues, Detroit ramps that are close to the city centers are only metered in the off-peak direction. Another ramp meter in Seattle also operates on weekends, as well as weekdays (*8*).

Nationwide Status of Guidelines for Operating Ramp Meters

This section highlights some of the guidelines used by other agencies in operating their ramp control signals.

Arizona Department of Transportation

The operation of ADOT ramp meters, which are located in the Phoenix area, is the responsibility of the Traffic Operations Center (TOC).

Startup Procedure. The stand-alone local operation of an ADOT ramp meter requires ramp meter signals to go through "startup" procedures to begin operation:

- Single-lane ramp — A meter starts from a darkened state to a green signal.
- Dual-lane ramp — The left meter gives a green signal, while the right meter remains dark. Once the left meter gives a red signal, the right meter gives a green signal.

- To reduce the probability of rear-end collisions, a soft start of the ramp metering sequence is recommended. The soft-start sequence for a dual-lane ramp meter is typically as follows:
    - Activate the flashing beacon.
    - Wait 10 seconds.
    - Display a green ball in the primary lane while the second lane remains dark.
    - Begin normal metering.

Ramp Metering Modes. ADOT ramp meters can operate under the following modes:

- Manual — The user specifies the current operation of the meter from the front panel of the controller.
- Central override mode — Communication with the Freeway Management System (FMS) center must be present for this mode to function.
- Locally traffic responsive — The metering rate is selected by monitoring the volume and/or speed of traffic flow in the mainline lanes adjacent to the ramp meter.
- Time of day/day of week — The times and days when the meter will operate are constrained by the user.
- Fixed time — The meter operates at a set rate at the times specified by the user and the days specified by the user.

ADOT has a queue override feature that changes the rate plan based on the presence of vehicles on a queue detector to the fastest rate until the queue dissipates.

Ramp Metering Rates. ADOT specified the parameters used in the plan as shown in Table 5. Six uniform metering rates used by ADOT are shown in Table 6. The appropriate metering rate is selected based on the volume of the mainline right lane as follows:

- Until a central ramp control strategy can be implemented, operation of the meters in a locally traffic responsive mode using a fixed time of day schedule is recommended.
- The parameter recommended for selecting the rate plan should be right lane mainline detector volume.
- Begin metering at rate plan #1 (least restrictive) when the right lane volume reaches 1800 vph.
- Gradually increase to rate plan #6 (most restrictive) as the right lane volume builds to 2200 vph.

- If the right lane volume is not available, move one lane over to the left and use that lane's detector information until detector data become available.

Table 5. ADOT Parameter Settings for Ramp Meters.

Interval Parameter	Standard Controller Setting
Minimum Green	1.5 seconds
Maximum Green	1.5 seconds
Minimum Red	1.5 seconds
Maximum Red	10.0 seconds

Table 6. ADOT Default Metering Rate Plans.

Metering Level	Rate [vehicle per minute (vpm)]	Rate (vph)	Cycle Length (Seconds)
1	20	1200	3
2	18	1080	3.33
3	16	960	3.75
4	14	840	4.29
5	12	720	5
6	10	600	6

Target Speeds. Based on the *Highway Capacity Manual* (*HCM*) (*22*), ADOT's guidelines adopt a freeway traffic speed between 50 to 53 mph as the goal of a ramp metering system. The HMC reports that highest throughputs on freeways are achieved at this speed range.

Nevada Department of Transportation

NDOT provides some guidelines to operate ramp metering in the *HOV/Managed Lanes and Ramp Metering Implementation Plan* (*23*). Policies are provided to ensure that deployed ramp metering equipment is operated correctly and in a consistent manner. NDOT is responsible for the majority of ramp meter operations, except for those in the Las Vegas area where the operation of ramp meters is through an agreement with Regional Transportation Commission of Southern Nevada (RTC). The following are some of NDOT's policies:

- Hours of operation:
  - Ramp meters shall be turned on/off at the same time every day during the initial period of operation, unless otherwise indicated by the supervisor in charge of ramp metering operations. The initial period depends on several factors including the degree to which motorists have familiarized themselves with ramp meters.

    - Ramp meters shall be operated only during the peak periods during the initial period of operation to reduce motorists' confusion.
    - Ramp meters will be considered for operation when emergencies occur or in unique situations where their use will benefit existing conditions.
- Day-to-day activities:
    - Ramp meters will be operated on a consistent basis for the entire region.
    - Ramp meter operations must be monitored on a periodic basis to confirm that they are working correctly and to adjust parameters when appropriate. The monitoring can be done remotely if closed-circuit television (CCTV) is present near metered ramps; otherwise, operators will schedule routine field visits.

Overview of Ramp Metering Strategies

Classification of ramp metering strategies varies based upon its purpose. According to the literature review, ramp metering strategies are classified by operating characteristics, algorithms, and types of traffic measurements. This section summarizes common types and classifications of ramp metering strategies currently used.

Single-Lane and Dual-Lane Metering

There are three common ramp metering strategies (*20*). The maximum theoretical ramp capacity depends on the type of strategy used.

Single Lane, One Car per Green. This strategy allows one car to enter the freeway during each signal cycle. Caltrans research suggested that the effective operating rate for a ramp meter ranges between 240 and 900 vphpl; 900 vphpl is equivalent to a 4-second cycle, which consists of 1 second of green, 1 second of yellow, and 2 seconds of red. However, in Arizona, the use of a 3-second cycle to achieve a 1200-vph metering rate has been reported (*9*).

Single Lane, Multiple Cars per Green. This strategy, also known as platoon or bulk metering, allows two or more vehicles to enter the freeway during each green indication. Platoon metering did not significantly increase the ramp capacity when compared to a single-lane one-car-per-green strategy. This is because the bulk metering strategy requires more green, yellow, and red times to ensure reliable operation as ramp speed increases, resulting in longer cycle length (*20*). Recommended controller timings for this strategy are presented in Table 7.

Table 7. Recommended Interval Timings (Seconds) for Bulk Metering (*20*).

Interval	Number of Vehicles per Green					
	1	2	3	4	5	6
Red (Seconds)	2.00	2.00	2.32	2.61	2.86	3.08
Yellow (Seconds)	1.00	1.70	2.00	2.22	2.41	2.58
Green (Seconds)	1.00	3.37	5.47	7.35	9.13	10.83
Cycle Length (Seconds)	4.00	7.07	9.79	12.18	14.40	16.49
Meter Capacity (vph)	900	1018	1103	1182	1250	1310

Dual-Lane Metering. Dual-lane (or tandem) metering requires two lanes on a ramp. This strategy operates by alternating the green-yellow-red cycle for each metered lane. The cycle may or may not be synchronized depending on the controller being used. In Texas, a synchronized cycle is used such that the green indications never occur concurrently in both signals (*20*). Dual-lane metering can provide a metering capacity of up to 1700 vph. In addition, dual-lane ramps provide more storage for queued vehicles.

Table 8 summarizes metering rate ranges for different metering arrangements and usage considerations.

Table 8. Ranges of Ramp Metering Rates — Adapted from (*9*).

Metering Strategies	Number of Metered Lanes	Approximate Range of Metering Rates (vph)	Comments
Single vehicle per green	1	240 to 900*	• Full stop at the meter usually not achieved at maximum rate.
Tandem or dual-lane metering	2	400 to 1700	• Applies when required metering rate exceeds 900 vph. • Vehicles may be released from each lane alternately, simultaneously, or randomly.
Platoon metering single lane	1	240 to 1100	• Platoon lengths permit passage of 1 to 2 vehicles per green interval. • Primarily used when geometric conditions are inadequate for increased metered volumes. • Requires changeable sign indicating permitted number of vehicles per green. • *MUTCD* requires yellow interval after green.
* ADOT reports a maximum rate of 1200 vph for this strategy using a 3-second cycle.			

Reactive/Proactive Strategies

Smaragdis and Papageorgiou (*24*) classified ramp metering strategies into two categories:

- Reactive strategies (tactical level) aim at maintaining the freeway operating conditions at prespecified, desired values using real-time measurements.

- Proactive strategies (strategic level) aim at maintaining optimal traffic conditions based on freeway network demand predictions over a sufficiently long time horizon.

Both types of strategies may be combined within a hierarchical control structure, whereby a proactive network-wide strategy delivers optimal traffic conditions to be used as set values by subordinate reactive strategies.

Local/Coordinated Strategies

Reactive ramp metering strategies can be local or coordinated. Local strategies make use of traffic measurements in the vicinity of each ramp to determine the corresponding individual metering rates. On the other hand, coordinated strategies make use of available measurements from greater portions of a freeway. Local strategies are much easier to design and implement; however, research has found that their performance is not inferior to more sophisticated coordinated approaches under recurrent congested traffic conditions (*25*).

The most well-known local ramp metering strategies were summarized in a recent study by Smaragdis and Papageorgiou (*24*). These include the demand-capacity (DC) strategy, the occupancy (OCC) strategy, and ALINEA.

DC Strategy. The DC strategy is expressed as follows:

$$r(k)=\begin{cases} q_{cap}-q_{in}(k-1); \text{ if } o_{in}(k-1)\le o_{cr} \\ r_{\min}; \text{ if otherwise} \end{cases} \tag{2}$$

where:

k = 1,2,… = discrete time index,

$r(k)$ = ramp flow (vph) to be implemented during the new period k,

$q_{in}(k-1)$ = last measured upstream freeway flow (vph),

$o_{in}(k-1)$ = last measured upstream freeway occupancy (percent),

q_{cap} = downstream freeway capacity,

r_{min} = minimum admissible ramp flow, and

o_{cr} = downstream critical occupancy (where freeway flow becomes maximum).

The DC strategy attempts to add to the upstream flow as much ramp flow as necessary to reach the known downstream freeway capacity. The DC strategy is not a feedback, but a feed-forward disturbance-rejection scheme, which is known to be somewhat sensitive to various immeasurable disturbances, e.g., slow vehicles, short shock waves, etc. (*25*).

OCC Strategy. Linearity between flow and occupancy can be approximated as:

$$q_{in} = \frac{v_f o_{in}}{g} \tag{3}$$

where v_f is the free-flow speed of the freeway and g is the g-factor. Replacing Eq. (3) with the upper part of Eq. (2) gives:

$$r(k) = K_1 - K_2 o_{in}(k-1) \tag{4}$$

where $K_1 = q_{cap}$, $K_2 = v_f/g$, and $r(k)$ is truncated if it exceeds a range $[r_{min}, r_{max}]$, where $r_{\max}$ is the ramp's estimated flow capacity. The OCC strategy is an occupancy-based feed-forward strategy. This strategy can become more inaccurate than the DC strategy due to the linearity assumption of the fundamental flow-occupancy relationship (*24*).

ALINEA Strategy. ALINEA is a feedback ramp metering strategy (*16, 17*):

$$r(k) = r(k-1) + K_R\left[\hat{o} - o_{out}(k-1)\right] \tag{5}$$

where $K_R > 0$ is a regulator parameter and $\hat{o}$ is a set (desired) value for the downstream occupancy. ALINEA was found to give better performance than DC and OCC strategies in several comparative field evaluations (*26*).

A recent study suggested modifications and extensions to ALINEA that allow the following aspects to be taken into account (*24*):

- use of upstream (instead of downstream) measurements,
- use of flow-based (instead of occupancy-based) set values and measurements, and
- efficient ramp-queue control to avoid interference with surface street traffic.

Generic Operations Guidelines

The *Traffic Control Systems Handbook* (*1*) provides general guidelines for some types of ramp metering systems given common applications; see Table 9.

Table 9. General Guidelines for Types of Ramp Metering — Adapted from (27).

Applications	Local		System-wide	
	Pretimed	Traffic Responsive	Pretimed	Traffic Responsive
1. Achieve smoother flow at merge (safety improvement — preserve merge capacity	Applicable	Applicable	Applicable	Applicable
2. Spot congestion problems — sufficient control for one meter to satisfy	Applicable if congestion period is stable	Applicable	Applicable	Applicable
3. Congestion requiring control distributed over multiple ramp meters	N/A	N/A	Applicable if congestion period is stable	Applicable
4. Scheduled special events	Applicable if one meter can satisfy and congestion period is stable	Applicable if one meter can satisfy	Applicable if congestion period is stable	Applicable
5. Highly variable mainline demand	N/A	Applicable if one meter can satisfy	N/A	N/A
6. Congestion due to spillback from exit ramp onto mainline	Applicable if one meter can satisfy and congestion period is stable	Applicable if one meter can satisfy	Applicable if congestion period is stable	Applicable
7. Congestion due to incidents	N/A	Applicable, but system-wide preferred	N/A	Applicable
8. Congestion due to construction	N/A	Applicable, but system-wide preferred	Applicable	Applicable
9. Use in combination with other controls: (a) closure, (b) Changeable Message Sign, (c) route guidance	(a) Unlikely to be applicable, (b) N/A, (c) N/A	(a) Applicable, (b) N/A, (c) N/A	(a) Unlikely to be applicable, (b) N/A, (c) N/A	(a) Applicable, (b) applicable, (c) applicable
10. Backup mode	Backup to local traffic responsive	Backup to system-wide traffic responsive	Backup to system-wide traffic responsive	N/A

WARRANTS FOR REMOVING RAMP METERS

If the upstream signal is close to the ramp meter and the use of a primary queue detector is not able to provide acceptable ramp metering operation, the following three feasible options can be pursued (*19*):

- meter traffic at the upstream signal,
- increase the ramp meter capacity provided that geometric conditions are feasible, and
- do not install a ramp meter.

As a result of a congressionally mandated study to decommission their ramp meters (*8*), the Minnesota Department of Transportation (Mn/DOT) examined the issue of when and where to remove ramp meters. One of the factors leading to the request to decommission the ramp meters in the Minnesota area was the amount of wait time travelers were expected to endure at some of the ramp meters. At certain times of day, travelers experienced prolonged wait times at some ramps on the order of 10 to 15 minutes (*8*). In an attempt to reduce wait times, Mn/DOT developed the following general criteria (*28*) to assist in identifying locations where removing the ramp meter has the potential to improve performance of the ramp and/or freeway:

- ramps operating with less than 400 vehicles per hour,
- ramps operating with volumes so high that wait times at the meters exceed 4 minutes,
- ramps where atypical geometries are causing sight distance or acceleration problems, and
- locations where the combination of freeway demand and ramp demand do not cause the freeway to experience congestion during typical hours in which the ramp meter would operate.

RAMP MANAGEMENT EVALUATIONS

The following section provides a summary of the measures of effectiveness commonly used to evaluate ramp control signal installations. The section also provides results from case study evaluations of ramp control signal deployments.

Measures of Effectiveness in Evaluating Ramp Control Signals

Common measures of effectiveness (MOEs) are listed below (*27*):

- freeway mainline speed,
- accident rate/frequency,
- freeway mainline occupancy,
- overall travel time/delay time,
- freeway mainline volume/flow/stability of flow,
- fuel savings,
- benefit/cost (B/C) ratio,
- ramp delays,
- arterial vehicle volume,
- overall travel demand, and
- public/motorist survey results (qualitative).

Types of Ramp Management Evaluation Studies

According to the *Ramp Management and Control Handbook* (*27*), analyses of ramp management applications generally fall into four categories:

- pre-deployment studies — where the analysis is performed prior to the installation of the ramp management strategy to determine the appropriateness of deploying a ramp management strategy at a particular location,
- system impact studies — where the analysis is used to identify the impacts of an existing ramp management strategy on one or more selected performance measures,
- benefit/cost analysis — where the analysis is used to evaluate the cost-effectiveness of a ramp management application at a particular location, and
- ongoing system monitoring and analysis — where a continuous analysis of the performance of a ramp operation is conducted in real time for the purposes of providing feedback to a system operator.

As implied by their name, pre-deployment studies are typically done to assess the feasibility and appropriateness of a ramp management strategy or treatment at a particular location prior to the actual physical installation of the treatment. Typically pre-deployment studies have been used to do the following:

- assess the potential impacts of introducing ramp management treatments in a region that currently does not use any,
- assess the impacts of expanding an existing ramp management program to a new location within a region, and
- estimate the impacts and effectiveness of changing or modifying the operation of an existing ramp management strategy at a particular location.

Because this type of analysis is generally performed *before* the actual implementation of the management strategy, the analysis is based upon a *prediction* of anticipated results, rather than on direct field observation. Common methods for conducting pre-deployment studies include using "before" and "after" results from previous deployments, and spreadsheet or micro-simulation programs to model traffic operations at the location with and without the ramp management strategy.

System impact studies are generally used to evaluate the impacts of a ramp management strategy on one or more particular performance measure. These types of studies typically involve comparing the operation of a ramp location before making a change in its operations to after making a change in its operations. This type of analysis can also be performed with and without a particular ramp management strategy in place or in operation. In most cases, this type of evaluation involves the direct measurement of traffic operations in the area influenced by the ramp management strategy; however, in some cases, micro-simulation models have been used to assess impacts of making changes in the operations of a ramp management strategy, particularly region-wide.

Benefit/cost analyses are similar to system impact studies in that they both represent an assessment of the impacts related to the implementation of a particular ramp management strategy at a location. Where they differ is in the scope of the analysis. Whereas system impact studies generally focus on one or two specific performance measures, benefit/cost analyses tend to be broader in scope by incorporating multiple measures from multiple users to a single measure to provide a more global assessment of the impacts of a ramp management strategy. Generally, benefit/cost analyses compare the observed (or predicted) impacts — both positive and negative — with the cost of deploying, operating, and maintaining a ramp management strategy over its life span. Benefit/cost analyses have been used for the following purposes:

- to identify the relative effectiveness of "investing" in a particular ramp management strategy at a location,
- to provide a common point of comparison with other strategies at a particular location,
- to prioritize funding for future improvements to a particular location, and
- to communicate the relative benefits of implementing a particular strategy to decision makers and the traveling public.

The final general type of ramp management evaluation study involves the ongoing, continuous monitoring and assessment of ramp operations. Generally, system operators use this type of analysis with a direct feedback of the status and performance of a ramp management strategy. This type of analysis allows the operator to assess the effectiveness of the strategy in real time and to make changes to the strategy as conditions warrant. Oftentimes, this strategy uses a combination of current and historical information to identify trends that show how the impacts of the ramp management strategy have changed over time or under different operating conditions. Because of the ongoing nature of this analysis type, operators depend on automated systems (such as traffic detection systems and closed-circuit television) for collecting and displaying performance data.

In general, evaluations of ramp control signal systems fall into three levels:

- Localized analysis — In this level of analysis, the focus of the evaluation is on the area immediately adjacent to where the ramp management strategy is applied. This level of analysis is most appropriate for deployments of a limited scale or where a limited number of narrowly defined performance measures are used to assess the impacts. An example of where a localized analysis might be appropriate is in assessing the ability of a ramp meter application to reduce the number of crashes occurring within the merge area of a ramp.
- Corridor analysis — In this level of analysis, the focus of the evaluation includes multiple ramp locations, generally on the same facility. This level of analysis is most appropriate when modifications are made to multiple ramp locations, or when the deployment of a strategy is anticipated to affect any of the selected performance measures along an entire corridor. An example of where this level of analysis might be appropriate is where a strategy was employed at multiple locations on the same

facility where the effects of the deployment are not likely to produce any significant impacts outside the defined corridor.

- Regional analysis — This level of analysis is most appropriate when a comprehensive accounting for all possible impacts is required or when the deployment is scattered across a large area or multiple facilities. Because these studies often involve a large geographic area, this level of analysis often requires the use of a large-scale analysis tool, such as a regional travel demand model or other similar type of tool.

Table 10 shows list of performance measures that generally been used in to evaluate ramp signal control systems these analyses.

Table 10. Common Ramp Meter Performance Measures — Adapted from (*27*).

Performance Goal	Performance Measure	Location			
		Merge/Weave Area	Ramps	Freeway	Arterial
Safety	Crash Rate	✓	✓	✓	✓
	Number of Conflicts	✓			
Throughput	Traffic Volume	✓	✓	✓	✓
	Facility Speed	✓		✓	✓
	LOS or V/C Ratio			✓	✓
	Intersection LOS				✓
Mobility	Travel Time			✓	✓
	Delay		✓	✓	✓
Reliability	Travel Time Variation		✓	✓	✓
Queue	Spillover		✓		✓
Environmental	Fuel Consumption	✓	✓	✓	✓
	Vehicle Emissions	✓	✓	✓	✓

Case Studies

The following represents several case study evaluations of the effectiveness of various ramp control signal deployments.

US 45 in Milwaukee, Wisconsin

In early 2000, WisDOT conducted a "with" and "without" type of study to measure the overall effects of installing ramp meters at an additional six ramps on US 45 from the Waukesha-Washington County line to just south of Greenfield Avenue (a distance of 14 miles) (*29*). Ramp metering was already present on six ramps; four of these ramps were located at the south end of the corridor, which carried the heaviest traffic volumes. A "without" and "with" type of evaluation was used in the evaluation. The "without" period represented freeway operating conditions with only the existing six ramp meters in operations, while the "with" period represented those conditions with the additional six ramp meters operational.

Table 11 shows the performance measures that were used in the evaluation. The gathering of performance data was limited to Tuesdays, Wednesdays, and Thursdays during consecutive weeks to ensure that travel patterns represented typical weekday commuter traffic. Two weeks of traffic data were collected in both the "without" and "with" periods. To allow drivers to become accustomed to the presence of the new ramp meters, four weeks separated the end of the "without" period and the "with" period. Data were collected during the morning (7:00 a.m. to 8:30 a.m.) and afternoon (4:00 p.m. to 5:30 p.m.) peak periods only. Data were collected at cut lines located approximately every 2 to 3 miles in the corridor. The data used to generate the performance measures included the following:

- travel time runs performed every 15 minutes in both directions during the peak periods,
- travel volume and speed data collected every 20 seconds through mainline and ramp system detectors,
- 15-minute traffic volume counts collected through specially installed tube counters, and
- on-ramp queue lengths recorded every 20 seconds through videotaped or manual observations in the field.

Table 11. Performance Measures Used in the US 45 Ramp Meter Evaluation in Milwaukee, Wisconsin.

Facility	Performance Measures
Corridor	• Crash Rates
Freeway	• Mainline Traffic Volumes • Vehicle-Miles of Travel (VMT) • Vehicle-Hours of Travel (VHT) • Speeds
Ramp	• Delay • Queue Length

The results from the analysis found the following:

- Mainline traffic volumes increased slightly in the corridor. The corridor experienced a 2 to 3 percent increase in traffic volumes at the southern end and a 4 percent increase at the northern end.
- Freeway vehicle-miles of travel increased by 1 percent during the morning peak and 2 percent during the afternoon peak.
- Freeway vehicle-hours of travel decreased by 2 percent in the morning peak and by 5 percent during the afternoon peak. Total corridor vehicle-hours of travel (which includes ramp delays) *increased* by 4 percent during the morning peak and decreased by 2 percent during the afternoon peak.
- Freeway speeds increased during both peaks when the new ramp meters were operational. Freeway speeds increased by 1.83 mph (3 percent) and 2.35 mph (4 percent) in the morning and afternoon peaks, respectively.
- Ramp delays increased by 64 percent during the morning peak and 34 percent during the afternoon peak. The majority of this increase was attributed to an increase in delays at the locations where new ramp meters were installed.
- On-ramp queue lengths did not change substantially when the new ramp meters were operational, even though ramp delays increased.

I-405 in Renton, Washington

WSDOT conducted a "before" and "after" evaluation of the ramp meters operating on I-405 in Renton after changing the logic used to control the ramp meter operations (*30*). The purpose of the evaluation was to assess the effectiveness of the new controller logic prior to initiating a wide-scale implementation of the logic. The new logic was installed in nine ramp meter controllers in the corridor.

WSDOT used corridor travel times and freeway speeds as the primary performance measures in the study. Drivers recorded travel time and speed data manually using the floating car method. Two weeks of data were collected during the "before" period and three days during the "after" period. The "after" period data collection was performed approximately one month after the change in the ramp meter logic was completed. Approximately the same number of travel time runs and speed measurements were made during each evaluation period. Data were collected during the peak hours on Tuesdays, Wednesdays, and Thursdays.

The results of the study showed the following:

- In the northbound direction, changing the ramp meter controller logic decreased the travel time during the morning commute but not in the afternoon peak. Likewise, southbound travel times decreased substantially in the morning peak but not during the afternoon peak.
- Changing the ramp meter controller logic increased travel speed in the morning peak in both northbound and southbound directions, while travel speeds decreased in the afternoon peak.

The study also concluded that ramp meters were effective when mainline travel speeds ranged between 33 and 55 mph. Although no data were collected to support the conclusion, the authors concluded that the meters would probably be effective even when the mainline travel speed dropped below 33 mph. The authors recommended that ramp meters be activated whenever the freeway travel speed dropped below 55 mph.

I-580 in Pleasanton and Livermore, California

The City of Pleasanton, in conjunction with the City of Livermore and Caltrans, conducted a "before" and "after" evaluation of the ramp meter system installed on I-580 (*31*). These ramp meters were installed to discourage cut-through traffic on arterials through the cities of Dubin, Pleasanton, and Livermore while relieving traffic congestion on a downstream bottleneck location (the Santa Rita Road on-ramp). Ramp meters were installed to increase traffic volume on I-580 eastbound without causing the diversion of traffic volumes away from the metered ramps and arterial cut-through routes to the freeway.

Both travel time and traffic volumes were the primary performance measures used in this study. Travel time was collected on a segment-by-segment basis. Average daily traffic was used to measure changes in volume levels before and after the ramp meters were installed.

The evaluation showed that the ramp meters achieved the agencies' design objectives. Freeway travel times decreased and traffic volumes increased upstream of the metered ramps, while travel times increased and traffic volume decreased downstream of the ramp meter. Installing the ramp meters was credited for significantly reducing traffic volumes on the Santa

Rita Road on-ramp. Travel time also decreased on the cut-through corridors not subject to increased queuing as a result of the ramp meter installation. On the arterials subjected to increased queuing, travel time increased more than 125 percent.

CHAPTER 3:
RESULTS OF SIMULATION STUDIES

A series of simulation studies were performed to examine various issues related to ramp control signal installation and operations. The first simulation study focused on establishing traffic volume criteria for installing ramp control signals. The second set of simulation studies examined the issues relating to setting the flushing parameters used by TxDOT to control queuing at their ramp control signals. The final simulation study examined alternatives to operating ramp control signals in the flush mode. All of these simulation studies were conducted using the VISSIM® traffic simulation program.

INVESTIGATION OF TRAFFIC VOLUME CRITERIA FOR INSTALLING RAMP CONTROL SIGNALS

The first simulation study focused on establishing threshold criteria for installing ramp control signals. In this study, we systematically varied freeway and ramp demand levels to gain an understanding of how these parameters impacted freeway operations, both with and without a ramp control signal. We then used the findings of the study to establish threshold criteria for installing ramp control signals.

Simulation Design

Figure 4 shows the basic geometry of the ramp used in this study. For the purposes of this study, we used a single-lane entrance ramp, typical of the type and design of ramps in Houston, Texas, where control signals have been deployed, entering a two-lane freeway. Only one direction of travel was modeled in the simulation, and each lane on the freeway, ramp, and frontage road was modeled to be 12 feet in width. Early test simulations showed that the queuing and shockwave effects of a single ramp extended for approximately 7 miles upstream on the freeway; therefore, we used an extended approach on the freeway to the ramp to allow sufficient storage length for any queues that developed.

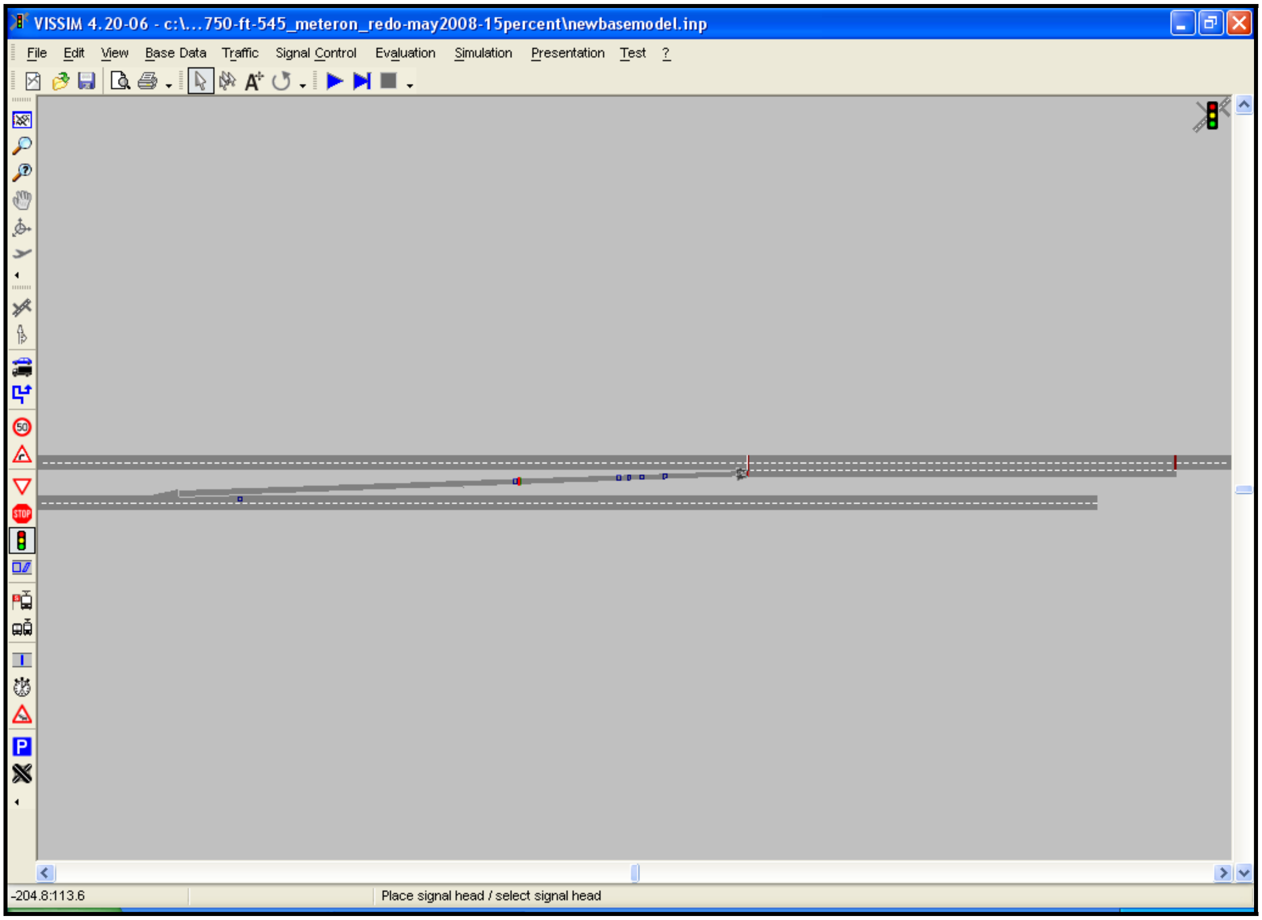


Figure 4. Schematic of Geometric Conditions Used in Simulations to Explore Installation Criteria for Ramp Control Signals based on Traffic Conditions.

The ramp was modeled as a single lane approximately 1000 feet in length. Researchers examined the impact of using a ramp control signal under different ramp acceleration lane lengths: 500, 750, 1000, 1250, and 1500 feet. As shown in Figure 4, these ramp acceleration lengths were measured from the freeway/ramp gore area.

A ramp control signal was placed approximately 400 feet upstream of the freeway/ramp gore area. The ramp control signal operations were modeled using a vehicle actuated program (VAP). The ramp meter was programmed to operate in a pre-timed (or fixed-time) mode. Only one vehicle was allowed to enter the freeway each cycle.

The effects of merging traffic on freeway main lane performance were examined with and without a ramp control signal controlling the rate at which traffic entered the freeway. Main lane traffic flow rates were set to the following levels: 1800, 1900, 2000, 2100, 2200, 2300, and

2400 passenger cars per hour per lane (pcphpl). We assumed trucks to be 10 percent of the traffic mix.

The cycle length (or metering rate) for the ramp control signal was set to provide a desired flow rate entering the ramp. Table 12 shows the ramp control signal cycle lengths and the corresponding entrance ramp volumes studied in the simulation. We used a 2-second green interval and a 1-second yellow interval for all ramp metering rates. The red interval was varied to achieve the desired cycle length of the ramp control signal.

Table 12. Ramp Control Signal Intervals and Corresponding Equivalent Ramp Flow Rate Entering Freeway.

Ramp Control Signal Cycle Length (Seconds)	Ramp Control Signal Interval Times (Seconds)			Equivalent Ramp Flow Rate Entering Freeway (pcphpl)
	Green	Yellow	Red	
10	2	1	7	360
9	2	1	6	400
8	2	1	5	450
7	2	1	4	515
6	2	1	3	600
5	2	1	2	720
4	2	1	1	900

The total duration of each simulation was 6300 seconds; however, the interval over which performance data were collected was 5800 seconds. Performance data were not collected during the first 900 seconds of the simulation to allow traffic to build and reach equilibrium on the network before performance statistics were collected. Performance measures were aggregated in 60-second intervals. Ten replications were performed at each freeway volume and entrance ramp demand level.

Results of Simulation

Data collection stations were used to collect travel time and volume count data performance measures in the simulation. Travel times on the freeway were collected over a segment length of 10 miles, with the upstream point extending well before freeway traffic experienced any effects of queuing from the ramp and extending to a point well beyond the ramp influence area. Freeway travel times for all vehicles were averaged over the simulation period. We then converted the travel time to average running speed by dividing the travel time by the travel time segment length. This was done for all ramp volumes, freeway volumes, and ramp acceleration lane lengths, both with and without the ramp control signal in operation. Figures were then developed that compared the average running speed of the traffic traveling on the freeway main lanes with and without the ramp demand being metered by the ramp control signal. An example is shown in Figure 5. Appendix A contains the figures for each combination of ramp demand, freeway volume, and length of ramp acceleration lane evaluated in this study.

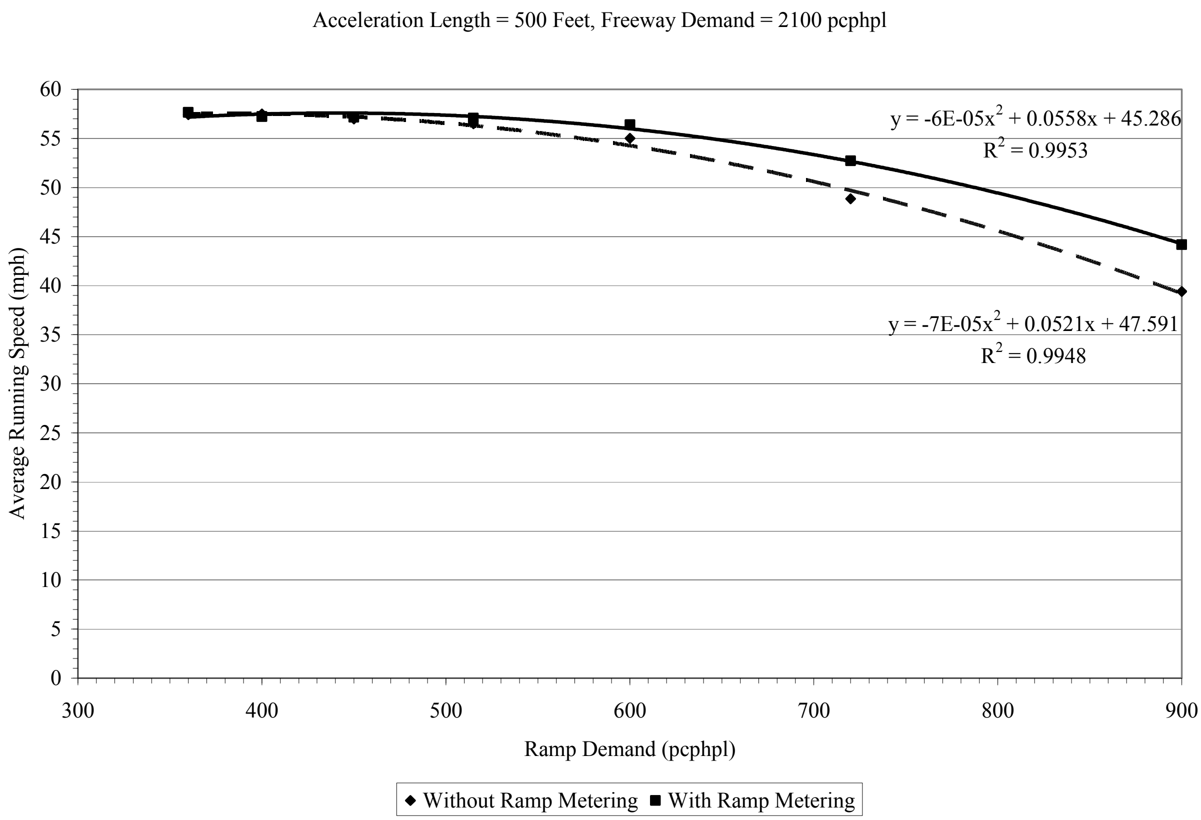


Figure 5. Example of How Using a Ramp Control Signal Can Impact Freeway Operations at a Particular Freeway Demand and Ramp Acceleration Length Level.

The following observations can be made after reviewing the figures in Appendix A:

- At any given ramp acceleration lane length and freeway demand, the effects of the ramp control signal on the average running speed of freeway traffic became more pronounced. This can be observed by noting the separation between the two lines (the solid line showing the average running speed of the freeway traffic with the ramp control signal metering the ramp demand, and the dashed line showing the average running speed of traffic on the freeway when there is no ramp control signal). When ramp demands are relatively low, there is little to no effect of the ramp control signal on freeway traffic. However, as ramp demand increases, using a ramp control signal results in higher average running speeds on the freeway compared to not using a ramp control signal.

- At any given ramp acceleration lane length, the average running speed decreases as the level of freeway demand increases, regardless of whether the ramp control signal is operating. This is intuitive — as the demand of the freeway approaches the capacity of the freeway, speeds are reduced. However, notice that average running speeds on the freeway are still higher when the ramp control signal is active than when there is no ramp meter. Also note that it takes less ramp demand to cause a reduction in average running speed (as denoted by a shift of point where the two lines diverge further to the left on the diagrams) as freeway demand increases. These figures illustrate that metering the ramp demand on the freeway produces smoother operation in the weaving area and allows traffic on the freeway to operate at a higher level.
- The length of the acceleration lane has a dramatic impact on the average running speed of traffic on the freeway. When the acceleration lane is very short (500 feet or 750 feet), the effects of implementing a ramp control signal are measurable at lower freeway and ramp demand levels than when ramp acceleration lengths are greater. As the length of the acceleration lane increases, it takes a higher combination of ramp and freeway demand to cause a difference in freeway performance with and without the ramp control signal. When the acceleration length was 1500 feet, the ramp control signal had little effect on the average running speed of traffic on the freeway. One would expect that with longer acceleration lanes, traffic entering from the ramp has more opportunities to merge into the main lanes at the prevailing speed, regardless of the freeway traffic demand.

We conducted a statistical analysis to determine at what ramp and freeway traffic demand level using a ramp control signal produced a statistically significant difference in the average running speed of traffic on the main lanes (compared to when a ramp control signal was not used). For this analysis, we used a standard t-test to compare the average running speed of traffic with and without the ramp control signal metering the demand on the freeway. We used a

95 percent confidence level to determine a statistical difference. We conducted this analysis for each ramp acceleration lane length. The results of this analysis are summarized in Table 13, and the actual results of the analysis are presented in Appendix B.

Development Criteria for Installing Ramp Control Signals

The purpose of conducting these simulations was to determine under what freeway and ramp demand level and ramp geometric conditions using a ramp control signal results in a significant improvement in freeway conditions. Once we found these conditions, they used the values to set threshold criteria for when to install ramp meters. When examining whether or not to install a ramp control signal, TxDOT personnel would probably go out to a location, watch operations, and possibly conduct a traffic volume count using either existing freeway surveillance detectors or temporary traffic counters.

The study team used the same process in their simulation studies. Traffic detector stations were installed in both lanes of the freeway upstream of the ramp and on the ramp itself. They used these sensors to collect volume counts during the simulations and then used these sensors to determine the actual main lane and ramp volumes.

Table 14 through Table 18 show the measured traffic volumes for each freeway and ramp demand level and ramp acceleration lane length. The shaded rows indicate those situations where the average running time on the freeway was statistically significant with the ramp control signal rather than without. These tables helped identify minimum freeway volume criteria and the combined freeway plus ramp demand criteria for determining when to install a ramp control signal.

For identifying the minimum freeway volume threshold, we averaged the traffic volumes in each lane of the freeway measured upstream of the entrance ramp. They used the average from both lanes because the simulation showed that at lower levels, traffic had a tendency to vacate the rightmost lane to allow entering traffic to merge onto the freeway. The team then identified the minimum volume levels in each scenario in which average running speed was statistically higher with the ramp control signal than without. They then averaged the minimum thresholds and used these averages to develop the plot shown in Figure 6. Table 19 shows these values.

Table 13. Summary of Traffic Conditions Resulting in Statistically Significant Higher Average Running Speeds When the Ramp Control Signal Was Active.

Ramp Demand Level (pcphpl)	Freeway Demand Level (pcphpl)						
	1800	1900	2000	2100	2200	2300	2400
Ramp Acceleration Lane Length = 500 Feet							
360	✗	✗	✗	✗	✗	✗	✗
400	✗	✗	✗	✗	✗	✗	✓
450	✗	✗	✗	✗	✓	✓	✓
515	✗	✗	✗	✓	✓	✓	✓
600	✗	✓	✓	✓	✓	✓	✓
720	✗	✓	✓	✓	✓	✓	✓
900	✓	✓	✓	✓	✓	✓	✓
Ramp Acceleration Lane Length = 750 Feet							
360	✗	✗	✗	✗	✗	✗	✓
400	✗	✗	✗	✗	✗	✓	✗
450	✗	✗	✗	✗	✗	✓	✓
515	✗	✗	✗	✗	✓	✓	✗
600	✗	✗	✗	✗	✓	✓	✓
720	✗	✗	✓	✓	✓	✓	✓
900	✓	✓	✓	✓	✓	✓	✓
Ramp Acceleration Lane Length = 1000 Feet							
360	✗	✗	✗	✗	✗	✗	✗
400	✗	✗	✗	✗	✗	✗	✗
450	✗	✗	✗	✗	✗	✗	✗
515	✗	✗	✗	✗	✗	✗	✓
600	✗	✗	✗	✗	✗	✓	✓
720	✗	✗	✗	✓	✓	✓	✓
900	✗	✗	✓	✓	✓	✓	✓
Ramp Acceleration Lane Length = 1250 Feet							
360	✗	✗	✗	✗	✗	✗	✗
400	✗	✗	✗	✗	✗	✗	✗
450	✗	✗	✗	✗	✗	✗	✓
515	✗	✗	✗	✗	✗	✗	✓
600	✗	✗	✗	✗	✗	✗	✓
720	✗	✗	✗	✓	✓	✓	✓
900	✗	✗	✓	✓	✓	✓	✓
Ramp Acceleration Lane Length = 1500 Feet							
360	✗	✗	✗	✗	✗	✗	✗
400	✗	✗	✗	✗	✗	✗	✗
450	✗	✗	✗	✗	✗	✗	✗
515	✗	✗	✗	✗	✗	✗	✗
600	✗	✗	✗	✗	✗	✗	✓
720	✗	✗	✗	✗	✗	✗	✓
900	✗	✗	✗	✗	✗	✗	✗

✓	Denotes condition where using a ramp control signal resulted in statistically significant difference in average running speed on the freeway (95% confidence level).
✗	Denotes condition where using a ramp control signal did *not* produce a statistically significant difference in average running speed on the freeway (95% confidence level).

Table 14. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 500-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph) Outside Lane		Freeway Main Lane Flow Rate (vph) Inside Lane		Freeway Main Lane Flow Rate (vph) Both Lanes		Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
1800	360	323	328	1614	1626	1639	1650	3253	3275	1937	1954	3576	3604
	400	369	360	1629	1634	1656	1660	3285	3294	1998	1994	3654	3654
	450	417	416	1633	1606	1654	1651	3288	3257	2051	2022	3705	3673
	515	458	466	1620	1616	1664	1657	3284	3273	2078	2082	3742	3740
	600	521	538	1615	1596	1664	1657	3279	3253	2136	2134	3800	3791
	720	641	637	1590	1634	1689	1722	3279	3357	2231	2272	3920	3994
	900	*816*	*821*	*1531*	*1560*	*1720*	*1711*	*6351*	*3270*	*2347*	*2381*	*4067*	*4092*
1900	360	326	326	1715	1719	1749	1753	3463	3472	2040	2044	3789	3798
	400	376	362	1702	1729	1726	1756	3428	3484	2078	2090	3804	3846
	450	407	404	1689	1709	1740	1747	3430	3455	2096	2112	3836	3859
	515	460	462	1700	1697	1750	1754	3450	3451	2160	2159	3910	3912
	600	*544*	*546*	*1687*	*1688*	*1772*	*1759*	*3458*	*3447*	*2231*	*2233*	*4003*	*3992*
	720	*662*	*654*	*1654*	*1666*	*1799*	*1772*	*3453*	*3438*	*2316*	*2320*	*4115*	*4092*
	900	*632*	*816*	*1536*	*1610*	*1819*	*1815*	*3355*	*3425*	*2368*	*2426*	*4187*	*4241*
2000	360	329	328	1809	1803	1848	1834	3657	3636	2139	2131	3986	3964
	400	362	355	1804	1800	1848	1850	3652	3650	2166	2155	4014	4005
	450	402	408	1796	1806	1845	1859	3641	3665	2198	2214	4042	4072
	515	464	463	1775	1786	1851	1863	3627	3649	2239	2250	4090	4112
	600	*547*	*551*	*1764*	*1777*	*1872*	*1861*	*3637*	*3638*	*2311*	*2328*	*4183*	*4189*
	720	*667*	*648*	*1711*	*1739*	*1883*	*1886*	*3594*	*3625*	*2379*	*2387*	*4262*	*4274*
	900	*816*	*818*	*1525*	*1600*	*1863*	*1883*	*3388*	*3483*	*2341*	*2418*	*4203*	*4301*
2100	360	323	326	1888	1895	1935	1923	3823	3818	2210	2221	4146	4144
	400	362	363	1878	1897	1921	1949	3800	3847	2240	2260	4161	4210
	450	414	407	1860	1881	1943	1940	3803	3821	2274	2287	4217	4228
	515	*471*	*460*	*1863*	*1871*	*1961*	*1854*	*3814*	*3825*	*2334*	*2332*	*4284*	*4285*
	600	*539*	*534*	*1815*	*1846*	*1946*	*1960*	*3761*	*3806*	*2355*	*2380*	*4301*	*4340*
	720	*665*	*643*	*1710*	*1788*	*1934*	*1978*	*3644*	*3766*	*2374*	*2431*	*4309*	*4409*
	900	*793*	*811*	*1540*	*1606*	*1882*	*1923*	*3422*	*3529*	*2333*	*2417*	*4215*	*4340*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 14. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 500-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph)						Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
				Outside Lane		Inside Lane		Both Lanes					
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
2200	360	324	330	1970	1979	2034	2013	4004	3993	2294	2310	4328	4323
	400	360	365	1960	1983	2033	2041	3994	4025	2320	2349	4353	4390
	450	*412*	*407*	*1946*	*1942*	*2039*	*2012*	*3985*	*3954*	*2358*	*2349*	*4397*	*4361*
	515	*461*	*470*	*1923*	*1941*	*2043*	*2046*	*3966*	*3988*	*2384*	*2411*	*4427*	*4457*
	600	*548*	*544*	*1830*	*1887*	*2002*	*2033*	*3832*	*3920*	*2378*	*2430*	*4380*	*4463*
	720	*647*	*643*	*1728*	*1800*	*1965*	*2024*	*3693*	*3823*	*2376*	*2443*	*4341*	*4466*
	900	*797*	*812*	*1518*	*1593*	*1877*	*1941*	*3395*	*3534*	*2314*	*2404*	*4191*	*4346*
2300	*360*	*331*	*322*	*2032*	*2060*	*2108*	*2123*	*4140*	*4183*	*2363*	*2382*	*4471*	*4505*
	400	*375*	*370*	*2008*	*2039*	*2100*	*2124*	*4108*	*4163*	*2383*	*2408*	*4483*	*4533*
	450	*413*	*410*	*1987*	*2013*	*2111*	*2119*	*4098*	*4131*	*2401*	*2423*	*4512*	*4542*
	515	*497*	*474*	*1894*	*1976*	*2061*	*2112*	*3955*	*4088*	*2391*	*2450*	*4452*	*4562*
	600	*553*	*541*	*1834*	*1906*	*2037*	*2083*	*3871*	*3989*	*2387*	*2447*	*4424*	*4530*
	720	*659*	*648*	*1683*	*1792*	*1961*	*2027*	*3644*	*3819*	*2341*	*2440*	*4303*	*4467*
	900	*811*	*825*	*1481*	*1566*	*1876*	*1935*	*3357*	*3502*	*2292*	*2391*	*4168*	*4327*
2400	*360*	*331*	*328*	*2062*	*2079*	*2152*	*2169*	*4213*	*4248*	*2393*	*2407*	*4545*	*4576*
	400	*368*	*357*	*2022*	*2074*	*2123*	*2166*	*4146*	*4239*	*2390*	*2431*	*4514*	*4596*
	450	*417*	*412*	*1987*	*2022*	*2116*	*2142*	*4102*	*4164*	*2403*	*2434*	*4519*	*4576*
	515	*470*	*467*	*1918*	*1972*	*2077*	*2113*	*3995*	*4085*	*2387*	*2440*	*4465*	*4553*
	600	*548*	*546*	*1843*	*1904*	*2042*	*2087*	*3884*	*3992*	*2391*	*2450*	*4432*	*4537*
	720	*664*	*647*	*1693*	*1786*	*1974*	*2030*	*3667*	*3815*	*2357*	*2433*	*4331*	*4462*
	900	*811*	*820*	*1503*	*1582*	*1891*	*1940*	*3395*	*3522*	*2314*	*2402*	*4205*	*4342*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 15. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 750-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph)						Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
				Outside Lane		Inside Lane		Both Lanes					
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
1800	360	328	329	1622	1618	1648	1636	3270	3253	1950	1946	3598	3582
	400	359	363	1626	1628	1632	1651	3258	3279	1985	1991	3617	3642
	450	412	397	1641	1639	1655	1646	3296	3284	2053	2035	3708	3681
	515	462	468	1625	1626	1631	1637	3256	3263	2087	2094	3718	3732
	600	540	543	1631	1612	1657	1633	3288	3245	2171	2155	3828	3788
	720	658	647	1627	1622	1649	1658	3276	3280	2285	2268	3934	3926
	900	*814*	*823*	*1575*	*1604*	*1673*	*1678*	*3248*	*3282*	*2388*	*2427*	*4062*	*4105*
1900	360	325	319	1720	1724	1730	1744	3450	3469	2046	2044	3775	3788
	400	360	367	1720	1724	1733	1732	3454	3457	2080	2091	3814	3824
	450	410	408	1720	1710	1733	1729	3452	3439	2129	2118	3862	3847
	515	468	466	1716	1705	1726	1732	3442	3437	2184	2171	3911	3902
	600	543	543	1717	1707	1747	1742	3464	3449	2260	2250	4007	3992
	720	646	642	1707	1701	1750	1744	3457	3444	2353	2343	4103	4086
	900	*821*	*807*	*1611*	*1682*	*1780*	*1776*	*3391*	*3458*	*2432*	*2489*	*4212*	*4265*
2000	360	331	330	1814	1820	1829	1832	3643	3652	2144	2150	3973	3982
	400	370	360	1805	1815	1815	1837	3620	3653	2175	2176	3990	4013
	450	416	406	1818	1811	1844	1820	3662	3631	2234	2217	4078	4036
	515	461	463	1806	1811	1829	1842	3635	3653	2267	2274	4096	4116
	600	538	544	1789	1794	1837	1837	3626	3631	2327	2338	4164	4175
	720	*657*	*654*	*1761*	*1790*	*1860*	*1870*	*3621*	*3659*	*2418*	*2443*	*4279*	*4313*
	900	*814*	*800*	*1619*	*1741*	*1836*	*1890*	*3454*	*3631*	*2432*	*2541*	*4268*	*4431*
2100	360	323	323	1903	1888	1924	1904	3827	3792	2227	2211	4151	4115
	400	366	363	1893	1901	1906	1927	3799	3828	2258	2264	4165	4191
	450	417	408	1898	1909	1919	1933	3817	3842	2315	2317	4234	4249
	515	477	464	1886	1887	1926	1912	3812	3799	2363	2351	4289	4263
	600	538	541	1884	1887	1939	1936	3823	3823	2423	2428	4361	4364
	720	*663*	*659*	*1767*	*1844*	*1943*	*1938*	*3710*	*3782*	*2430*	*2503*	*4373*	*4441*
	900	*812*	*805*	*1594*	*1759*	*1861*	*1962*	*3455*	*3721*	*2405*	*2564*	*4266*	*4526*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 15. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 750-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph): Outside Lane		Freeway Main Lane Flow Rate (vph): Inside Lane		Freeway Main Lane Flow Rate (vph): Both Lanes		Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
2200	360	319	329	1994	2001	2010	2021	4003	4021	2313	2329	4322	4350
	400	365	362	1992	1967	2013	1996	4004	3963	2356	2329	4369	4325
	450	408	405	1972	1975	2016	2001	3988	3976	2380	2379	4396	4381
	515	*477*	*470*	*1957*	*1978*	*2027*	*2035*	*3984*	*4023*	*2434*	*2449*	*4460*	*4484*
	600	*538*	*545*	*1911*	*1953*	*2016*	*2033*	*3928*	*3987*	*2449*	*2498*	*4466*	*4531*
	720	*652*	*654*	*1763*	*1890*	*1958*	*2045*	*3720*	*3935*	*2415*	*2544*	*4372*	*4589*
	900	*819*	*824*	*1575*	*1743*	*1871*	*1982*	*3446*	*3725*	*2394*	*2568*	*4265*	*4549*
2300	360	323	329	2067	2084	2077	2110	4144	4194	2390	2413	4466	4523
	400	*371*	*363*	*2060*	*2066*	*2096*	*2104*	*4156*	*4170*	*2431*	*2429*	*4527*	*4533*
	450	*407*	*412*	*2025*	*2052*	*2084*	*2105*	*4109*	*4157*	*2432*	*2464*	*4516*	*4569*
	515	*471*	*478*	*1977*	*2016*	*2066*	*2113*	*4043*	*4129*	*2447*	*2494*	*4514*	*4607*
	600	*550*	*547*	*1899*	*1970*	*2028*	*2099*	*3926*	*4069*	*2449*	*2517*	*4476*	*4616*
	720	*662*	*668*	*1758*	*1882*	*1963*	*2053*	*3720*	*3934*	*2420*	*2549*	*4382*	*4602*
	900	*811*	*824*	*1595*	*1741*	*1883*	*2000*	*3477*	*3741*	*2406*	*2565*	*4288*	*4565*
2400	*360*	*324*	*331*	*2129*	*2133*	*2160*	*2168*	*4289*	*4301*	*2453*	*2464*	*4613*	*4632*
	400	363	363	2078	2115	2134	2165	4212	4281	2440	2479	4574	4644
	450	*407*	*413*	*2048*	*2103*	*2121*	*2149*	*4169*	*4252*	*2455*	*2516*	*4577*	*4665*
	515	468	465	2002	2048	2090	2141	4092	4189	2470	2513	4560	4654
	600	538	544	1919	1989	2050	2120	3969	4110	2457	2533	4506	4654
	720	661	654	1753	1899	1956	2072	3709	3972	2413	2553	4370	4626
	900	832	811	1558	1726	1874	1999	3431	3725	2390	2537	4263	4536

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 16. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1000-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph)						Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
				Outside Lane		Inside Lane		Both Lanes					
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
1800	360	324	329	1634	1627	1653	1641	3288	3269	1958	1958	3511	3587
	400	360	360	1620	1627	1656	1646	3276	3274	1980	1987	3636	3634
	450	404	409	1619	1614	1636	1642	3255	3256	2023	2023	3659	3665
	515	460	452	1616	1621	1643	1640	3259	3261	2076	2073	3719	3713
	600	547	538	1624	1619	1648	1651	3272	3270	2171	2156	3819	3807
	720	653	661	1613	1614	1652	1651	3265	3265	2267	2274	3918	3925
	900	816	820	1614	1612	1660	1683	3273	3296	2430	2433	4090	4116
1900	360	327	326	1714	1725	1748	1763	3462	3457	2041	2050	3789	3813
	400	362	360	1692	1706	1724	1734	3415	3442	2054	2067	3778	3802
	450	408	414	1713	1704	1729	1732	3442	3436	2121	2118	3850	3850
	515	466	470	1723	1703	1745	1729	3468	3433	2189	2174	3934	3903
	600	549	547	1723	1705	1744	1740	3467	3445	2272	2251	4016	3991
	720	658	654	1710	1700	1752	1747	3463	3448	2368	2354	4120	4101
	900	809	813	1687	1700	1759	1773	3446	3473	2496	2513	4255	4286
2000	360	323	327	1821	1826	1839	1839	3659	3665	2154	2153	3993	3992
	400	361	357	1806	1810	1826	1839	3632	3649	2167	2167	3993	4006
	450	412	399	1803	1808	1830	1839	3632	3647	2215	2207	4045	4046
	515	469	465	1811	1809	1822	1846	3633	3656	2280	2275	4102	4121
	600	550	542	1804	1789	1830	1835	3634	3624	2354	2330	4184	4166
	720	655	646	1781	1793	1821	1861	3603	3654	2436	2439	4257	4300
	900	*817*	*826*	*1705*	*1754*	*1866*	*1877*	*3571*	*3631*	*2522*	*2580*	*4388*	*4457*
2100	360	317	327	1899	1891	1924	1915	3823	3806	2216	2218	4140	4133
	400	362	361	1899	1893	1912	1924	3612	3817	2261	2254	4179	4178
	450	409	401	1904	1890	1933	1921	3837	3811	2314	2291	4247	4212
	515	469	472	1903	1883	1940	1914	3842	3797	2372	2355	4312	4289
	600	540	547	1881	1867	1934	1923	3815	3790	2421	2414	4355	4337
	720	*656*	*659*	*1834*	*1850*	*1947*	*1921*	*3761*	*3770*	*2490*	*2508*	*4437*	*4429*
	900	*829*	*817*	*1689*	*1796*	*1827*	*1985*	*3616*	*3761*	*2518*	*2612*	*4445*	*4597*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 16. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1000-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph) — Outside Lane		Freeway Main Lane Flow Rate (vph) — Inside Lane		Freeway Main Lane Flow Rate (vph) — Both Lanes		Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
2200	360	317	323	1971	1969	2002	2008	3974	3977	2289	2292	4291	4300
	400	370	360	1983	1988	2018	2021	4001	4009	2353	2348	4371	4369
	450	407	404	1986	1978	2025	2026	4010	4004	2393	2383	4418	4408
	515	455	467	1984	1980	2032	2030	4016	4009	2440	2447	4471	4477
	600	546	547	1950	1955	2038	2041	3988	3996	2496	2502	4534	4543
	720	*649*	*656*	*1862*	*1904*	*2016*	*2042*	*3879*	*3947*	*2511*	*2560*	*4529*	*4602*
	900	*798*	*816*	*1714*	*1784*	*1955*	*2024*	*3670*	*3809*	*2513*	*2600*	*4468*	*4624*
2300	360	320	332	2076	2071	2114	2109	4190	4180	2396	2403	4511	4512
	400	362	364	2073	2066	2112	2111	4185	4177	2435	2431	4547	4542
	450	414	405	2043	2059	2108	2110	4146	4170	2457	2464	4560	4575
	515	464	471	2030	2042	2098	2123	4128	4165	2494	2513	4592	4636
	600	*548*	*546*	*1951*	*1995*	*2057*	*2110*	*4007*	*4106*	*2498*	*2541*	*4595*	*4651*
	720	*650*	*647*	*1840*	*1905*	*2014*	*2079*	*3854*	*3984*	*2490*	*2552*	*4503*	*4631*
	900	*827*	*811*	*1700*	*1779*	*1951*	*2044*	*3652*	*3817*	*2527*	*2584*	*4479*	*4627*
2400	360	329	322	2121	2127	2174	2178	4296	4305	2450	2449	4624	4627
	400	365	364	2107	2116	2155	2181	4262	4297	2471	2479	4627	4660
	450	412	407	2079	2096	2144	2168	4223	4265	2491	2503	4635	4672
	515	*464*	*468*	*2025*	*2070*	*2117*	*2166*	*4143*	*4236*	*2490*	*2538*	*4607*	*4703*
	600	*550*	*556*	*1946*	*1989*	*2078*	*2134*	*4024*	*4123*	*2496*	*2545*	*4574*	*4679*
	720	*654*	*650*	*1857*	*1903*	*2022*	*2091*	*3880*	*3995*	*2511*	*2553*	*4534*	*4644*
	900	*821*	*809*	*1699*	*1770*	*1958*	*2051*	*3657*	*3821*	*2520*	*2578*	*4478*	*4629*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 17. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1250-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph): Outside Lane		Freeway Main Lane Flow Rate (vph): Inside Lane		Freeway Main Lane Flow Rate (vph): Both Lanes		Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
1800	360	320	330	1635	1642	1628	1636	3262	3277	1955	1971	3583	3607
	400	365	363	1644	1642	1629	1630	3273	3272	2009	2005	3638	3635
	450	410	413	1642	1644	1626	1640	3268	3583	2052	2056	3678	3696
	515	472	461	1628	1627	1636	1623	3264	3250	2100	2087	3736	3711
	600	548	534	1647	1636	1637	1629	3284	3265	2195	2170	3832	3799
	720	648	645	1649	1611	1650	1621	3299	3232	2297	2255	3947	3876
	900	813	810	1639	1615	1651	1628	3290	3243	2452	2425	4103	4053
1900	360	323	320	1734	1738	1731	1736	3466	3473	2057	2057	3788	3793
	400	370	364	1733	1720	1734	1721	3467	3441	2103	2084	3837	3805
	450	411	411	1731	1715	1726	1712	3457	3427	2142	2126	3868	3838
	515	456	473	1730	1739	1735	1743	3464	3482	2186	2213	3921	3956
	600	549	535	1733	1713	1735	1725	3468	3438	2282	2248	4017	3974
	720	650	653	1718	1712	1726	1730	3444	3442	2368	2365	4094	4095
	900	820	816	1719	1710	1733	1758	3452	3467	2539	2526	4272	4283
2000	360	322	323	1818	1823	1813	1820	3631	3642	2140	2146	3953	3966
	400	372	360	1817	1823	1806	1820	3624	3643	2189	2183	3995	4003
	450	410	412	1815	1815	1811	1822	3626	3638	2225	2227	4036	4050
	515	460	475	1825	1809	1827	1812	3653	3621	2285	2284	4113	4096
	600	544	548	1826	1821	1827	1828	3653	3649	2369	2369	4196	4197
	720	646	645	1816	1810	1825	1836	3641	3646	2462	2455	4287	4291
	900	*819*	*799*	*1787*	*1784*	*1848*	*1838*	*3635*	*3622*	*2605*	*2583*	*4453*	*4421*
2100	360	330	324	1921	1915	1925	1909	3846	3824	2251	2239	4176	4148
	400	361	373	1898	1907	1896	1895	3795	3802	2259	2280	4156	4175
	450	416	404	1912	1921	1902	1920	3814	3841	2328	2326	4230	4246
	515	468	471	1906	1812	1908	1916	3814	3828	2374	2383	4283	4299
	600	549	535	1916	1903	1922	1921	3838	3824	2465	2438	4387	4359
	720	*648*	*653*	*1891*	*1895*	*1928*	*1940*	*3819*	*3835*	*2538*	*2548*	*4466*	*4488*
	900	*824*	*820*	*1816*	*1805*	*1935*	*1947*	*3751*	*3753*	*2640*	*2626*	*4575*	*4573*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 17. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1250-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph)						Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
				Outside Lane		Inside Lane		Both Lanes					
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
2200	360	331	333	2007	2008	1996	2012	4003	4020	2338	2341	4334	4353
	400	369	359	2003	2019	1998	2007	4002	4026	2373	2378	4371	4384
	450	413	409	1997	1988	1985	1994	3982	3982	2410	2397	4395	4391
	515	463	464	1991	1992	2001	2013	3992	4005	2454	2456	4455	4469
	600	544	546	1989	1978	2007	2019	3995	3998	2532	2524	4939	4544
	720	*656*	*652*	*1925*	*1941*	*1999*	*2039*	*3925*	*3980*	*2581*	*2593*	*4581*	*4632*
	900	*811*	*822*	*1813*	*1815*	*1959*	*1995*	*3772*	*3810*	*2624*	*2637*	*4583*	*4632*
2300	360	334	310	2095	2105	2090	2092	4186	4197	2430	2423	4520	4515
	400	361	365	2092	2089	2096	2103	4187	4192	2452	2454	4548	4557
	450	404	402	2089	2078	2090	2094	4179	4173	2493	2480	4583	4574
	515	472	463	2072	2067	2088	2113	4160	4179	2544	2530	4632	4643
	600	541	547	2023	2026	2066	2094	4088	4119	2564	2573	4630	4667
	720	*654*	*638*	*1935*	*1953*	*2032*	*2080*	*3967*	*4034*	*2589*	*2592*	*4621*	*4672*
	900	*816*	*819*	*1789*	*1808*	*1957*	*2027*	*3746*	*3834*	*2605*	*2627*	*4562*	*4653*
2400	360	330	325	2168	2170	2166	2172	4333	4342	2498	2495	4664	4667
	400	364	367	2148	2146	2147	2169	4294	4315	2511	2513	4658	4682
	450	*406*	*410*	*2121*	*2135*	*2135*	*2154*	*4256*	*4289*	*2527*	*2545*	*4661*	*4699*
	515	*463*	*468*	*2094*	*2095*	*2112*	*2136*	*4206*	*4231*	*2557*	*2563*	*4669*	*4699*
	600	*546*	*539*	*2027*	*2044*	*2067*	*2121*	*4094*	*4165*	*2573*	*2583*	*4640*	*4704*
	720	*646*	*659*	*1945*	*1929*	*2034*	*2078*	*3979*	*4007*	*2591*	*2588*	*4625*	*4666*
	900	*824*	*830*	*1789*	*1814*	*1953*	*2029*	*3742*	*3843*	*2613*	*2644*	*4567*	*4673*

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 18. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1500-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph)						Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
				Outside Lane		Inside Lane		Both Lanes					
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
1800	360	316	326	1647	1642	1642	1631	3289	3273	1963	1967	3605	3598
	400	365	362	1628	1643	1623	1637	3251	3280	1993	2005	3616	3642
	450	406	412	1637	1617	1636	1622	3273	3240	2004	2029	3679	3651
	515	463	465	1633	1625	1631	1626	3264	3251	2096	2090	3726	3717
	600	540	537	1635	1629	1631	1640	3267	3269	2176	2165	3807	3806
	720	649	656	1631	1619	1633	1643	3263	3262	2280	2275	3912	3918
	900	810	815	1633	1631	1641	1656	3274	3288	2443	2446	4084	4103
1900	360	324	323	1735	1725	1729	1736	3465	3461	2059	2048	3788	3784
	400	362	358	1722	1720	1724	1724	3446	3445	2084	2078	3808	3803
	450	411	403	1736	1723	1733	1718	3469	3441	2147	2125	3880	3844
	515	466	464	1728	1735	1734	1746	3463	3481	2194	2198	3928	3945
	600	544	539	1731	1740	1742	1752	3473	3492	2274	2279	4016	4031
	720	665	663	1716	1720	1729	1738	3444	3458	2381	2383	4109	4121
	900	824	820	1730	1702	1750	1730	3480	3432	2554	2522	4303	4252
2000	360	325	325	1828	1822	1825	1821	3652	3643	2153	2146	3978	3967
	400	361	361	1816	1823	1815	1838	3631	3661	2177	2184	3992	4021
	450	409	407	1825	1813	1822	1819	3647	3633	2233	2220	4056	4039
	515	472	462	1815	1811	1815	1820	3630	3631	2287	2273	4102	4094
	600	542	544	1801	1811	1807	1815	3608	3626	2344	2355	4150	4170
	720	652	652	1812	1793	1820	1814	3632	3607	2464	2445	4284	4259
	900	811	812	1804	1774	1833	1827	3637	3601	2615	2586	4448	4413
2100	360	328	321	1906	1911	1896	1914	3802	3825	2234	2232	4130	4146
	400	367	368	1916	1915	1899	1921	3814	3837	2283	2283	4181	4205
	450	411	415	1916	1917	1915	1932	3832	3849	2327	2333	4242	4265
	515	468	462	1898	1922	1905	1923	3803	3845	2366	2384	4271	4307
	600	539	548	1903	1907	1912	1924	3814	3831	2442	2455	4354	4380
	720	655	650	1902	1892	1916	1931	3819	3823	2558	2542	4474	4473
	900	835	813	1839	1841	1943	1959	3783	3800	2675	2654	4618	4614

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 18. Measured Ramp and Freeway Main Lane Flow Rates Upstream of Ramp Control Signal Installation — 1500-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Ramp Flow Rate (vph)		Freeway Main Lane Flow Rate (vph): Outside Lane		Freeway Main Lane Flow Rate (vph): Inside Lane		Freeway Main Lane Flow Rate (vph): Both Lanes		Ramp + Outside Freeway Lane Flow Rate (vph)		Ramp + Both Freeway Lanes Flow Rate (vph)	
		Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter	Without Ramp Meter	With Ramp Meter
2200	360	326	325	1999	2005	2001	2010	3999	4015	2324	2330	4325	4340
	400	367	365	1993	1978	1990	1991	3984	3969	2360	2343	4351	4334
	450	408	416	2009	1994	2003	1998	4013	3992	2417	2410	4420	4408
	515	472	463	1996	1996	2003	2027	3999	4022	2468	2459	4471	4485
	600	546	542	1983	1984	2013	2019	3995	4003	2529	2527	4542	4546
	720	649	663	1965	1950	2008	2030	3973	3980	2614	2613	4622	4643
	900	811	809	1853	1851	1981	2020	3835	3872	2664	2660	4645	4680
2300	360	330	326	2101	2064	2098	2073	4199	4138	2431	2391	4529	4464
	400	361	358	2101	2092	2097	2098	4198	4190	2463	2450	4560	4549
	450	411	401	2083	2061	2094	2090	4177	4151	2494	2463	4588	4553
	515	468	471	2073	2064	2088	2092	4161	4156	2541	2535	4629	4627
	600	544	548	2043	2044	2081	2095	4124	4139	2587	2593	4669	4687
	720	661	642	1970	1955	2040	2068	4009	4023	2631	2596	4670	4665
	900	814	809	1850	1836	1983	2029	3833	3866	2665	2645	4648	4674
2400	360	323	322	2157	2144	2177	2160	4334	4304	2480	2466	4856	4626
	400	364	363	2151	2157	2159	2182	4311	4338	2515	2519	4675	4701
	450	413	405	2129	2137	2137	2173	4266	4310	2542	2542	4679	4715
	515	470	463	2107	2102	2140	2160	4246	4262	2577	2565	4717	4725
	600	*549*	*537*	*2038*	*2049*	*2086*	*2123*	*4124*	*4172*	*2587*	*2586*	*4674*	*4709*
	720	*653*	*662*	*1972*	*1952*	*2041*	*2087*	*4013*	*4038*	*2624*	*2613*	*4666*	*4700*
	900	826	809	1844	1845	1993	2031	3838	3876	2670	2654	4663	4685

XXX Represents conditions where the average running speed on the freeway was statistically significant with ramp metering rather than without ramp metering (95% confidence level).

Table 19. Development of Minimum Freeway Volume Thresholds for Installing Ramp Control Signals.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Minimum Main Lane Flow Rate Resulting in Statistically Significant Change in Average Running Speed on Freeway (vph)			
		Right Lane	Left Lane	Total	Average per Lane
500-Foot Ramp Acceleration Lane Length					
1800	900	1531	1720	3251	1625
1900	900	1536	1819	3355	1677
2000	900	1525	1863	3388	1694
2100	900	1540	1882	3422	1711
2200	900	1518	1877	3395	1697
2300	900	1481	1876	3357	1678
2400	900	1503	1891	3395	1697
				Average	**1683**
750-Foot Ramp Acceleration Lane Length					
1800	900	1575	1673	3242	1621
1900	900	1611	1780	3391	1696
2000	900	1619	1836	3495	1748
2100	900	1594	1861	3455	1728
2200	900	1575	1871	3446	1723
2300	900	1595	1883	3477	1739
2400	900	1558	1874	3431	1716
				Average	**1710**
1000-Foot Ramp Acceleration Lane Length					
1800	900	-	-	-	-
1900	900	-	-	-	-
2000	900	1705	1866	3571	1786
2100	900	1689	1827	3516	1758
2200	900	1714	1955	3670	1835
2300	900	1700	1951	3652	1826
2400	900	1699	1958	3657	1829
				Average	**1807**
1250-Foot Ramp Acceleration Lane Length					
1800	900	-	-	-	-
1900	900	-	-	-	-
2000	900	1787	1848	3635	1818
2100	900	1816	1935	3751	1876
2200	900	1813	1959	3772	1886
2300	900	1789	1957	3746	1873
2400	900	1789	1953	3742	1871
				Average	**1865**
1500-Foot Ramp Acceleration Lane Length					
1800	900	-	-	-	-
1900	900	-	-	-	-
2000	900	-	-	-	-
2100	900	-	-	-	-
2200	900	-	-	-	-
2300	900	-	-	-	-
2400	900	1844	1993	3838	1919
				Average	**1919**

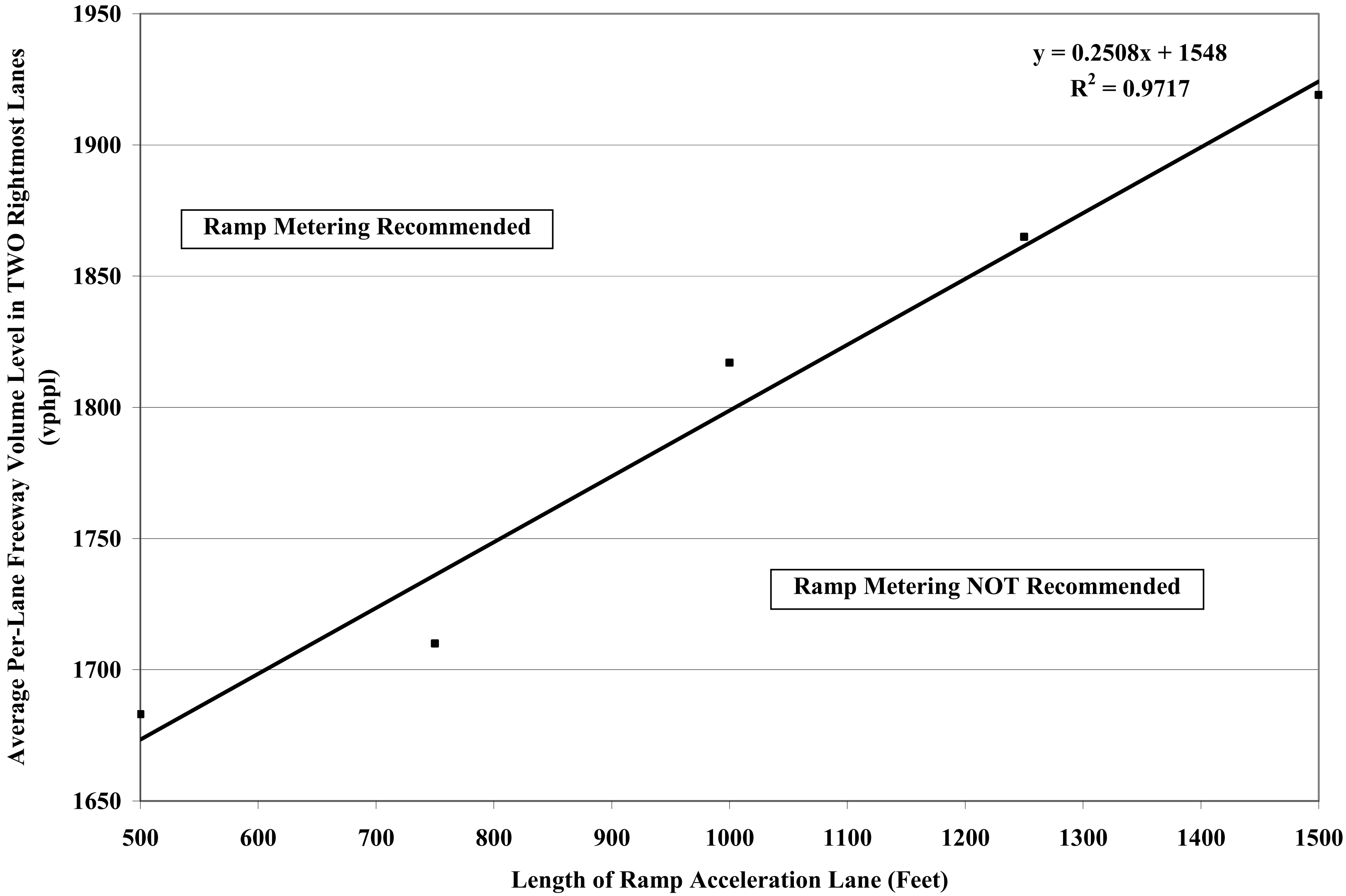


Figure 6. Plot of Freeway Volume Criteria (Average of Two Rightmost Lanes) for Installing Ramp Control Signals.

We used a similar process for identifying the combined freeway and ramp volume criteria. Clearly the simulation shows that the interaction between the entering ramp traffic and the traffic traveling in the rightmost lane of the freeway influences freeway performance. As the combination of the traffic in the rightmost lane and the entering ramp traffic approaches the downstream capacity of the freeway, the overall performance of the freeway declines. If traffic volumes on the freeway are high, then less traffic can enter the freeway from the entrance ramp before disrupting traffic flow on the freeway. If traffic volumes on the freeway are relatively light (compared to capacity flow), then the average running speed remains relatively high. Therefore, we used Table 14 through Table 18 to find under which combined freeway and ramp traffic volume levels freeway performance was statistically different with the ramp control signal. Table 20 shows which combination of measured ramp and freeway volumes first resulted in a statistically higher average running speed with the ramp control signal than without. We then used averages of these conditions to develop a plot of the combined ramp plus freeway volume levels that benefited from installing a ramp control signal (see Figure 7). Figure 6 and Figure 7 form the basis for the traffic conditions criteria for installing ramp control signals.

Analysis of Queue Detector Parameter Settings

The standard ramp metering operation in Texas uses a queue detector to prevent ramp queues from spilling back into and blocking the upstream intersection or free U-turn lane. The ramp controller uses two parameters — queue-on and queue-off thresholds — for this purpose. In general, the standard queue control mechanism operates as follow:

- When in normal operation, the controller begins flush operation if the queue detector is continuously occupied for a duration (in seconds) greater than or equal to the queue-on threshold specified by the user.
- During the flush operation, the signal head remains dark, and the ramp vehicle entry onto the freeway is controlled by the vehicle arrival rate and freeway merge capacity.
- A flush operation terminates if the queue detector is continuously unoccupied for a duration less than or equal to the queue-off threshold.
- When coming out of a flush operation, the controller displays a continuous green signal for 15 seconds (called startup green) before resuming normal metering cycles of green, yellow, and red signal indications.

Table 20. Development of Combination Ramp plus Main Lane Volume Threshold for Installing Ramp Control Signal.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Combination of Ramp and Main Lane Flow Rate Resulting in Statistically Significant Change in Average Running Speed on Freeway		
		Ramp Volume (vph)	Freeway Outside Lane Volume (vph)	Ramp plus Outside Freeway Lane Volume (vph)
500-Foot Ramp Acceleration Lane Length				
1800	900	816	1531	2347
1900	600	544	1687	2231
2000	600	547	1764	2311
2100	515	471	1863	2334
2200	450	412	1946	2358
2300	450	413	1987	2401
2400	400	368	2022	2390
			Average (vph)	**2338**
750-Foot Ramp Acceleration Lane Length				
1800	900	814	1575	2388
1900	900	821	1611	2432
2000	720	657	1761	2418
2100	720	663	1767	2430
2200	515	477	1957	2434
2300	400	371	2060	2431
2400	360	324	2129	2453
			Average (vph)	**2412**
1000-Foot Ramp Acceleration Lane Length				
1800	-	-	-	-
1900	-	-	-	-
2000	900	817	1705	2522
2100	720	656	1834	2490
2200	720	649	1862	2511
2300	600	548	1951	2498
2400	515	464	2025	2490
			Average (vph)	**2502**
1250-Foot Ramp Acceleration Lane Length				
1800	-	-	-	-
1900	-	-	-	-
2000	900	818	1787	2605
2100	720	648	1891	2538
2200	720	656	1925	2581
2300	720	654	1935	2589
2400	450	109	2121	2527
			Average (vph)	**2568**
1500-Foot Ramp Acceleration Lane Length				
1800	-	-	-	-
1900	-	-	-	-
2000	-	-	-	-
2100	-	-	-	-
2200	-	-	-	-
2300	-	-	-	-
2400	600	549	2038	2587
			Average (vph)	**2587**

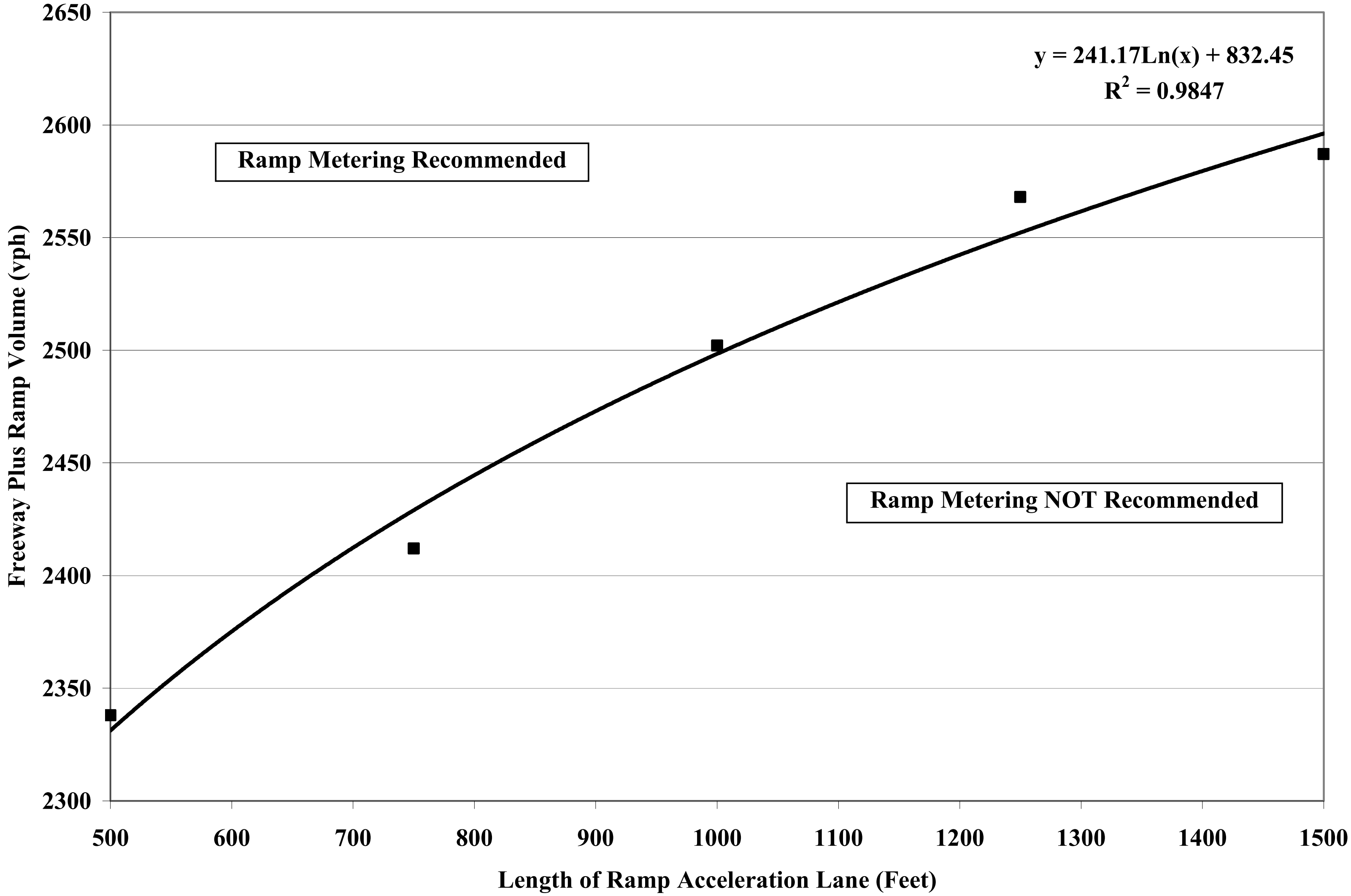


Figure 7. Plot of Combined Ramp plus Freeway (Outside Lane) Volume Criteria for Installing Ramp Control Signals.

The value of the queue-on threshold must be selected to maximize the total metering time and to prevent queues from causing safety and operational problems at upstream facilities. The value of the queue-on threshold should be selected to prevent premature termination of the flush operation, while ensuring that the normal operation resumes as the last vehicle in the queue clears. Although these desirable features are recognized, no formal investigation has ever been conducted to study the sensitivities of these important parameters. Researchers used VISSIM®-based computer simulations to study these factors.

As shown in Figure 8, the VISSIM® simulation used a simple geometry very similar to typical on-ramps in Houston.

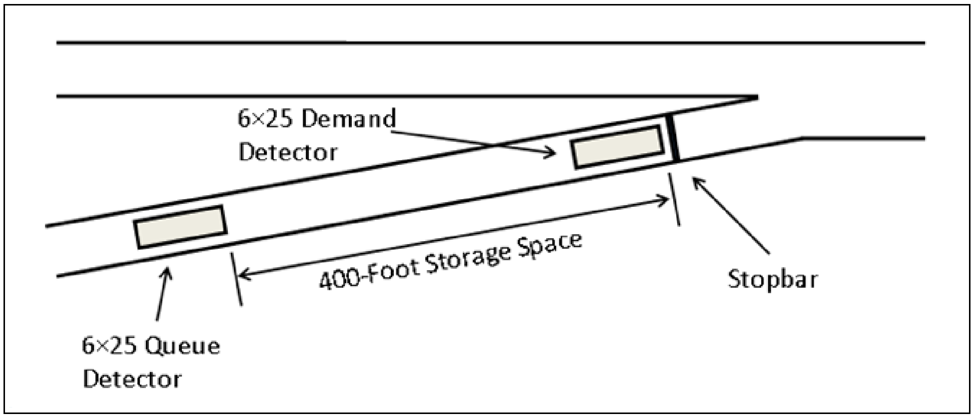


Figure 8. Geometry of Simulated System.

In VISSIM®, the ramp metering operation was provided by a VAP developed for use in this project. VAP is a VISSIM® feature to allow simulation of custom control algorithms. Because the objective of this subtask was to study performance measures related to ramp operation, all simulations were conducted on an isolated ramp using several different freeway capacity–related factors. The following factors were studied:

- ramp demands (or arrival rates) of 900, 1000, 1100, 1200, 1300, 1400, and 1500 vph;
- queue-on thresholds of 7, 8, 9, 10, 11, and 12 seconds; and
- queue-off thresholds of 2, 2.5, 3, 3.5, and 4 seconds.

To further simplify the simulation and data analysis process, only one metering (service) rate of 900 vph was used. Combined with the above demands, this value resulted in demand-minus-capacity (D-M) scenarios ranging from 0 to 600 vph. Thus, there were 210 unique scenarios. Each of these scenarios was simulated for 5 hours, and VISSIM® was configured to report the maximum ramp queue during each successive 5-minute period. Thus, each simulation produced 60 samples for the maximum queue. From these 5-minute data, researchers calculated 85th percentile maximum (max) queue, average max queue, and standard deviation (SD). In addition, they used the VAP to collect flush data for each simulation run, and processed that data further to obtain the number of flushes, mean flush time, standard deviation of flush time, and meter availability. Meter availability is the percent of total metering time a meter is operating as intended (*32*). Because a startup time of 15 seconds after each flush is the effective flush time, they added 15 seconds to the total flush (dark) time at the end of each flush. Figure 9 reproduces a meter efficiency diagram developed by Chaudhary and Messer (*32*) using a simple analytical approach that did not incorporate excess queue-flush operation. This theoretical figure will be useful for comparison purposes and to assess how simulation and real data match the three quality measures of good, fair, and fail identified in this figure.

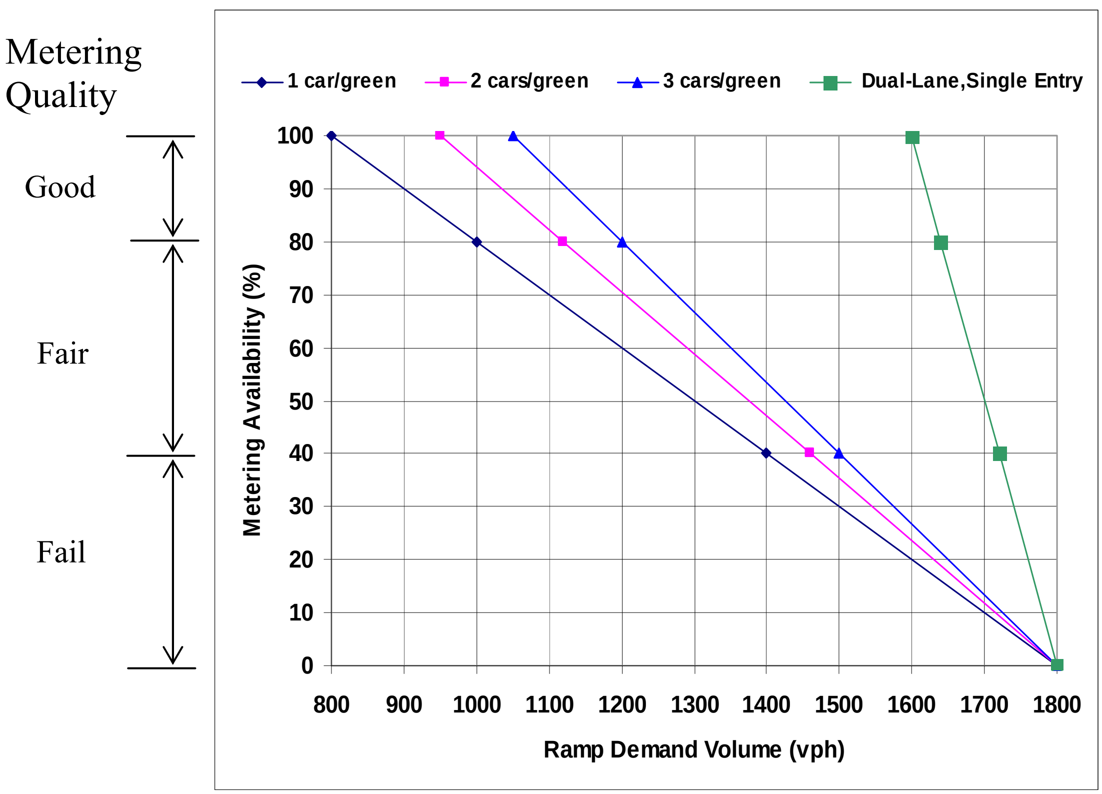


Figure 9. Metering Quality of Ramp Metering Strategies for Various Ramp Demands (*33*).

In Houston, many ramps experience peak-hour demands in the range of 1100 to 1200 vph. Therefore, it is worthwhile to look at some simulation results for a case in this demand range. Figure 10 shows the 85th percentile maximum queue for a case where demand (average arrival rate) is more than the service (or metering) (D-M) rate by 200 vph, which is equivalent to a demand of 1100 vph and metering rate of 900 vph. As shown in this figure, increasing the queue-on threshold from 7 to 12 seconds causes the 85th percentile queue to grow from an average value (across all queue-off thresholds) of approximately 500 feet to almost 600 feet. This means that sluggish detection of the queue condition results in longer queues. As shown in Figure 11 and Figure 12, the logical consequences of such operation are fewer and longer flushes.

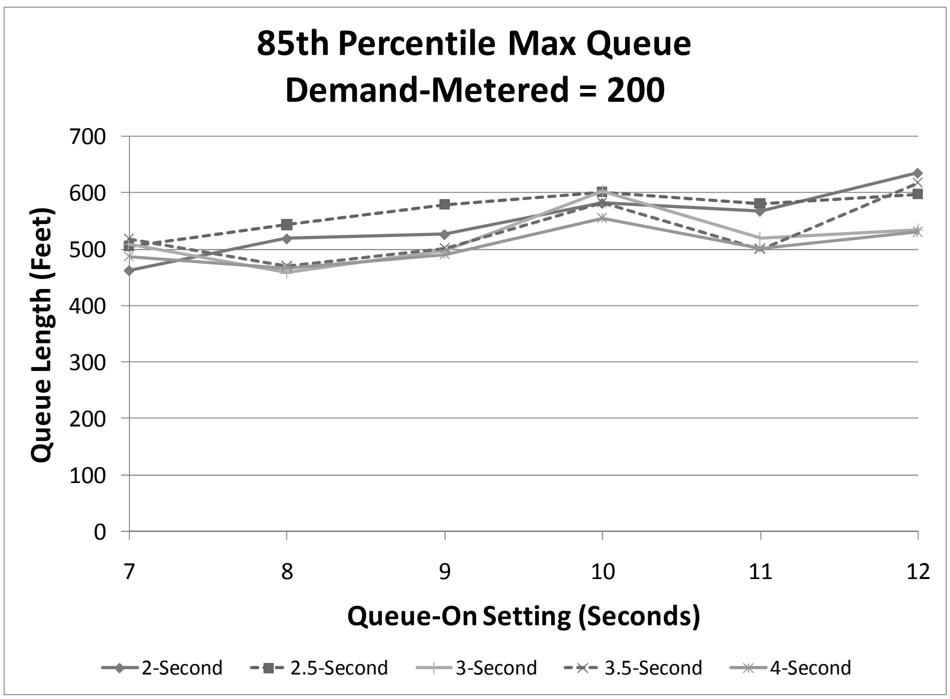


Figure 10. Five-Minute Queue Statistics for 1100-vph Demand Scenario.

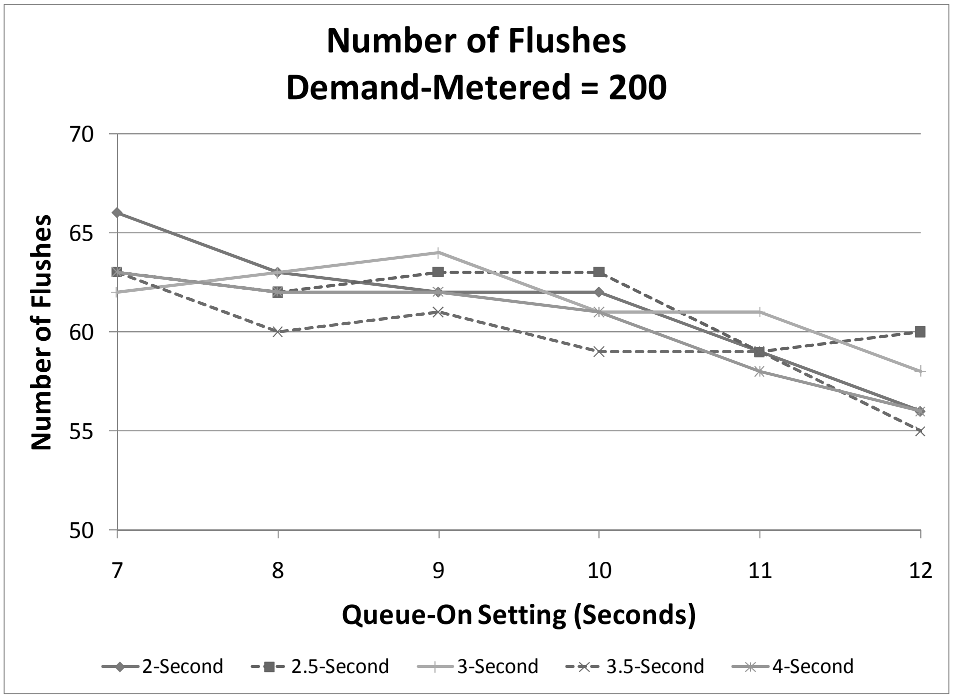


Figure 11. Number of Flushes for 1100-vph Demand Scenario.

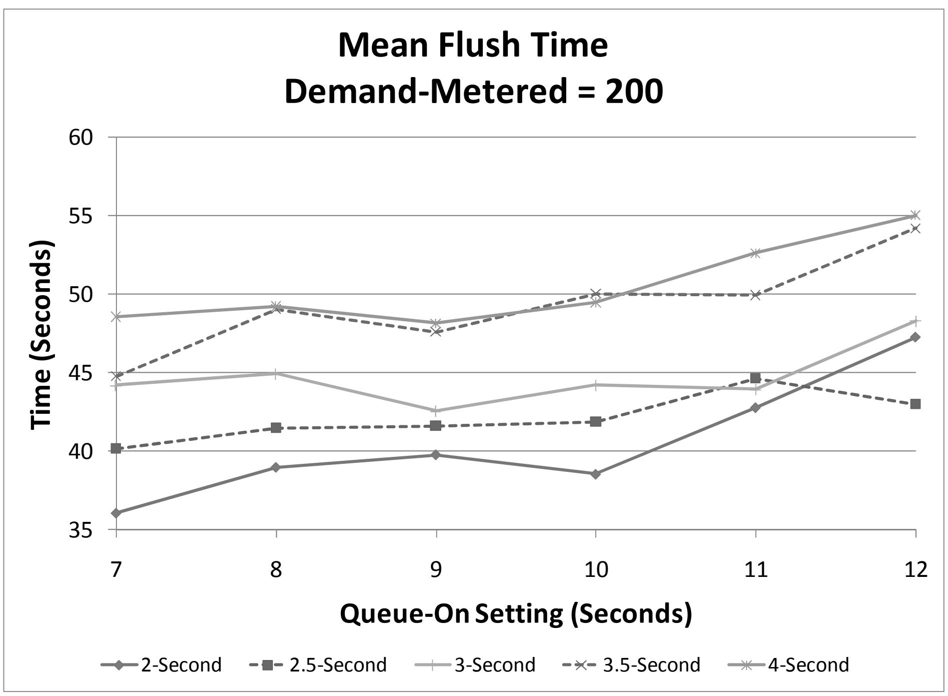


Figure 12. Mean Flush Time for 1100-vph Demand Scenario.

Appendix C provides plots of 85th percentile queue statistics for all scenarios simulated. From these plots, it is evident that queue-on threshold settings of 9 seconds or less can effectively contain the 85th percentile maximum queue within an 800-foot distance from the meter (or 400 feet upstream of the queue detector). A more aggressive resumption of metering by selecting a smaller value of queue-off threshold can further contain this queue to within 600 feet of the stopbar (queue detector).

Meter availability (the percent of time a meter is operating normally) is a key indicator of the effectiveness of a ramp meter. Meter availability is a function of demand, capacity, and queue thresholds. Appendix D provides meter availability plots for all scenarios studied. As can be seen by inspecting these plots, for scenarios with low D-M values, there is little difference between the values of the two queue thresholds, and the meter availability is high. However, as D-M starts to increase, meter availability starts to decrease, and the impact of various values of queue thresholds starts to become visible, with a clear distinction between the queue-off thresholds, showing that a value of 2 seconds for this threshold provides the best meter availability. Thus, simulation results support the superiority of field-tuned queue-on and queue-off values of 9 and 2 seconds, respectively. Figure 13 compares the meter availability of simulated results corresponding to a queue-off threshold equal to 2 seconds against a theoretical meter availability of one-car-per-green metering from Figure 9. Note that simulation shows higher meter availabilities than the theoretical computation does. There is no significant difference between various values of the queue-on threshold in the 7- to 10-second range. Furthermore, these values drop at a lower rate than the theoretical values with increases in demand. This difference is due to the modeling of the queue flush mechanism, which is absent from the previous analysis by Chaudhary and Messer (*32*). The results for other queue-off settings produced similar but slightly different slopes. Figure 14 illustrates these differences for a fixed queue-on setting of 9 seconds. This figure shows that smaller values of the queue-off threshold produce higher availability with more pronounced differences at higher demands. As stated previously, a value of 2 seconds for the queue-off threshold works well in the field with a 25-foot queue detector.

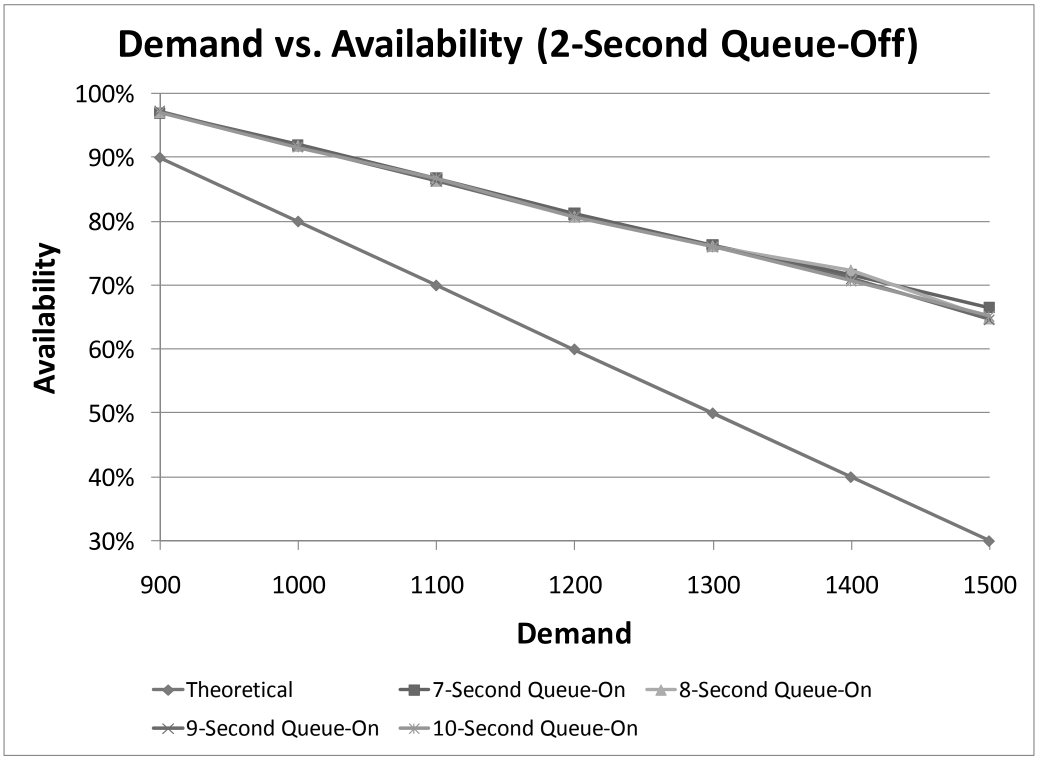


Figure 13. Meter Availability for Scenarios with Queue-Off Threshold of 2 Seconds.

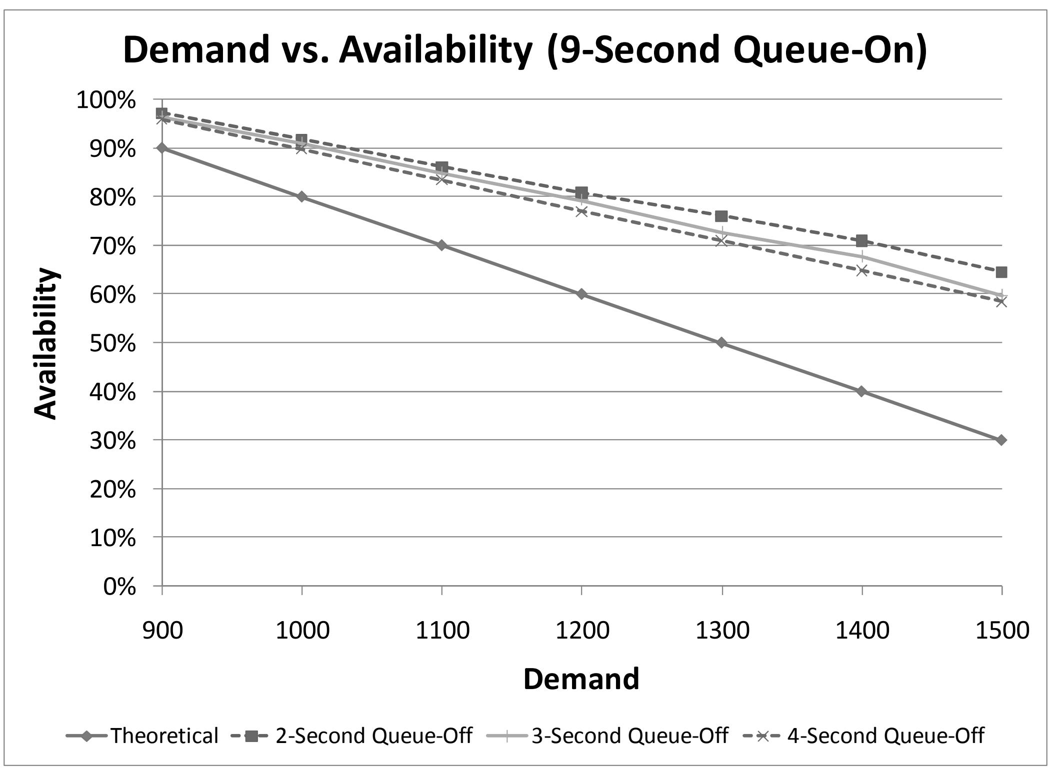


Figure 14. Meter Availability for Scenarios with 9-Second Queue-On Threshold.

ANALYSIS OF ALTERNATIVES TO FLUSHING RAMP CONTROL SIGNALS

The researchers conducted a simulation study to evaluate the effectiveness of the current ramp metering operations as well as to explore alternative strategies for improving current meter operations.

Study Location

Two ramp meters in the Houston metropolitan area were recently activated. The first meter was located at the entrance ramp of I-610 West Loop and North Braeswood Boulevard. The second meter was located at the entrance ramp of I-610 West Loop and Beechnut Street. Both meters were installed to meter the ramp traffic going northbound on I-610 West Loop. The locations of both meters are shown in Figure 15. For brevity, these two ramps are referred to as Braeswood and Beechnut ramps.

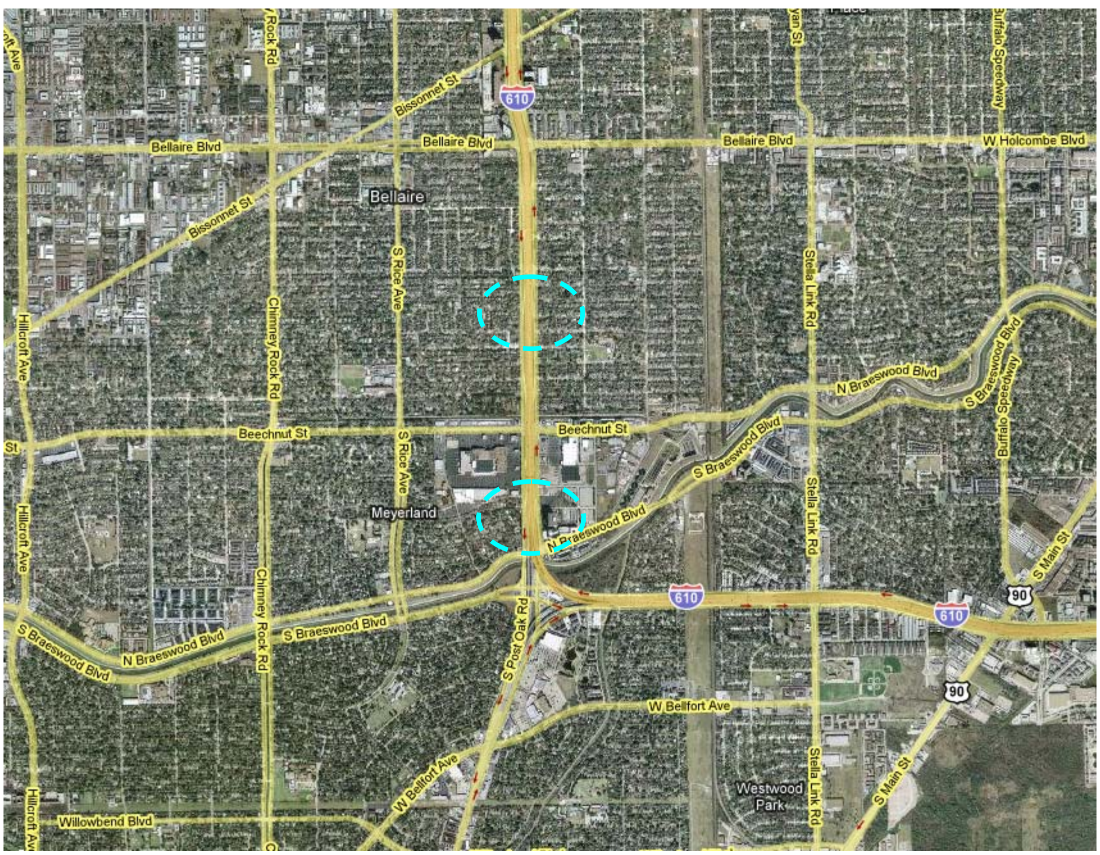


Figure 15. Study Locations.

Currently both ramp meters are operating on a fixed-time basis from 6:45 a.m. to 9:00 a.m. every weekday. The flush mode is also in use at both locations. If the queue detector is continuously occupied for a specific amount of time (configurable in the controller), the ramp signal will go into flush mode (dark mode) to clear the on-ramp queue. Once the queue has been cleared or the queue detector is unoccupied for a specified period, the meter will resume normal metering operations with a constant 15-second solid green followed by normal cycling based on demand detector actuation.

Simulation Model and Calibration

The researchers used VISSIM® microscopic simulation software to conduct the simulation in this study. Both ramp meters were coded into VISSIM® along with the I-610 freeway segment. The ramp geometry and the placement of the actual detector and stopline were measured in the field and then coded into the VISSIM® network. Then, VAP files were developed to control the ramp meter operations. These customized VAP files are commonly used in signal operations to change and evaluate various parameters and test new strategies that are not commonly available within off-the-shelf modules in the simulation software. The following are the key features of the VAP files designed to control both ramp meters in this simulation:

- The VAP files were designed to mimic the current cycling and flushing operations of both ramps.
- Each VAP file is independent of each other. Therefore, the changes can be made individually, and the new strategies can be tested independently at each ramp meter controller.

The following are the ramp operations strategies that are specifically coded in the VAP files for evaluation and testing purposes:

- Flush mode — The queue detector occupancy time is used to activate and deactivate the flush. Also, the flush mode can be turned on or off as needed.
- Fixed metering mode — The strategy allows a fixed number of vehicles to go through the ramp every cycle based on the fixed green time. The cycle length and the green time can be configured as needed. Bulk metering is a strategy that allows multiple cars to go through the signal in each cycle.

- Variable metering mode — This strategy allows a meter to switch between single-car-per-green and bulk metering modes based on the queue detector occupancy. This strategy is not currently deployed in standard ramp controllers. It was incorporated into this simulation study to evaluate its potential as an alternative to Houston's current flushing operations.

The following are specific VAP parameters that are configurable in the simulation process:

- Ramp meter on and off times — The simulation network was coded to simulate the 4-hour traffic volume from 6 a.m. to 10 a.m. on this freeway segment. The ramp meters can be turned on and off based on a simulation timer to reflect the current time-of-day meter operation.
- Queue flush mode — The flush mode can be turned on and off as needed. This feature aimed at evaluating the impacts of flushing on freeway traffic.
- Queue activation threshold — The queue detector must be continuously occupied by the specified threshold to the trigger flush mode or bulk metering.
- Queue deactivation threshold — The queue detector must be in flush mode or bulk metering mode and continuously unoccupied by the specified threshold in order to resume normal cycling (typically one-car-per-green metering).
- Steady green period after dark flush — The green interval is set at 15 seconds to reflect current meter operations.

The VISSIM® model was calibrated as follows:

- Freeway traffic volumes were obtained from a Wavetronix SmartSensor radar installed upstream of the Braeswood entrance ramp. The volume data on weekdays were retrieved and then aggregated into 15-minute intervals. Then, researchers averaged the volume data from Monday to Friday and constructed a 15-minute volume profile, which was used as volume inputs for freeway traffic in VISSIM®. Although the traffic patterns could vary during the weekdays, the use of an average profile does not invalidate the results because the analysis focused mainly on comparative evaluation (e.g., with and without flush modes).
- Ramp traffic volumes were obtained from actual merge detector counts from both ramps. Researchers installed a specialized computer inside a cabinet for each ramp

and logged the actuation events observed at the demand, queue, and merge detectors. They post-processed these data logs to retrieve the counts observed at each detector by time of day. The data from the merge detector was used because the counts are least affected by the queue and stop-and-go vehicles. Since researchers started logging the data before the ramp meters were actually installed, they had data from both pre- and post-meter operations at both ramps. The volume data from the pre-meter operations were used in the simulation since they represent the actual on-ramp demand and are unaffected by ramp metering.

- Ramp meter controller parameters were specified in the VAP files using the same configurations as in the actual controllers. In the first few weeks of operations, the meters were active from 6:45 a.m. to 9:00 a.m. The meters were then changed to 6:30 a.m. to 9:00 a.m. on April 8, 2008. The queue activation and deactivation occupancy thresholds were set at 8 and 2 seconds, respectively.

The volume profiles obtained were then adjusted and rounded to simplify the process of entering the data into VISSIM®. Table 21 summarizes the volume inputs used in the VISSIM® simulation for both ramp and main lanes. Table 22 provides the ramp meter controller settings and the date that the settings became effective.

Table 21. VISSIM® Volume Inputs.

Actual Time (Interval End)	Simulation Time	Actual Vehicle Count			Simplified VISSIM® Input		
		Main Lane	Braeswood	Beechnut	Main Lane	Braeswood	Beechnut
6:15	900	5056	268	288	5000	300	300
6:30	1800	6708	396	312	6800	350	350
6:45	2700	7900	568	488	8000	550	550
7:00	3600	8852	712	704	8800	700	700
7:15	4500	8892	872	848	8800	850	850
7:30	5400	8864	1124	1252	8800	1200	1200
7:45	6300	77608	1208	1276	7600	1250	1250
8:00	7200	6992	1232	1600	7000	1250	1250
8:15	8100	7152	1240	1216	7200	1250	1250
8:30	9000	7844	1000	1108	7800	1050	1050
8:45	9900	7808	808	820	7800	800	800
9:00	10800	7004	748	744	7000	750	750
9:15	11700	6104	612	856	6200	750	750
9:30	12600	5852	596	728	5800	650	650
9:45	13500	5648	572	704	5600	650	650
10:00	14400	5676	504	600	5600	550	550

Table 22. Ramp Meter Controller Parameters.

Parameters	Braeswood		Beechnut	
	02/26/2008	04/08/2008	02/26/2008	04/08/2008
Queue-On to Begin Flush	9	8	9	8
Queue-Off to Resume Metering	2	2	2	2
Ramp Metering On	6:45 a.m.	6:30 a.m.	6:45 a.m.	6:30 a.m.
Ramp Metering Off	9:00 a.m.	9:00 a.m.	9:00 a.m.	9:00 a.m.

Using the VISSIM® simulation and the developed VAP files, the following operations strategies were examined:

- No metering — This is a base case that represents the operations prior to the installation of both meters.
- Fixed metering: single car per green without flushing — A 4-second cycle length (1/1/2 for green, yellow, and minimum red time) is used in this scenario with the flush mode off. This scenario was simulated to determine the impacts of flushing operations.
- Fixed metering: single car per green with flushing — A 4-second cycle length is used with the flush mode active. This scenario mimics current ramp meter operations. The meter will go into dark flush when the queue activation threshold is reached and will resume metering again with a 15-second steady green followed by normal cycling when the queue deactivation threshold is reached.
- Variable metering — This strategy was considered as an alternative to flushing operations. The meter switches between single-car-per-green and bulk metering instead of going into flush mode using the queue detector occupancy. In the bulk metering mode, the green time and overall cycle length are lengthened to accommodate more vehicles per cycle. While the flush mode will not be used, the bulk metering in this strategy can be viewed as a mini-flush. It is a compromise option between no flush and full flush (dark flush until the queue is cleared). The steady green used when coming out of dark flush is not needed in this case. The variable metering strategies are denoted as 1/2 if the meter switches between one-vehicle-per-green car and two-vehicles-per-green. The strategies evaluated were 1/2, 1/3, and 1/4, and the cycle length settings were 4/7, 4/10, and 4/12 (green

interval/clearance interval), respectively. These settings are taken from recommendations provided in the previous study (*33*).

The simulation was programmed to simulate the operations from 6 a.m. to 10 a.m., but the simulation data were logged for two separate periods:

- Entire simulation period — This includes the periods before and after the active ramp metering period.
- Active ramp metering period — This logs the data only during the active ramp metering period.

The following provides a list of measures of effectiveness collected from the simulation. Both mean and standard deviation were obtained for each MOE from multiple simulation runs.

- Main lane throughput (vph) — A number of vehicles passing through the freeway segment are measured at a location downstream of the Beechnut ramp.
- Main lane travel time — The time is collected by defining a travel time segment (defined by origin-destination pair) in VISSIM®.
- Main lane speed — The speed is calculated by dividing the segment length with the travel time.
- Mainlane speed variation — This measure represents the fluctuation of mainlane traffic flow over time. A large speed variation would indicate instability in the traffic stream resulting from frequent stop-and-go traffic conditions. This measure, also known as coefficient of variation in speed (CVS), is calculated by taking the standard deviation of 5-minute average speed over the simulation period and then dividing by the mean speed. Its safety implication was previously examined in recent TTI studies (*34, 35*).
- Average delay — The delay was retrieved directly from the simulation, which is the difference between actual and ideal travel times. The delay is linked to the travel time segment. In this study, the researchers specifically collected the delay for the main lane vehicles, the ramp vehicles, and the system (combined main lane and ramp vehicles).
- Ramp queue length — The queue length was measured in feet and was obtained directly from the simulation. In the simulation, the vehicles are considered joining the queue when their speeds drop below a configurable threshold (e.g., 3 mph).

Simulation Runs

Figure 16 graphically shows an example of MOEs collected from the simulation. In the figure, the speed profiles for fixed metering with flushing and no metering are very similar. The speed profile shifted higher when the flush mode was turned off. Several operations scenarios were evaluated with several combinations of queue activation and deactivation settings. Five simulation runs were carried out for each scenario. Table 23 presents a selected list of simulation scenarios discussed in the next section.

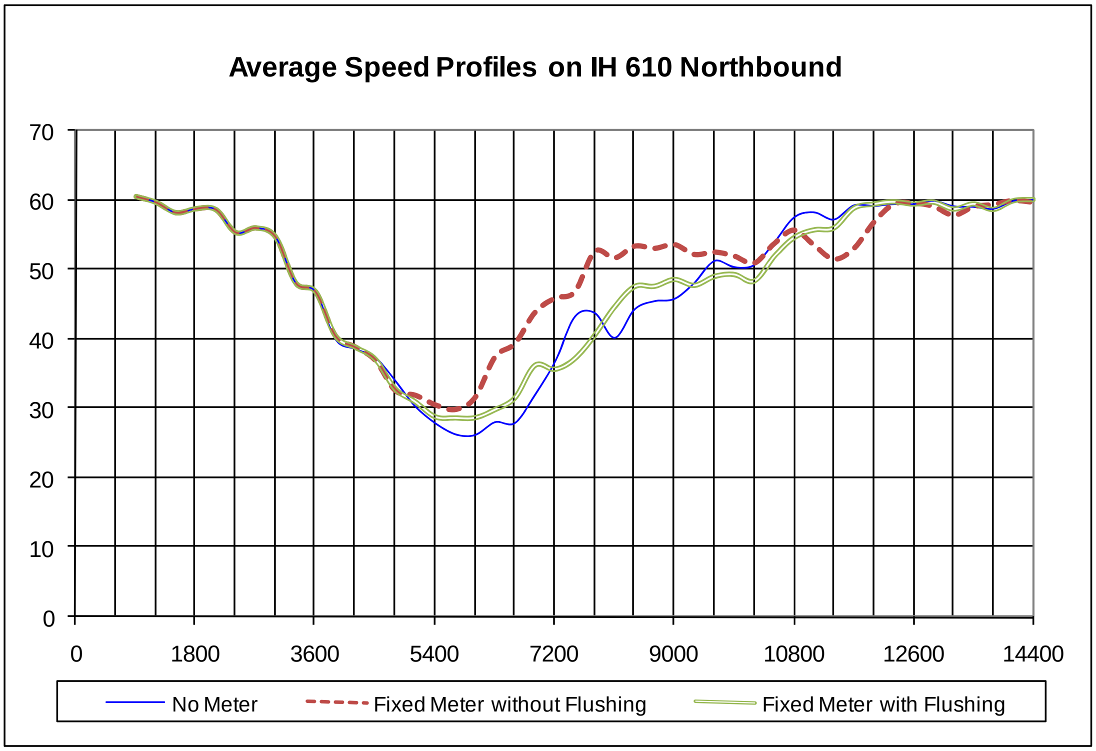


Figure 16. Example of Simulation Results.

Table 23. Selected Simulation Scenarios.

Scenario	Meter Strategy	Active Metering	Fixed Rate	Variable Meter (Vehicles per Green)	Queue Activate	Queue Deactivate	Cycle Settings
1	No Meter	NA	900	NA	NA	NA	NA
2	Fixed	No	900	NA	NA	NA	4
3	Fixed	Yes	900	NA	10	3	4
4	Variable	NA	NA	1 and 2	10	3	4 and 7
5	Variable	NA	NA	1 and 2	10	5	4 and 7
6	Variable	NA	NA	1 and 2	10	7	4 and 7
7	Variable	NA	NA	1 and 3	10	5	4 and 10
8	Variable	NA	NA	1 and 4	10	5	4 and 12

Results and Findings

The primary objective of a ramp control signal is to improve the traffic flow conditions on the freeway main lane. For this reason, an increase in freeway main lane throughput and speed and a decrease in freeway main lane average delay and average CVS would be an indicator of effective ramp control signal operations. Table 24 summarizes selected MOEs obtained from selected simulation scenarios.

Table 24. Selected Simulation Results.

Scenario	Main Lane Throughput (vph)	Weighted Average Main Lane Speed (mph)	Main Lane Average Delay (Seconds/Vehicle)	Main Lane CVS (%)
1	7947	26.62	387.24	40.80
2	7791	29.68*	338.22*	36.79*
3	7849	27.10**	393.16**	45.41**
4	7832	28.72***	360.70	40.40
5	7881	28.63	358.72***	39.98***
6	7860	28.39	362.41	40.62
7	7856	27.63	378.15	42.61
8	7928	27.87	373.46	42.32

*Current Operation
** Next Best Strategy without Flushing
*** Next Best Strategy with Variable Metering
Note: Evaluation results are based on active ramp metering period.

The following are what the researchers observed from the simulation results:

- Scenarios 1 and 3 represent the freeway conditions pre-signal and post-signal installation, respectively. The differences in the MOEs are negligible. In fact, the average speed on the freeway main lanes increases by only 1.8 percent after the ramp control signal was installed, while the average delay on the freeway main lanes increased by 1.5 percent. There was also no evidence for an improvement in the flow smoothness as indicated by an unexpected increase in CVS value. Researchers hypothesize that the conditions were not improved because of frequent flushes.
- Compare scenarios 2 and 3 where the flush mode was turned off in the former and turned on in the latter (current operations). The main lane traffic conditions have improved by allowing the ramp control signal to continue to operate. By turning off the flush mode and leaving the meter to run in one-car-per-green cycling, the main lane average speed increases by 9.5 percent, and the average delay decreases by

14.0 percent. The smoothness of the flow as measured by CVS also shows a 19.0 percent improvement.

- Turning off the flush mode may not always be a viable option in practice because of potential queue spillbacks to the upstream intersections. We tested multiple variable meter strategies, i.e., mini-flushes, in which the ramp control signal was allowed to switch between one-vehicle-per-green and multiple-vehicles-per green. Of these strategies, we found the variable metering strategy that allowed the ramp control signal to switch between one-car-per-green and two-car-per-green when the queue detector is occupied to be the next best alternative (short of not allowing the ramp to flush at all) in terms of performance on freeway traffic. We expected to see this result because switching between one-vehicle-per-green to two-vehicles-per-green is the most restrictive metering among the variable metering strategies considered.
- The queue activation and deactivation thresholds also have an impact on the MOEs of the operations in the variable metering mode. A longer queue deactivation threshold implies that the ramp control signal will stay in a bulk metering mode for a longer time since it would take a longer gap within the ramp traffic stream to switch the meter back into the one-car-per-green mode.
- Degradation in the performance of the main lane traffic flows was observed when the number of cars allowed per green is increased in the variable metering mode. This can be expected because one function of a ramp control signal is to break the platoons, which becomes less effective when more cars are allowed in the bulk metering. Practically, when more cars are allowed in each cycle, the variable metering will simply become a flush mode and the main lane traffic flow will no longer benefit from the ramp metering.

From these studies, we concluded that the current meter operation with flush mode provides no improvement to the main lane traffic flow when the ramp traffic demand is heavy. Further, the simulation results also indicated that the main lane traffic conditions can actually be improved markedly by simply disallowing the flush mode. However, we realize that this may not be a viable option due to its potential excessive delays and safety implications. A variable metering strategy that switches between one-car-per-green and bulk metering showed that it has a potential as a compromise solution between the most restrictive metering (no flush) and the current practice in Houston (with flush). More study is still needed, however, to determine how the strategy could be implemented and when it should be considered.

CHAPTER 4:
FIELD STUDIES

Ramp control signals were recently deployed at two adjacent entrance ramps along I-610 West northbound in Houston, Texas. Data were collected to evaluate the effectiveness of ramp meter deployment and to quantify its operational and safety impacts on the existing traffic conditions. This chapter summarizes the collected data, analyses, results, findings, and recommendations from this field study.

DATA COLLECTION

Several technologies were used to collect field data for analyzing before and after conditions at two adjacent ramp meters in Bellaire, Texas. Figure 17 identifies the locations of various types of data collection devices.

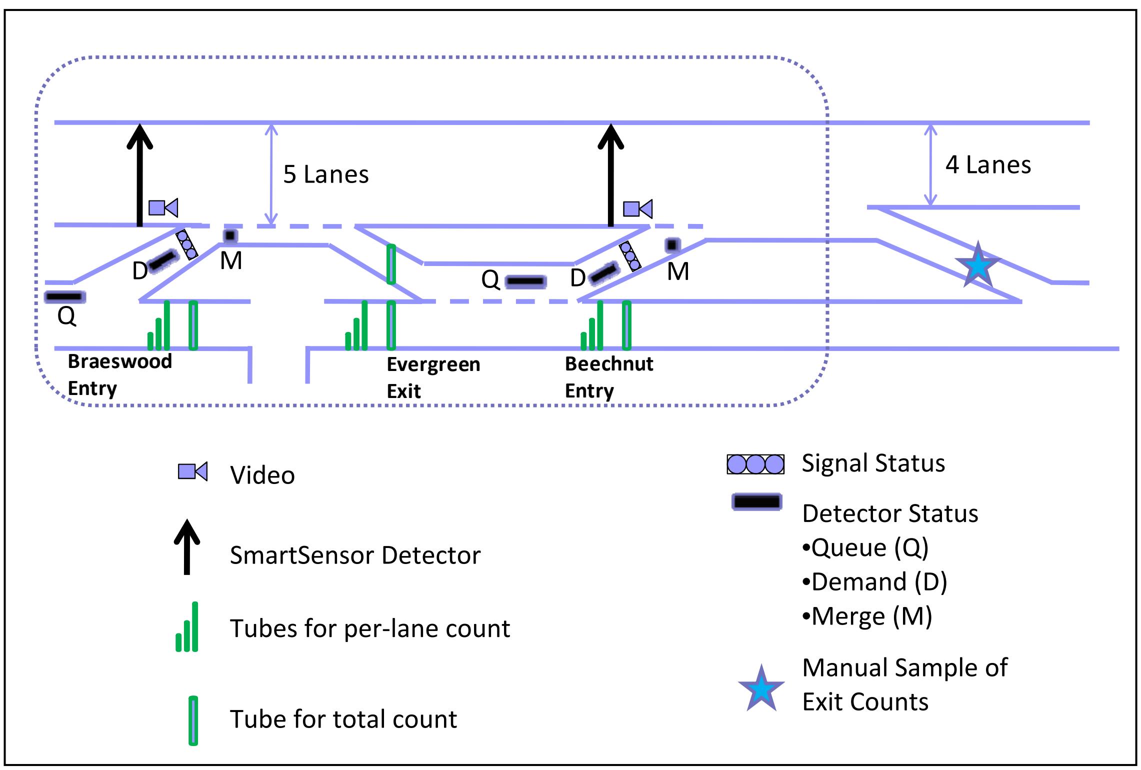


Figure 17. Technologies and Locations of Field Data Collection Devices.

In this figure, the dotted rectangle identifies the main field study area. The Evergreen exit ramp is located approximately 2700 feet downstream of the Braeswood entrance ramp, and the Beechnut entrance ramp is located about 2050 feet downstream of the Evergreen exit. As identified in the figure, the following data were collected within the main study area:

- tube counts;
- signal and detector status;
- per-lane 30-second speed, occupancy, and vehicle counts for freeway locations just upstream of each entrance ramp from SmartSensors; and
- video recording of the merge area at the two entrance ramps.

As shown in the figure, limited data were manually collected at the Beechnut exit ramp immediately downstream of the study area. This chapter provides more detailed information about the data collection and analysis of items identified in the above list.

To conduct accurate data analysis, the dates of important events were recorded. The chronological order of these events was as follows:

- The President's Day holiday was February 18, 2008.
- Ramp metering operation began February 26, 2008:
  - Meters operated from 6:45 a.m. to 9:00 a.m.
  - Initial queue-on and queue-off thresholds were set at 9 and 2 seconds, respectively.
- Daylight savings time changed March 10, 2008.
- The Houston Independent School District's spring break was March 14-24, 2008.
- TxDOT adjusted metering operation April 8, 2008.
  - The metering start time was changed from 6:45 a.m. to 6:30 a.m.
  - The queue-on threshold setting was changed to 8 seconds.

The following are the analyses conducted in this field study:

- before-after evaluation of the effects of ramp meter deployment on freeway traffic conditions,
- analysis of the effectiveness of ramp meter operations,
- analysis of traffic diversion from ramp metering, and
- analysis of safety impacts from ramp metering.

BEFORE-AFTER EVALUATION OF FREEWAY TRAFFIC CONDITIONS

TxDOT recently installed two ramp control signals along I-610 West in the northbound direction at the Braeswood and Beechnut entrance ramps. The meters aimed at improving recurrent traffic breakdowns during the morning peak period. The meters became active on Tuesday, February 26, 2008, and remain active as of October 2008. The objective of this analysis is to conduct a before-after evaluation to determine if the main lane traffic flow on this segment benefits from the ramp meter operations. A Wavetronix SmartSensor® radar installed upstream of the Braeswood ramp was used to retrieve the speed, volume, and occupancy observed from the main lane traffic. The data retrieved from the sensor were originally in 30-second intervals. These data were aggregated into 5-minute intervals to simplify the analytical process.

The typical traffic profiles prior to the ramp meter installation during the morning peak are shown in Figure 18 and Figure 19. The data from Wednesday, February 6, 2008, were used in this example.

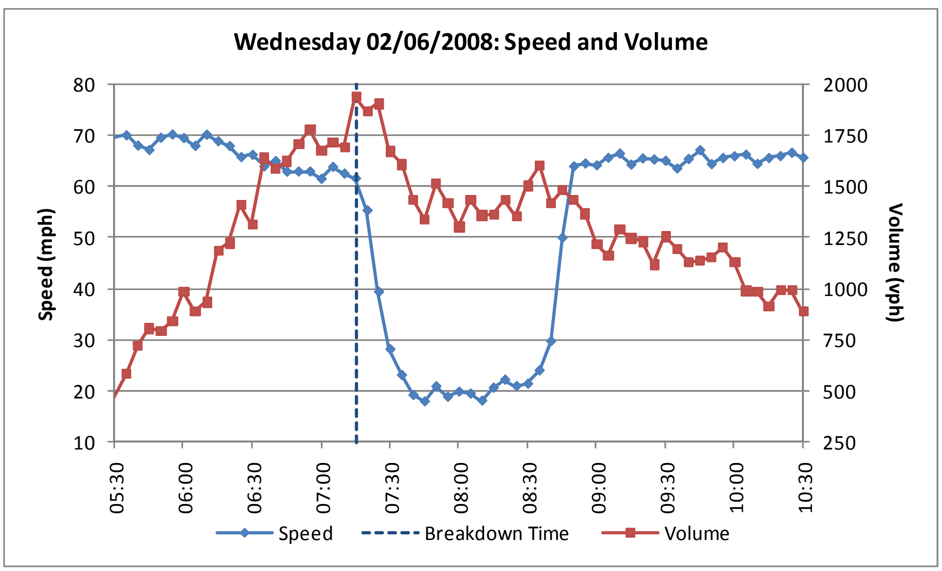


Figure 18. Speed and Flow Profile before Ramp Meter Installation.

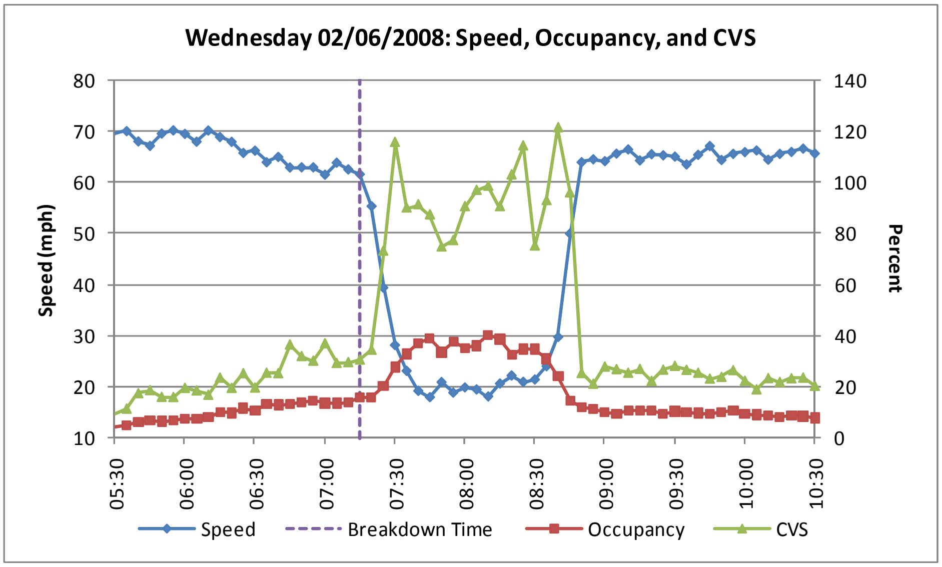


Figure 19. Speed, Occupancy, and CVS Profile before Ramp Meter Installation.

Figure 18 shows that the speed and flow breakdown on the main lane occurred around 7:15 a.m. At this point, the average speed drops sharply from above 60 mph to below 20 mph within half an hour. The traffic flow briefly jumps above 1800 vphpl and then drops to the range of 1250 to 1550 vphpl throughout the rest of the peak period, which ends slightly before 9 a.m.

Figure 19 displays the relationships between the speed profile and the occupancy and CVS profiles. Similarly, an abrupt increase in occupancy and speed variation (CVS) occurred shortly after 7:15 a.m. The average occupancy remained above 30 percent throughout the peak period. During the same period, the calculated values of CVS were in the range of 80 percent and 120 percent, which indicates that the standard deviations of the speeds during these time periods are about as large as the value of the average speeds themselves. This indicates a high level of instability in the traffic flow conditions during the breakdown.

Measures of Effectiveness

Approximately one month of main lane traffic data before and after ramp meter installation was retrieved for the analysis. To evaluate the benefits of the ramp meters on freeway traffic flow, we considered the following MOEs in the evaluation:

- weighted average speed — measures the average speed of the main lane traffic flow across all lanes,

- average occupancy — measures the average occupancy of the main lane traffic flow across all lanes, and
- coefficient of variation in speed — measures the fluctuation or smoothness of main lane traffic flow across all lanes.

The following describes the MOE calculation process based on the original 30-second data obtained from the radar sensor. The total volume per output interval is calculated as:

$$Q_k = \sum_{j=1}^{l} \sum_{i=1}^{n} q_{ij} \tag{6}$$

where q_{ij} is the 30-second volume count of the ith input interval at lane j, Q_k is the aggregated volume count of the k^{th} output interval, n is the number of intervals within the aggregation time window, and l is the number of lanes in a station (configurable by users).

The average occupancy per lane per interval is calculated using:

$$\overline{O}_k = \frac{1}{n} \cdot \frac{1}{l} \sum_{j=1}^{l} \sum_{i=1}^{n} o_{ij} \tag{7}$$

where o_{ij} is the 30-second average percent occupancy of the i^{th} input interval at lane j and $\overline{O}_k$ is the averaged occupancy rate of the k^{th} output interval. Note that the occupancy is a proportional indicator of density.

The weighted average speed per lane is calculated as:

$$\overline{V}_k = \frac{\sum_{j=1}^{l} \sum_{i=1}^{n} q_{ij} v_{ij}}{\sum_{j=1}^{l} \sum_{i=1}^{n} q_{ij}} \tag{8}$$

where v_{ij} is the 30-second weighted average speed of the i^{th} interval at lane j and $\overline{V}_k$ denotes the weighted average speed of the k^{th} output interval. The weighted average speed has an advantage that better describes the true fluctuation of vehicles' speed over time, particularly during the light traffic volume condition.

The CVS is calculated as:

$$CVS_k = \frac{\sigma_{v_{ij}}}{\overline{V}} = \sqrt{\frac{\sum_{j=1}^{l}\sum_{i=1}^{n} q_{ij}(v_{ij} - \overline{V})^2}{\sum_{j=1}^{l}\sum_{i=1}^{n} q_{ij}}} \cdot \frac{1}{\overline{V}} \tag{9}$$

where CVS_k represents the fluctuation of average speeds for the k^{th} output intervals. The CVS can be used as a surrogate safety measure where the higher CVS values indicate instability in the traffic stream, which leads to a higher risk of collisions (*3*).

In cases where invalid or missing volume data are present in the interval, the total volume is re-estimated by linear extrapolation using the following equation:

$$\hat{\theta}_k = \frac{1}{p} \cdot \theta_k \tag{10}$$

where θ_k is the measure (e.g., volume) calculated for the k^{th} output interval, $\hat{\theta}_k$ is the re-estimated measure extrapolated from θ_k, and p denotes the proportion of valid data.

Data Validation

To ensure the validity of the data used in the analysis, we retrieved the incident reports for the study segment from Houston TranStar's incident data archive during the study. Then, we plotted the speed profiles for the peak period (7 a.m. to 9 a.m.) for every day of the data used in the analysis. Using both visual observation and incident logs, days with irregularities observed in the traffic flows can be filtered out. Those days with unusual speed profiles as well as holidays were excluded from the before-after evaluation.

Figure 20 and Figure 21 show examples of Mondays' and Tuesdays' speed profiles examined in the analysis. The days with unusual patterns observed were noted in the picture and excluded from the analysis. For example, February 18, 2008, was not used because it is a holiday (President's Day), and February 26, 2008, was excluded because it was the first day that ramp meters became active.

Table 25 summarizes the days that were validated and selected for the before-after evaluation. The evaluation focused on the morning peak period from 7 a.m. to 9 a.m. At least three days worth of data for both before and after conditions were used in the analysis.

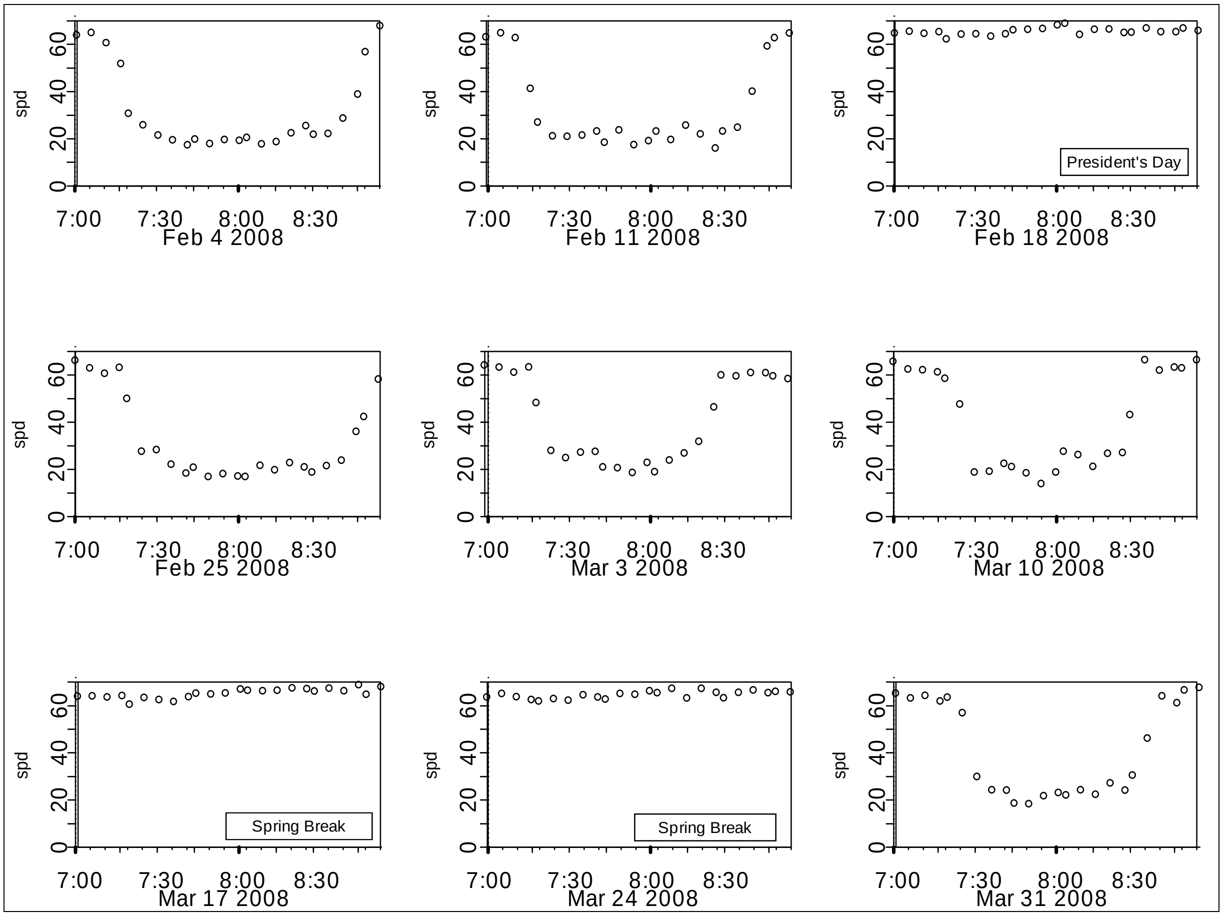


Figure 20. Monday Speed Profiles.

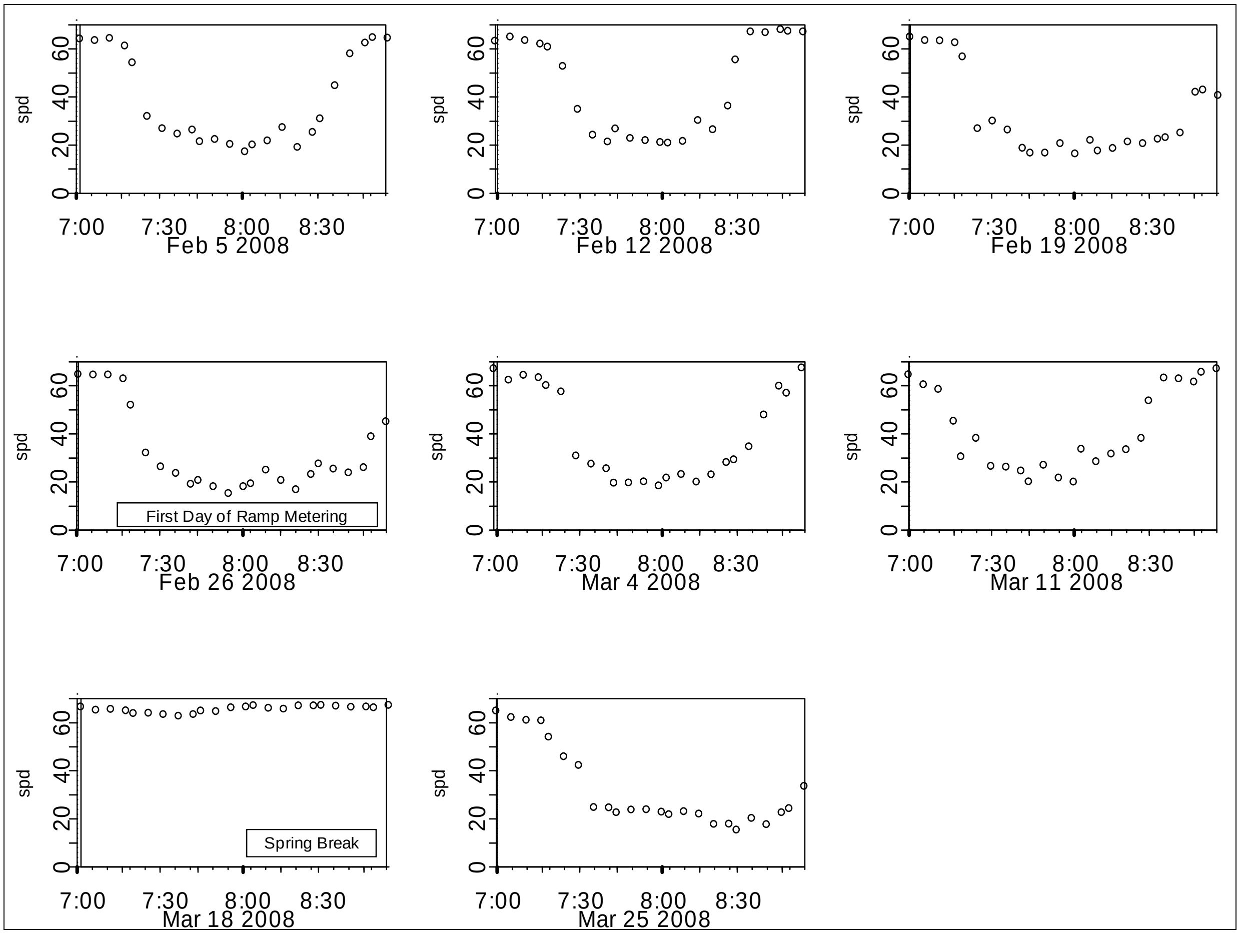


Figure 21. Tuesday Speed Profiles.

Table 25. Selected Days for Before-After Evaluation.

Day*	Before Dates	After Dates
Mondays	02/04/2008; 02/11/2008; 02/25/2008	03/03/2008; 03/10/2008; 03/31/2008
Tuesdays	02/05/2008; 02/12/2008; 02/19/2008	03/04/2008; 03/11/2008; 03/25/2008
Wednesdays	02/06/2008; 02/13/2008; 02/20/2008	02/27/2008; 03/05/2008; 03/12/2008; 03/26/2008
Thursdays	02/07/2008; 02/14/2008; 02/21/2008	02/28/2008; 03/13/2008; 03/27/2008
Fridays	02/08/2008; 02/15/2008; 02/22/2008	02/29/2008; 03/07/2008; 03/14/2008

* All data collected between 7:00 a.m. and 9:00 a.m.

Methodology

Researchers conducted a statistical t-test to compare the MOEs observed by day of week to ensure the changes in the speed profiles were not caused by the daily traffic pattern. In this case, they did not have any prior knowledge whether the MOEs for the after condition would be higher or lower; therefore, the two-sided t-test was selected. The assumption of equal population variances is central to the standard two-sample t-test. This test can be misleading when population variances are not equal because the null distribution of the test statistic is no longer a t-distribution. Since the assumption of equal variances is doubtful with respect to the before and after datasets, the Welch modification of the t-test was used in this study (*36*).

Results

Table 26 summarizes the results from the Welch modified two-sample t-test for each MOE by day of week using the before and after data from the radar sensor. The t-statistics were calculated by the before minus the after condition. Hence, a positive t-statistic indicates an improvement in occupancy and CVS, and vice versa for speed. The p-values indicate the statistical significance of the difference. A p-value of 0.05 or less means that the observed difference in the MOEs for the before and after conditions is statistically significant at 95 percent confidence level.

Table 26. Statistical Comparison of Before-After Differences in MOEs.

Data Source:	Wavetronix Radar SS105 (Main Lane)				
Location:	Upstream of Braeswood Entrance Ramp				
Aggregation Interval:	5 minutes				
Method:	Welch Modified Two-Sample Two-Sided t-Test (*36*)				

Days	Speed		Occupancy		CVS	
	t-statistic	p-value	t-statistic	p-value	t-statistic	p-value
Mondays	-2.7854	0.0061	2.8646	0.0048	24.707	0.0147
Tuesdays	0.2826	0.7779	0.0628	.9500	-0.8780	0.3815
Wednesdays	0.0492	.9609	0.7552	0.4515	-1.7634	0.0798
Thursdays	0.7279	0.4679	-1.0832	0.2805	-1.1714	0.2434
Fridays	0.0151	0.9880	-0.0213	0.9831	0.3731	0.7096

Note: The differences were calculated by before MOE minus after MOE. Therefore, the negative t-statistics for speed and the positive t-statistics for occupancy and CVS would indicate improvement in the main lane traffic flow.

The evaluation results indicated that the differences in all three MOEs (speed, occupancy, and CVS) calculated were not statistically significant at 95 percent confidence level except for Mondays. In other words, only on Mondays was an improvement observed in main lane traffic conditions after the ramp meters became active, and the changes were statistically significant at 95 percent confidence level.

It was hypothesized from the beginning of this analysis that the improvement in main lane traffic flow from ramp metering could be marginal because of frequent flushes observed at the ramp meters. Houston's ramp metering policy is to use the flush mode to clear the on-ramp queue once the queue detector has been occupied for a specified amount of time. When the ramp demand is heavy as observed in this case, the meters will operate in flush mode most of the time and thus reduce the benefits of ramp meters to prevent undesirable spillbacks into the intersections. The evaluation results appear to confirm this hypothesis. To determine why this is the case, researchers further analyzed ramp meter operations using cabinet data logs by day of week to identify possible causes, as discussed in the next section.

Findings

In this analysis, researchers conducted a statistical comparison of main lane traffic conditions before and after the deployment of ramp meters. Approximately one month of before and after freeway traffic data were retrieved from the Wavetronix radar sensor located upstream of the Braeswood entrance ramp. The Welch modified two-sample t-test (*36*) was used to evaluate if the differences in the observed MOEs (speed, occupancy, and CVS) are statistically significant. The evaluation results indicated that the improvements in the MOEs were statistically significant only for Mondays. The differences in the MOEs on the other days of the week were not statistically significant at $\alpha = 0.05$. While the results suggested that the deployment of ramp meters did not provide substantial operational benefits at this location, the analysis of ramp meter operations in the next section allowed us to identify specific conditions where ramp meter operations would be less effective and could potentially be considered for removal.

EFFECTIVENESS OF RAMP METER OPERATIONS

Signal and detector status data were used to evaluate the effectiveness of ramp meter operations. A data logger was installed in each ramp cabinet to collect event data for detectors and phases. The data logger consists of a personal computer (PC) with a digital input-output card and a special connector panel to interface the PC with the controller cabinet via its back panel. It uses custom software to record all events. Figure 22 shows a data logger installed at one of the sites, along with a sample of cabinet events recorded by it. Each record contains:

- the event time in hours, minutes, seconds, and milliseconds;
- identification of the detector or signal phase that this record applies to;
- whether the event was on or off;
- duration (if on, how long it was off; if off, how long it was on); and
- the count of this event since midnight.

Logs of selected days were further processed to calculate ramp metering statistics for both ramps. This section describes the results of this processing. Since the objective of this analysis was to evaluate metering operation, only 4 hours of data, from 6:00 a.m. to 10:00 a.m., was analyzed.

Figure 23 and Figure 24 provide plots of 5-minute flow rates (the 5-minute count multiplied by 60) in vehicles per hour for the Braeswood on-ramp on a Monday (March 3, 2008) and a Wednesday (March 5, 2008) in the same week. The counts used for this calculation were obtained from merge detector events. Because ramp-metering-with-flush operation guarantees service to all traffic, 60 consecutive five-counts can be summed to obtain the demand for any selected hour. Figure 23 and Figure 24 also display the durations of all flushes during the same time period. The duration of these flushes does not include the 15-second steady green signal after each flush.

- 6,40,11,734,DDET,Onn,453,941
- 6,40,12,328,MDET,Onn,3094,1357
- 6,40,12,984,MDET,Off,656,1357
- 6,40,13,718,DDET,Off,1984,941
- 6,40,14,15,QDET,Off,10734,1312
- 6,40,14,156,MDET,Onn,1172,1358
- 6,40,14,640,DDET,Onn,922,942
- 6,40,14,984,QDET,Onn,969,1313
- 6,40,15,31,MDET,Off,875,1358
- 6,40,16,484,MDET,Onn,1453,1359
- 6,40,17,359,MDET,Off,875,1359
- 6,40,17,796,YelS,Onn,21906,612
- 6,40,17,796,GrnS,Off,15000,612
- 6,40,18,796,RedS,Onn,21093,612
- 6,40,18,796,YelS,Off,1000,612
- 6,40,18,968,DDET,Off,4328,942
- 6,40,19,500,DDET,Onn,532,943

Figure 22. Data Logger PC in a Ramp Cabinet and a Sample of Logged Events.

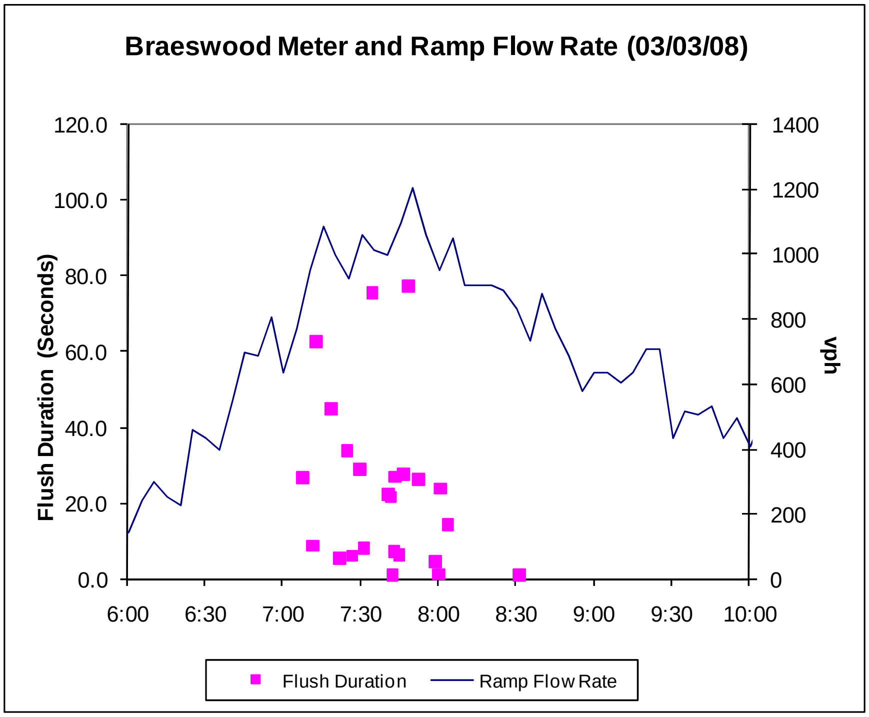


Figure 23. Braeswood On-Ramp Peak-Hour Demand for a Selected Monday.

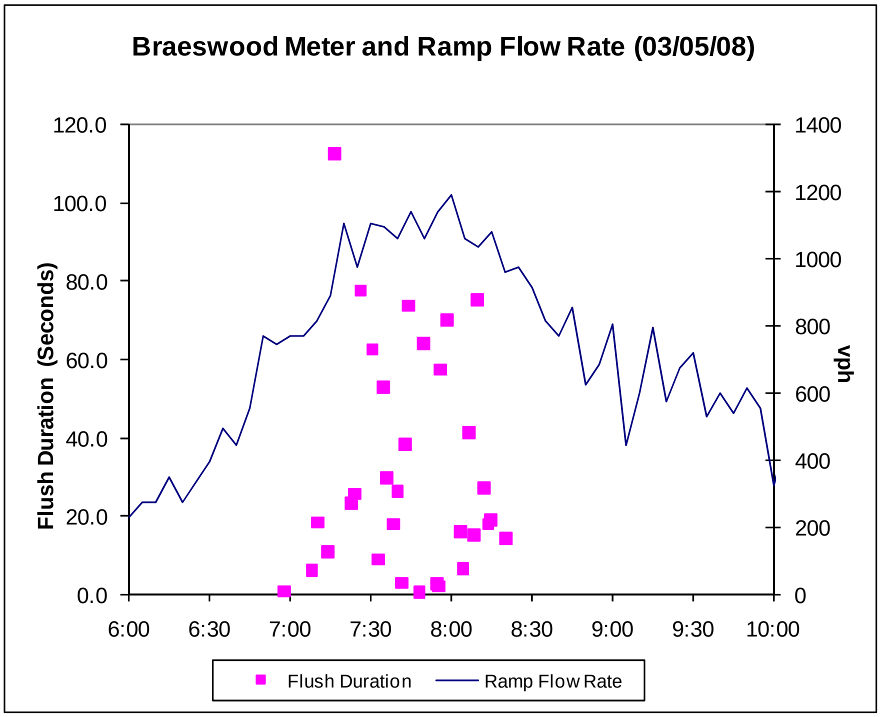


Figure 24. Braeswood On-Ramp Peak-Hour Demand for a Selected Wednesday.

A comparison of Figure 23 and Figure 24 reveals the following information:

- On Monday:
  - Peak flow occurred between 7:15 a.m. and 8:30 a.m. The highest portion of this flow rate varied around 1000 vph, with one peak of 1200 vph.
  - Most flushes were shorter than 40 seconds. Only three flushes were longer than 50 seconds.
- On Wednesday:
  - Peak flow occurred during the same time, but the flow rates were higher than Monday. Similar to Monday, the maximum flow rate was around 1200 vph, but the highest sustained flow rate was around 1100 vph.
  - There were six flushes (twice as many) of durations longer than 50 seconds.

Table 27 provides detailed statistics for these two days plus three other weekdays. The following points can be observed from this table:

- Peak hour started at different times for Monday and Friday (7:05 a.m. to 7:10 a.m.) and the three days in the middle of the week (around 7:20 a.m.).
- Approximately 90 percent of flushes occurred during the peak hour.

- Monday had the fewest flushes, most of which occurred during the peak hour.
- Monday had the lowest peak-hour flush frequency of 3.8 per 10 minutes; however, this variable does not provide any distinction between other days.
- Monday had the highest overall and peak-hour meter availabilities of 88.8 and 74.9 percent, respectively.
- The actual flow rate on Friday was the same as Monday, but Friday's peak-hour flow rate was slightly higher. This seems to be the probable cause of eight more flushes and over 4 percent less meter availability on Friday than Monday.
- The peak-hour flow rate on Tuesday was the same as that on Friday, with slightly fewer flushes and slightly higher meter availability.
- The median time-to-next flush ranged between 101 to 120 seconds and averaged 111 seconds. This generally coincided with the 120-second cycle length of the upstream intersection.
- Peak-hour meter availability seems to be the best indicator of meter effectiveness.

Figure 25 and Figure 26 provide plots of ramp flow rates for the Beechnut on-ramp on a Monday (March 31, 2008) and a Wednesday (April 2, 2008). These figures also show flush durations on those two days. The following points can be observed from these figures:

- The peak 5-minute flow rate on Monday reached as high as 1200 vph on two occasions. On Wednesday, the peak 5-minute flow rate was the same or higher than 1200 vph on seven occasions and peaked at almost 1400 vph. Wednesday also experienced a much longer duration of time during which the 5-minute flow rate was significantly higher than 1000 vph.
- Even though Monday had lower ramp demand, it experienced four more longer-than-80-second flushes than Wednesday.

Table 27. Metering Statistics for Braeswood Ramp Control Signal.

Performance Measures	Date and Day of Week				
	03/03/08 Mon.	03/04/08 Tues.	03/05/08 Wed.	03/06/08 Thurs.	02/29/08 Fri.
Active Duration (Minutes)	135	135	135	135	135
Number of Flushes	24	29	35	36	32
Flush Frequency (per 10 Minutes)	1.8	2.1	2.6	2.7	2.4
Time to First Flush (Minutes)	22.3	34.7	12.8	29.1	27.1
Mean Flush Duration (Seconds)	23	22	30	27	21
Median Flush Duration (Seconds)	22	16	19	20	15
Minimum Flush Duration (Seconds)	0.7	2.0	0.5	3.4	0.9
Maximum Flush Duration (Seconds)	77.3	63.8	112.5	128.0	75.7
Dark & Startup Green (Minutes)	15.3	18.1	26.2	25.3	19.2
Overall Meter Availability	88.8%	86.8%	80.7%	81.4%	85.9%
Mean Time to Next Flush (Seconds)	219	165	160	133	126
Median Time to Next Flush (Seconds)	115	115	120	101	106
Ramp Flow Rate (vphpl)	886	912	932	959	888
Ramp Peak-Hour Start Time	7:05	7:20	7:17	7:25	7:10
Peak-Hour Ramp Flow Rate (vphpl)	1029	1058	1085	1100	1059
Peak-Hour Number of Flushes	23	27	27	29	29
Peak-Hour Flush Frequency (per 10 Minutes)	3.8	4.5	4.5	4.8	4.8
Peak-Hour Meter Availability	74.9%	70.9%	61.9%	65.3%	70.5%

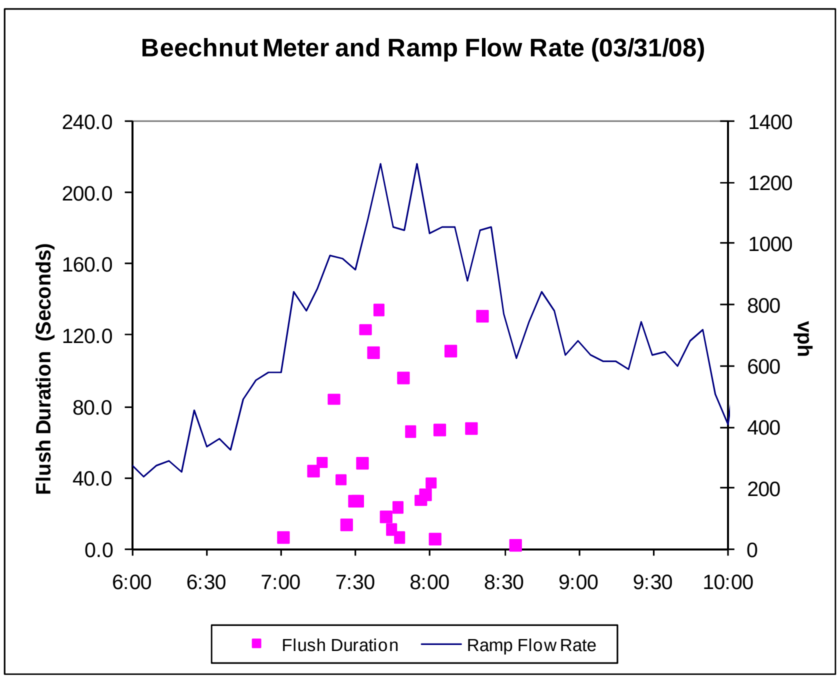


Figure 25. Beechnut On-Ramp Peak-Hour Demand for a Monday.

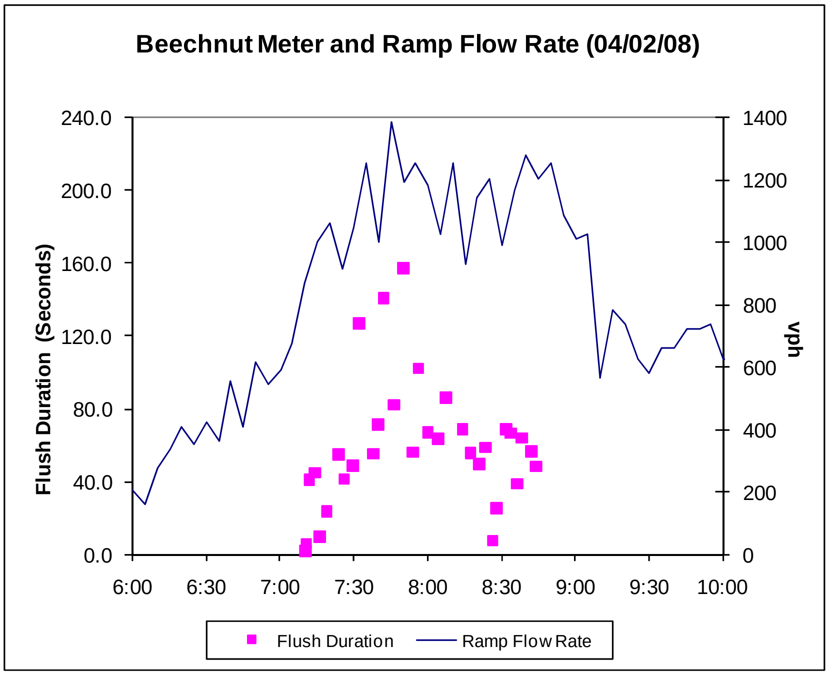


Figure 26. Beechnut On-Ramp Peak-Hour Demand for a Wednesday.

Table 28 provides detailed statistics for these two and the other three weekdays. The following points can be observed from this table:

- With the exception of Wednesday (7:40 a.m.), the peak hour started around 7:20 a.m.
- As compared to the Braeswood on-ramp, the demand on Friday was lower, while demands on the other days were higher. On Wednesday, the difference was substantial.
- Meter availabilities for all days, except Friday, were lower than those for the Braeswood on-ramp. Except for Friday (with a value of 69.8 percent), all peak-hour meter availabilities were less than 59 percent on all days, clearly indicating the ineffectiveness of metering at this ramp. Note, however, for all but Wednesday, the overall meter availability was approximately 75% or better. TxDOT has deemed this as an acceptable operating condition.

Table 28. Metering Statistics for Beechnut Ramp Control Signal.

Performance Measure	Date and Day of Week				
	03/31/08	04/01/08	04/02/08	04/03/08	04/04/08
	Mon.	Tues.	Wed.	Thurs.	Fri.
Active Duration (Minutes)	135	135	135	135	135
Number of Flushes	27	34	36	27	19
Flush Frequency (per 10 Minutes)	2.0	2.5	2.7	2.0	1.4
Time to First Flush (Minutes)	17.3	27.2	27.3	29.1	31.0
Mean Flush Duration (Seconds)	52	45	57	48	48
Median Flush Duration (Seconds)	39	39	56	46	37
Minimum Flush Duration (Seconds)	1.6	2.7	2.0	1.6	2.6
Maximum Flush Duration (Seconds)	133.6	200.5	157.3	118.6	106.3
Dark & Startup Green (Minutes)	29.9	34.1	43.4	28.6	19.9
Overall Meter Availability	78.0%	74.9%	68.0%	79.0%	85.4%
Mean Time to Next Flush (Seconds)	217	161	181	208	261
Median Time to Next Flush (Seconds)	155	129	159	134	178
Ramp Flow Rate (vphpl)	878	909	1015	903	838
Ramp Peak-Hour Start Time	7:25	7:15	7:40	7:15	7:20
Peak-Hour Ramp Flow Rate (vphpl)	1061	1111	1162	1102	1022
Peak-Hour Number of Flushes	21	25	19	23	16
Peak-Hour Flush Frequency (per 10 Minutes)	3.5	4.2	3.2	3.8	2.7
Peak-Hour Meter Availability	58.8%	53.3%	55.1%	58.3%	69.8%

Analysis of Traffic Diversion from Ramp Metering

The primary objective of obtaining tube counts was to determine if ramp metering caused any significant diversion of freeway demand to the frontage road. To obtain the needed data, TTI staff installed pneumatic tubes and counters at four locations during the following two consecutive data collection periods:

- January 22, 2008, through February 3, 2008; and
- February 18, 2008, through March 10, 2008.

As shown in Figure 17, a single tube counter was placed on the Evergreen exit ramp, and two counters — one for obtaining total frontage road (FR) counts and the other for obtaining per-lane FR counts — were placed at three locations. The first location was downstream of the Braeswood entrance ramp, the second location was upstream of the Evergreen exit, and the third location was downstream of the Beechnut entrance ramp. To provide accurate data, pairs of counters on the FR were used to ensure that there was no origin or destination between the counters in a pair. The configuration of the counter (with multiple tubes) for collecting per-lane data also produced the total count across all lanes. For explanation purposes, the text refers to these data as Count-A. Data obtained from the other counter are referred to as Count-B.

Data obtained from these counters were processed to obtain hourly counts. Inspection of the results of this processing allowed researchers to identify and remove from consideration numerous instances of bad data. Because the objective was to assess before and after conditions, only data collected from 6:00 a.m. to 9:00 a.m. were further processed to allow a more in-depth look. The data collection schedules produced no more than two days of before data for Monday and Tuesday, no more than three days of good before data for the remaining three weekdays, and a maximum of two days worth of after data for all days.

Table 29 through Table 31 provide before and after comparisons of Braeswood on-ramp data for Tuesday. As can be seen in Table 29, Count-A data for February 26, the first day of ramp metering operation, is surprisingly low. These data cannot be correct because Count-B data (Table 30), obtained for the same day using another counter placed nearby, do not show the same problem. If this column is included in calculating the average for the two after days (as shown in Table 29), the results show almost a 10 percent reduction in total (6:00 a.m. to 9:00 a.m.) average frontage road traffic downstream of the ramp. Ignoring this day, on the other hand, shows a 10 percent increase. Count-B data (Table 30) are more consistent. Using these data, the same computation produces a 5.7 percent increase. Based on observations in other parts of the country, this amount of diversion is possible. Table 31 provides a comparison of Tuesday data for the same ramp obtained from the two counters. Data in the table were computed by dividing Count-B data by corresponding Count-A data and then multiplying by 100. Count-B is less than Count-A in all but two cases, and the difference ranged from approximately –14 to 7 percent. These differences are unexpected since the two counters were closely located and point to the inefficacy of tube counter data for operational analysis.

Table 29. Tuesday Count-A Data on Frontage Road Downstream of Braeswood.

Time	Before			After		
	1/29/08	2/19/08	Average	2/26/08	3/4/08	Average
6-7 a.m.	625	540	582.5	249	659	454
7-8 a.m.	1214	1160	1187.0	854	1344	1099
8-9 a.m.	935	1119	1027.0	907	1130	1018
9-10 a.m.	569	626	597.5	458	683	571
Total	**3343**	**3445**	**3394**	**2468**	**3816**	**3142**

Table 30. Tuesday Count-B Data on Frontage Road Downstream of Braeswood.

Time	Before			After		
	1/29/08	2/19/08	Average	2/26/08	3/4/08	Average
6-7 a.m.	572	578	575.0	540	569	555
7-8 a.m.	1166	1187	1176.5	1142	1294	1218
8-9 a.m.	908	1076	992.0	1154	1080	1117.0
9-10 a.m.	543	614	578.5	588	662	625.0
Total	**3189**	**3455**	**3322**	**3424**	**3605**	**3515**

Table 31. Tuesday Braeswood Count-B as a Percent of Count-A.

Time	Before			After		
	1/29/08	2/19/08	Average	2/26/08	3/4/08	Average
6-7 a.m.	91.5%	107.0%	98.7%	Data Not Available	86.3%	Not computed
7-8 a.m.	96.0%	102.3%	99.1%		96.3%	
8-9 a.m.	97.1%	96.2%	96.6%		95.6%	
9-10 a.m.	95.4%	98.1%	96.8%		96.9%	

Table 32 through Table 34 provide Braeswood on-ramp data for Wednesdays, and Table 35 through Table 37 provide the same data for Thursdays.

Table 32. Wednesday Count-A Data on Frontage Road Downstream of Braeswood.

Time	Before				After		
	1/23/08	1/30/2008	2/20/2008	Average	2/27/08	3/5/08	Average
6-7 a.m.	664	652	530	615	254	644	634
7-8 a.m.	1378	1416	1207	1334	960	1419	1391
8-9 a.m.	1147	1068	996	1070	968	1257	1195
9-10 a.m.	687	630	597	638	441	680	666
Total	**3876**	**3766**	**3330**	**3657**	**2623**	**4000**	**3312**

Table 33. Wednesday Count-B Data on Frontage Road Downstream of Braeswood.

Time	Before				After		
	1/23/08	1/30/2008	2/20/2008	Average	2/27/08	3/5/08	Average
6-7 a.m.	554	570	560	561.3	576	578	572
7-8 a.m.	1168	1268	1238	1224.7	1370	1380	1325
8-9 a.m.	980	954	947	960.3	1319	1237	1172
9-10 a.m.	583	558	590	577.0	616	677	623
Total	**3285**	**3350**	**3335**	**3323**	**3881**	**3872**	**3692**

Table 34. Wednesday Braeswood Count-B as a Percent of Count-A.

Time	Before				After		
	1/23/08	1/30/2008	2/20/2008	Average	2/27/08	3/5/08	Average
6-7 a.m.	83.4%	87.4%	105.7%	91.2%	226.8%	89.8%	128.5%
7-8 a.m.	84.8%	89.5%	102.6%	91.8%	142.7%	97.3%	115.6%
8-9 a.m.	85.4%	89.3%	95.1%	89.7%	136.3%	98.4%	114.9%
9-10 a.m.	84.9%	88.6%	98.8%	90.4%	139.7%	99.6%	115.3%

Table 35. Thursday Count-A Data on Frontage Road Downstream of Braeswood.

Time	Before				After		
	1/24/08	1/31/2008	2/21/2008	Average	2/28/08	3/6/08	Average
6-7 a.m.	640	681	568	630	272	604	438
7-8 a.m.	1501	1307	1204	1337	952	1587	1270
8-9 a.m.	1447	823	885	1052	1042	1620	1331
9-10 a.m.	758	592	598	649	453	690	572
Total	**4346**	**3403**	**3255**	**3668**	**2719**	**4501**	**3610**

Table 36. Thursday Count-B Data on Frontage Road Downstream of Braeswood.

Time	Before				After		
	1/24/08	1/31/2008	2/21/2008	Average	2/28/08	3/6/08	Average
6-7 a.m.	538	605	588	577	559	583	571
7-8 a.m.	1281	1221	1242	1248	1331	1590	1461
8-9 a.m.	1252	780	846	959	1349	1592	1471
9-10 a.m.	650	536	584	590	672	696	684
Total	**3721**	**3142**	**3260**	**3374**	**3911**	**4461**	**4186**

Table 37. Thursday Braeswood Count-B as a Percent of Count-A.

Time	Before				After		
	1/24/08	1/31/2008	2/21/2008	Average	2/28/08	3/6/08	Average
6-7 a.m.	84.1%	88.8%	103.5%	91.6%	205.5%	96.5%	130.4%
7-8 a.m.	85.3%	93.4%	103.2%	93.3%	139.8%	100.2%	115.0%
8-9 a.m.	86.5%	94.8%	95.6%	91.2%	129.5%	98.3%	110.5%
9-10 a.m.	85.8%	90.5%	97.7%	90.9%	148.3%	100.9%	119.7%

The following is a summary of observations for the Braeswood on-ramp for Wednesdays and Thursdays:

- Similar to the Tuesday case, the hourly counts for the first Wednesday and the first Thursday after metering were extremely low as compared to the average of the three before days. For these days, the total 4-hour counts were less by 1034 and 949 vehicles, respectively.
- Similar to the Tuesday case, counts for Wednesday and Thursday a week after were higher (by 343 and 833 vehicles, respectively) as compared to the 3-day average of before days.
- As shown in Table 34 and Table 37, there were significant variations in counts from the two adjacent counters for the same hour on the same day, even after excluding the days with unusually low counts immediately following the start of ramp metering.
- Inclusion of all Count-A data showed a reduction in downstream frontage road traffic in after conditions by 7 and 2 percent for the two days, respectively.
- Inclusion of all Count-B data showed an increase in downstream frontage road traffic (a possible diversion) during the after case by 17 and 24 percent for the two days, respectively.

Table 38 through Table 43 provide a comparison of before and after conditions for the Beechnut on-ramp. Note that Count-A data consisted of only one day for the after conditions for all three days. Observations from the analysis of these data are described below.

Table 38. Tuesday Count-A Data on Frontage Road Downstream of Beechnut.

Time	Before			After		
	1/29/08	2/19/08	Average	2/26/08	3/4/08	Average
6:00 a.m.	224	241	233	Data Not Available	137	137
7:00 a.m.	1364	1389	1377		1030	1030
8:00 a.m.	1191	1295	1243		1487	1487
9:00 a.m.	410	477	444		519	519
Total	**3189**	**3402**	**3296**		**3173**	**3173**

Table 39. Tuesday Count-B Data on Frontage Road Downstream of Beechnut.

Time	Before			After		
	1/29/08	2/19/08	Average	2/26/08	3/4/08	Average
6:00 a.m.	221	Data Not Available	221	208	208	208
7:00 a.m.	1362		1362	1297	1360	1329
8:00 a.m.	1214		1214	1316	1230	1273
9:00 a.m.	409		409	418	442	430
Total	**3206**		**3206**	**3239**	**3240**	**3240**

Table 40. Wednesday Count-A Data on Frontage Road Downstream of Beechnut.

Time	Before				After		
	1/23/08	1/30/2008	2/20/2008	Average	2/27/08	3/5/08	Average
6:00 a.m.	236	198	220	218	Data Not Available	126	126
7:00 a.m.	1322	1351	1346	1340		1115	1115
8:00 a.m.	1233	1148	1183	1188		1486	1486
9:00 a.m.	418	421	443	427		607	607
Total	**3209**	**3118**	**3192**	**3173**		**3334**	**3334**

Table 41. Wednesday Count-B Data on Frontage Road Downstream of Beechnut.

Time	Before				After		
	1/23/08	1/30/2008	2/20/2008	Average	2/27/08	3/5/08	Average
6:00 a.m.	212	206	230	216	218	208	213
7:00 a.m.	1334	1363	1354	1350	1398	1458	1428
8:00 a.m.	1256	1190	1174	1207	1418	1282	1350
9:00 a.m.	415	432	437	428	458	477	468
Total	**3217**	**3191**	**3195**	**3201**	**3492**	**3425**	**3459**

Table 42. Thursday Count-A Data on Frontage Road Downstream of Beechnut.

Time	Before				After		
	1/24/08	1/31/2008	2/21/2008	Average	2/28/08	3/6/08	Average
6:00 a.m.	219	231	215	222	Data Not Available	124	124
7:00 a.m.	1383	1383	1383	1383		1544	1544
8:00 a.m.	1433	944	1139	1172		1641	1641
9:00 a.m.	560	398	807	588		803	803
Total	**3595**	**2956**	**3544**	**3365**		**4112**	**4112**

Table 43. Thursday Count-B Data on Frontage Road Downstream of Beechnut.

Time	Before				After		
	1/24/08	1/31/2008	2/21/2008	Average	2/28/08	3/6/08	Average
6:00 a.m.	235	226	222	228	222	200	211
7:00 a.m.	1434	1384	1404	1407	1370	1834	1602
8:00 a.m.	1490	967	1117	1191	1376	1582	1479
9:00 a.m.	589	442	802	611	458	567	513
Total	**3748**	**3019**	**3545**	**3437**	**3426**	**4183**	**3805**

An analysis of Tuesday data shows the following:

- Count-A and Count-B data showed a –4 and 1 percent diversion, respectively;
- Count-B to Count-A variations within before data ranged from 85.7 to 101.9 percent; and
- Count-B to Count-A variations within after data ranged from 82.7 to 151.8 percent.

Similarly, we found the following from an analysis of Wednesday data:

- Count-A and Count-B data showed 5 and 8 percent diversion, respectively;
- Count-B to Count-A variations within before data ranged from 89.4 to 104 percent; and
- Count-B to Count-A variations within after data ranged from 75.5 to 173 percent.

Finally, an analysis of Thursday data showed the following:

- Count-A and Count-B data showed 22 and 11 percent diversion, respectively;
- Count-B to Count-A variations within before data ranged from 97.8 to 104 percent; and
- Count-B to Count-A variations within after data ranged from 63.8 to 170 percent.

The Count-B to Count-A variations in hourly data in the before days were much less than those for the after days. In some of the latter cases, these variations were extremely high. The reasons are unclear from these data but can be attributed to the limitations of tube counters. Also, in general the data show that diversion increased after ramp metering, but it is difficult to assess the accuracy of actual numbers (percentages) given the fact that the data from two adjacent tubes did not closely match in most cases.

ANALYSIS OF SAFETY IMPACTS FROM RAMP METERING

Before/after studies were performed to assess the safety and operational impacts of ramp metering at Braeswood and Beechnut on I-610 northbound. The evaluation was based on comparisons of the following MOEs:

- vehicle conflicts in merge area as an MOE for safety, and
- travel time and space mean speed as operational MOEs.

These MOEs were determined from video data collection conducted before and after activation of ramp metering at the two entrance ramps.

Video Data Collection

Vehicle conflict data were determined from video files recorded using two cameras installed on I-610 northbound upstream of the gores of the entrance ramps at Braeswood and Beechnut. Houston TranStar provided two video feeds. The cameras had tilting and zooming capabilities, and spacing between them was about 1 mile. The fields of view of the two cameras are shown in Figure 27.

Traffic was video-recorded simultaneously at the two sites between 6 a.m. and 9 a.m. for two weeks: one week before and one week after ramp metering was activated on February 26, 2008. Traffic on the weekends was not recorded. “Before” studies were performed between February 19 and 25, 2008. After the ramp meters were deployed and activated, traffic was videotaped for another week between February 27 and March 4, 2008.

The recorded videos were saved in digital format on one of the computers in Houston TranStar’s traffic management center. A week-long recording between 6 a.m. and 9 a.m. required about 25 Gb of disk space.

Figure 27. Video Capture on I-610 Northbound at Braeswood (Left) and Beechnut (Right).

Video Data Reduction

Vehicle Conflicts

Assessment of the safety impacts of ramp metering would ideally be based on a comprehensive review of long-term (for several years) accident records before and after the activation of ramp meters. However, the very limited time available did not make such analyses possible. Therefore, vehicle conflicts as surrogate safety measures were used instead of accident history.

Data on vehicle conflicts were determined by reviewing the video files recorded at the two study sites. Time periods covering both free-flow and congested traffic conditions during morning peaks were of particular interest. The most common vehicle conflicts observed in the merge areas of both sites were:

- Type 1: entering vehicles crossing solid line and
- Type 2: exiting vehicles crossing solid line.

Figure 28 shows actual vehicle conflicts captured from videos recorded at the merge area of the entrance ramps at Beechnut and Braeswood.

Travel Times and Speeds

The video files were also used for assessing the operational impact of ramp metering by estimating travel times and average speeds of vehicles traversing the 0.82-mile freeway segment between the two entrance ramps. The boundaries of the freeway segment were defined by the noses of the entrance ramp gores at Braeswood (upstream boundary) and Beechnut (downstream boundary). Vehicles with some unique features were identified on the video, and the time when they passed the upstream and downstream boundaries of the segment were recorded. Note that there was a drift between the camera time settings at the two sites. The drift was determined for each day of the recording period, and it was used to synchronize the time-stamped videos and correct the estimated travel times. Thus the travel times were calculated as

$$TT = t_{BEECHNUT} - t_{BRAESWOOD} + \varepsilon \qquad (11)$$

where:

TT = travel time (minutes),

$t_{BEECHNUT}$ = time of crossing the downstream boundary of the freeway segment,

$t_{BRAESWOOD}$ = time of crossing the upstream boundary of the freeway segment, and

ε = time drift.

Average vehicle speed v[mph] over the 0.82-mile segment was estimated as

$$v = 60 * 0.82/\mathrm{TT}. \qquad (12)$$

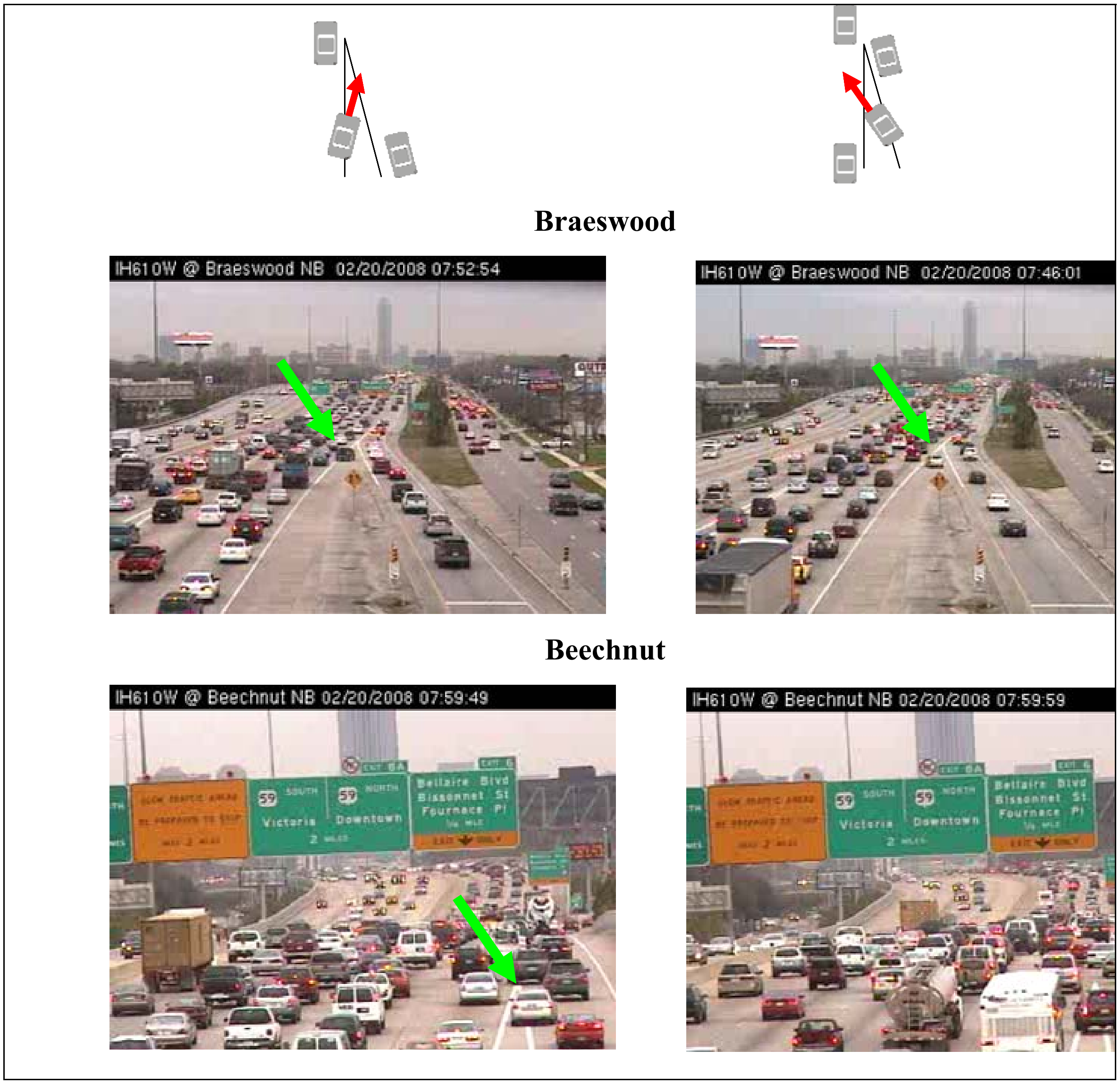


Figure 28. Vehicle Conflicts Observed at the Two Study Sites.

Video Data Analysis

Vehicle Conflicts

The temporal variations of vehicle conflicts during the morning peaks of two consecutive Wednesdays, February 20 and 27, 2008, are shown Figure 29. The white bars correspond to the 5-minute frequencies of both conflict types observed before ramp metering was activated. The black bars show the same frequencies when ramp metering was activated.

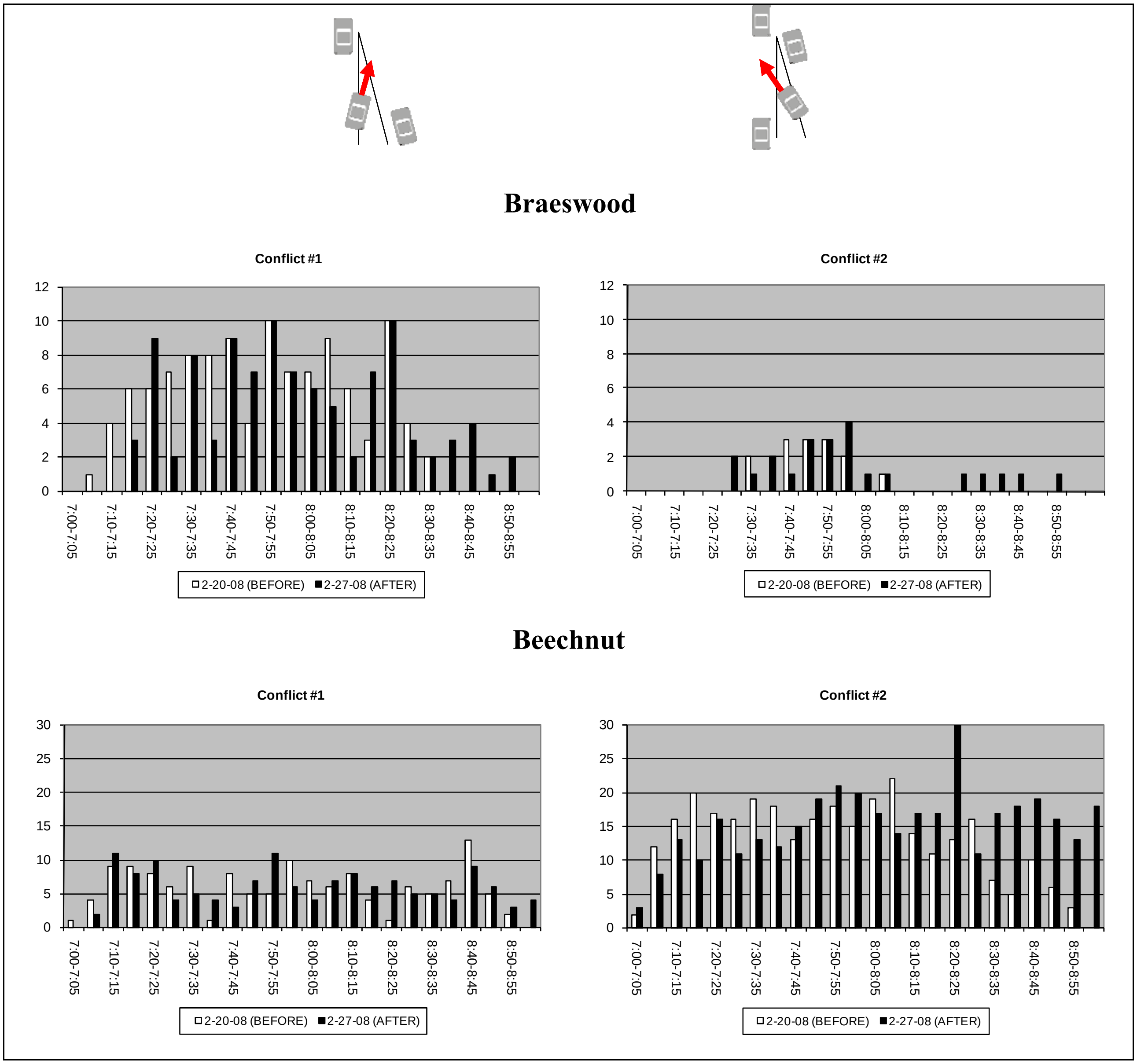


Figure 29. Five-Minute Vehicle Conflicts without (White) and with (Black) Ramp Metering — Wednesdays 7 a.m. to 9 a.m.

Exiting vehicles crossing the entrance ramp gore and often forcing entering vehicles to slow down was the dominant type of vehicle conflict in the merge area at Braeswood. In contrast, entering vehicles crossing the gore and forcefully merging with freeway traffic was the dominant type of vehicle conflict at Beechnut. These observations are not surprising due to the relatively high volume of exiting traffic at Braeswood and entering traffic at Beechnut.

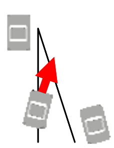
An obvious difference in the temporal variation of vehicle conflicts between the "before" and "after" periods can be observed even by a simple visual inspection of the bar graphs. The graphs in Figure 29 suggest that ramp metering delayed the time periods when vehicle conflicts occurred; they started later but also lasted longer. An analysis of variance (ANOVA) was performed to determine if the average 5-minute conflicts had significantly changed after ramp metering was activated. The ANOVA results in Table 44 and Table 45 indicate that the differences in 5-minute conflicts are statistically not significant at the 95 percent confidence level.

The temporal variations of vehicle conflicts during the morning peaks of two consecutive Mondays, February 25 and March 3, 2008, are shown Figure 30. Again, the white bars correspond to the 5-minute frequencies of both conflict types observed before ramp metering was activated. The black bars show the same frequencies when ramp metering was turned on. Note that on February 25, there was limited visibility due to dense fog between 7:45 a.m. and 8:20 a.m., and video data collection during this period was not possible. Figure 30 indicates that the number of both types of vehicle conflicts decreased after ramp metering was turned on. However, the ANOVA tests in Table 46 and Table 47 show that these reductions were statistically not significant at the 95 percent confidence level.

Table 44. ANOVA of Merge Area Vehicle Conflicts at Beechnut without (C1-Before) and with (C2-After) Ramp Metering during Wednesday Morning Peak.

Conflict

#1



SUMMARY

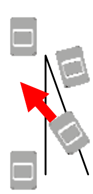
Groups	Count	Sum	Average	Variance
C1-Before	24	139	5.791667	10.60688
C1-After	24	137	5.708333	6.998188

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.083333	1	0.083333	0.009467	0.922912	4.051749
Within Groups	404.9167	46	8.802536			
Total	405	47				

Conflict

#2



SUMMARY

Groups	Count	Sum	Average	Variance
C2-Before	24	316	13.16667	31.18841
C2-After	24	368	15.33333	27.10145

ANOVA

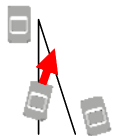
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	56.33333	1	56.33333	1.932869	0.171136	4.051749
Within Groups	1340.667	46	29.14493			
Total	1397	47				

Note: Cx-Before: Vehicle conflict x observed on February 20, 2008, 7 a.m. to 9 a.m.

Cx-After: Vehicle conflict x observed on February 27, 2008, 7 a.m. to 9 a.m.

Table 45. ANOVA of Merge Area Vehicle Conflicts at Braeswood without (C1-Before) and with (C2-After) Ramp Metering during Wednesday Morning Peak.

Conflict #1



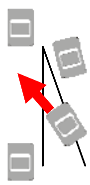
SUMMARY

Groups	Count	Sum	Average	Variance
C1-Before	24	111	4.625	12.7663
C1-After	24	103	4.291667	11.34601

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.333333	1	1.333333	0.110594	0.74098	4.051749
Within Groups	554.5833	46	12.05616			
Total	555.9167	47				

Conflict #2



SUMMARY

Groups	Count	Sum	Average	Variance
C2-Before	24	23	0.958333	1.259058
C2-After	24	14	0.583333	1.210145

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.6875	1	1.6875	1.366838	0.248379	4.051749
Within Groups	56.79167	46	1.234601			
Total	58.47917	47				

Note: Cx-Before: Vehicle conflict x observed on February 20, 2008, 7 a.m. to 9 a.m.

Cx-After: Vehicle conflict x observed on February 27, 2008, 7 a.m. to 9 a.m.

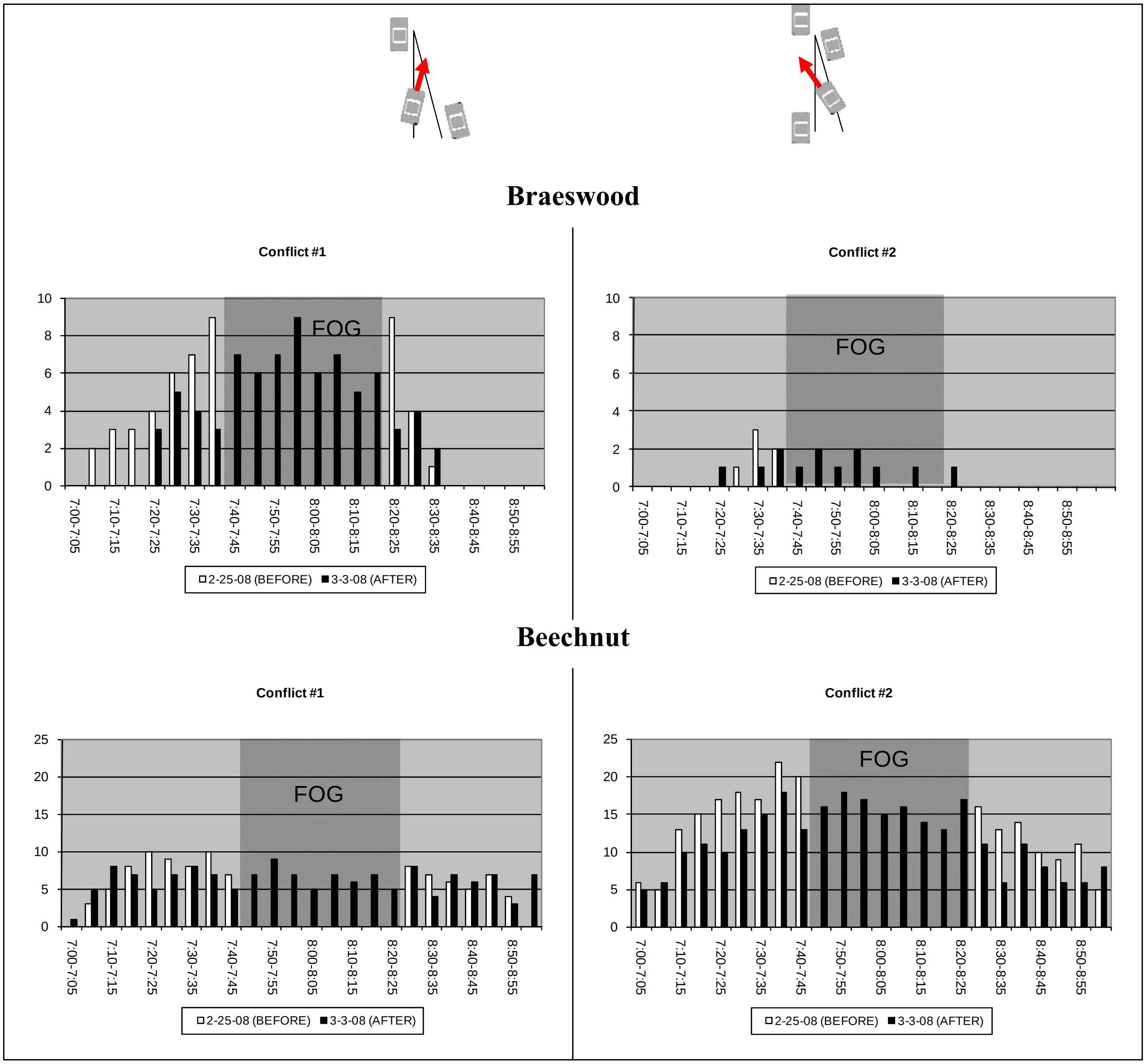
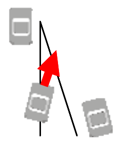


Figure 30. Five-Minute Vehicle Conflicts without (White) and with (Black) Ramp Metering — Mondays 7 a.m. to 9 a.m.

Table 46. ANOVA of Merge Area Vehicle Conflicts at Beechnut without (C1-Before) and with (C2-After) Ramp Metering during Monday Morning Peak.

Conflict #1



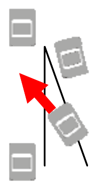
SUMMARY

Groups	Count	Sum	Average	Variance
C1-Before	16	97	6.0625	9.529167
C1-After	24	148	6.166667	3.188406

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.104167	1	0.104167	0.018303	0.893099	4.09817
Within Groups	216.2708	38	5.691338			
Total	216.375	39				

Conflict #2



SUMMARY

Groups	Count	Sum	Average	Variance
C2-Before	16	211	13.1875	27.09583
C2-After	24	283	11.79167	17.99819

ANOVA

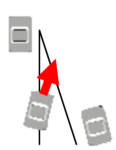
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	18.70417	1	18.70417	0.86636	0.357841	4.09817
Within Groups	820.3958	38	21.58936			
Total	839.1	39				

Note: Cx-Before: Vehicle conflict x observed on February 20, 2008, 7 a.m. to 9 a.m.

Cx-After: Vehicle conflict x observed on February 27, 2008, 7 a.m. to 9 a.m.

Table 47. ANOVA of Merge Area Vehicle Conflicts at Braeswood without (C1-Before) and with (C2-After) Ramp Metering during Monday Morning Peak.

Conflict #1



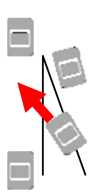
SUMMARY

Groups	Count	Sum	Average	Variance
C1-Before	16	48	3	10.53333
C1-After	24	77	3.208333	8.780797

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.416667	1	0.416667	0.043987	0.834999	4.098172
Within Groups	359.9583	38	9.472588			
Total	360.375	39				

Conflict #2



SUMMARY

Groups	Count	Sum	Average	Variance
C2-Before	16	6	0.375	0.783333
C2-After	24	13	0.541667	0.519928

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.266667	1	0.266667	0.427417	0.517196	4.098172
Within Groups	23.70833	38	0.623904			
Total	23.975	39				

Note: Cx-Before: Vehicle conflict x observed on February 20, 2008, 7 a.m. to 9 a.m.

Cx-After: Vehicle conflict x observed on February 27, 2008, 7 a.m. to 9 a.m.

Travel Times and Vehicle Speeds

The time series of travel times and travel speeds observed during Wednesday morning peaks are shown in Figure 31 and Figure 32. The travel times and speeds for Monday morning peaks are plotted in Figure 33 and Figure 34. The results of the corresponding statistical tests (ANOVA) are in Table 48 through Table 51.

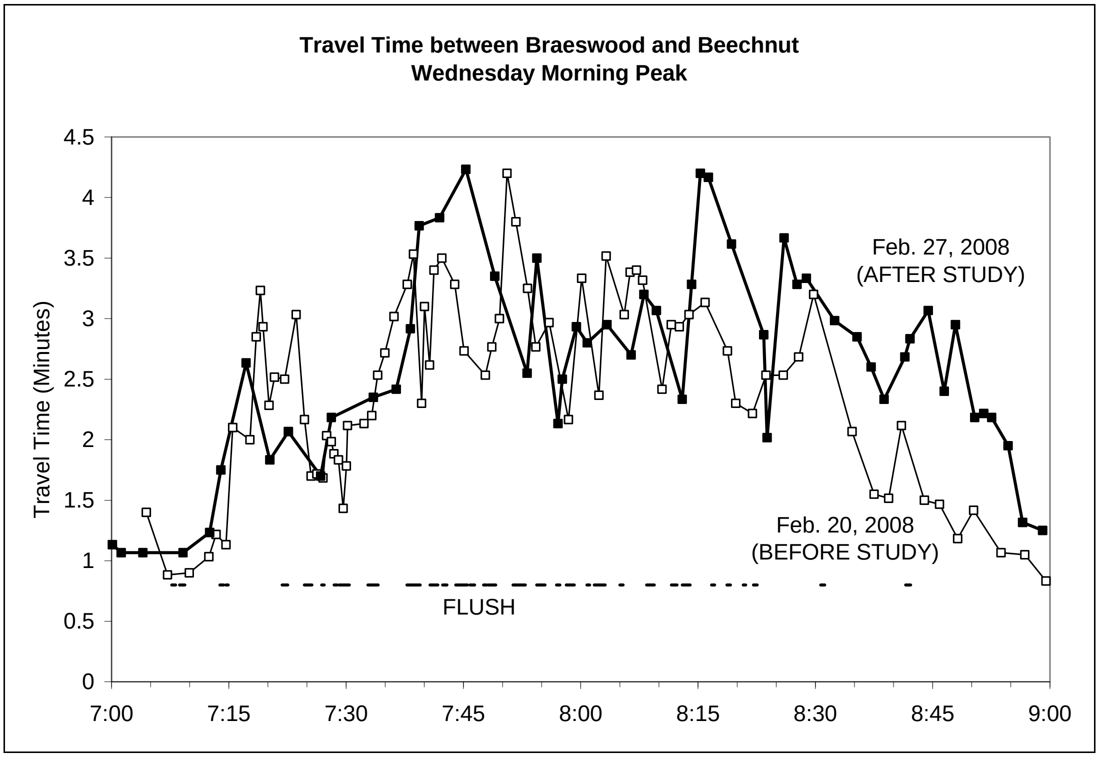


Figure 31. Travel Times (Minutes) — Wednesday Morning Peak.

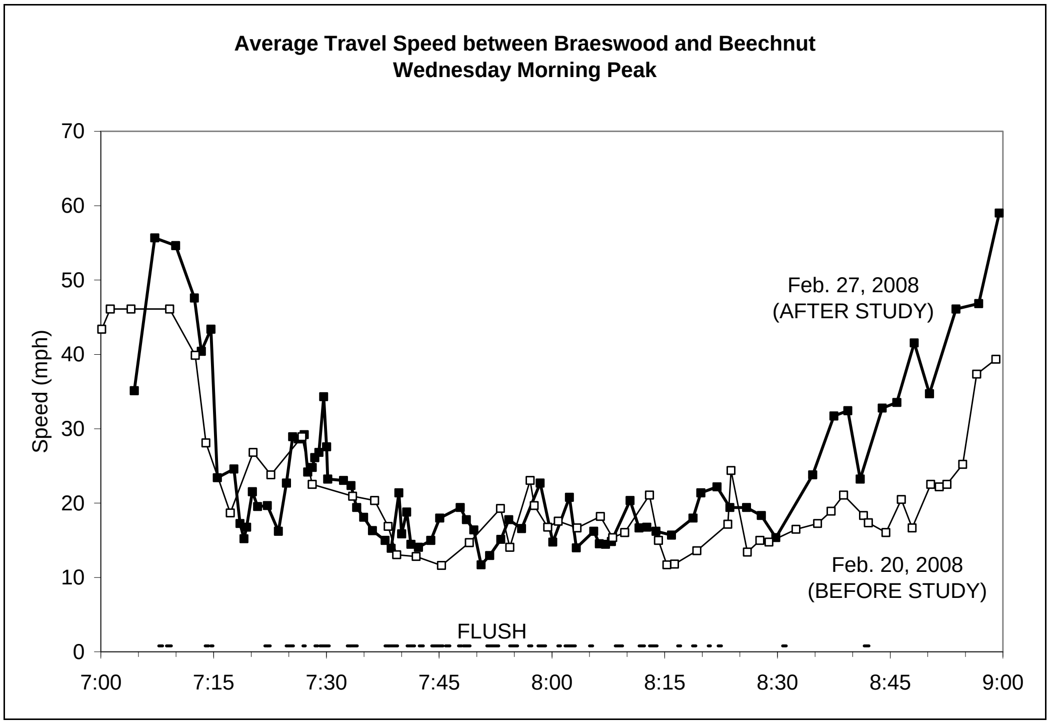


Figure 32. Travel Speeds (mph) — Wednesday Morning Peak.

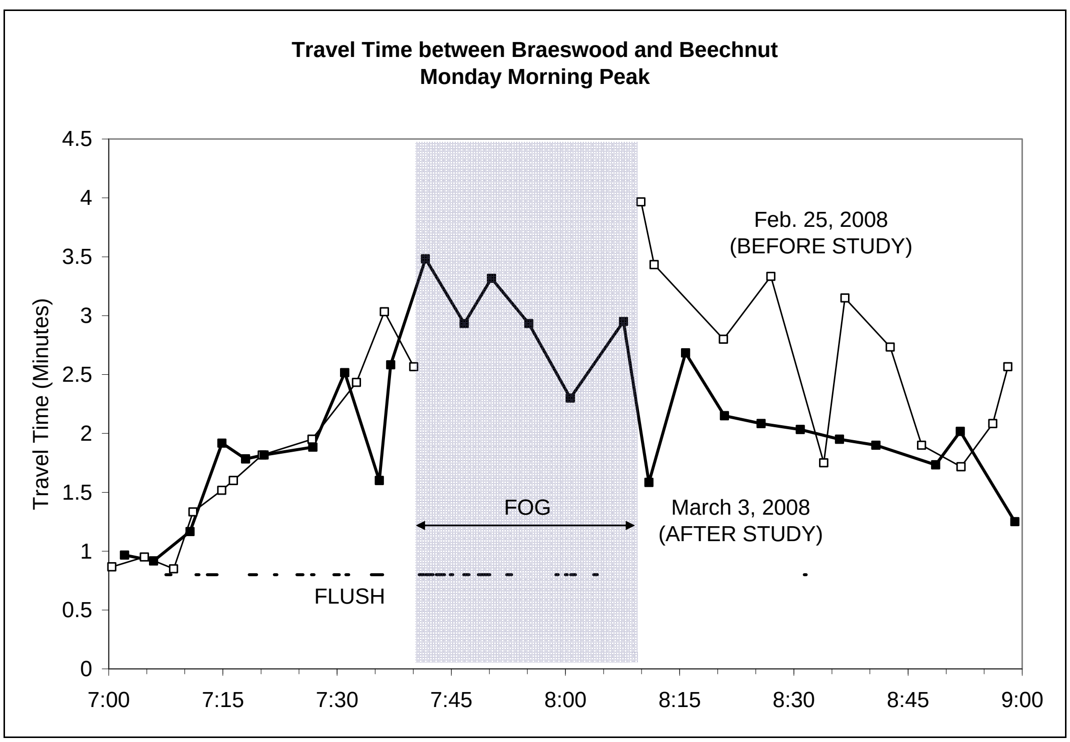


Figure 33. Travel Times (Minutes) — Monday Morning Peak.

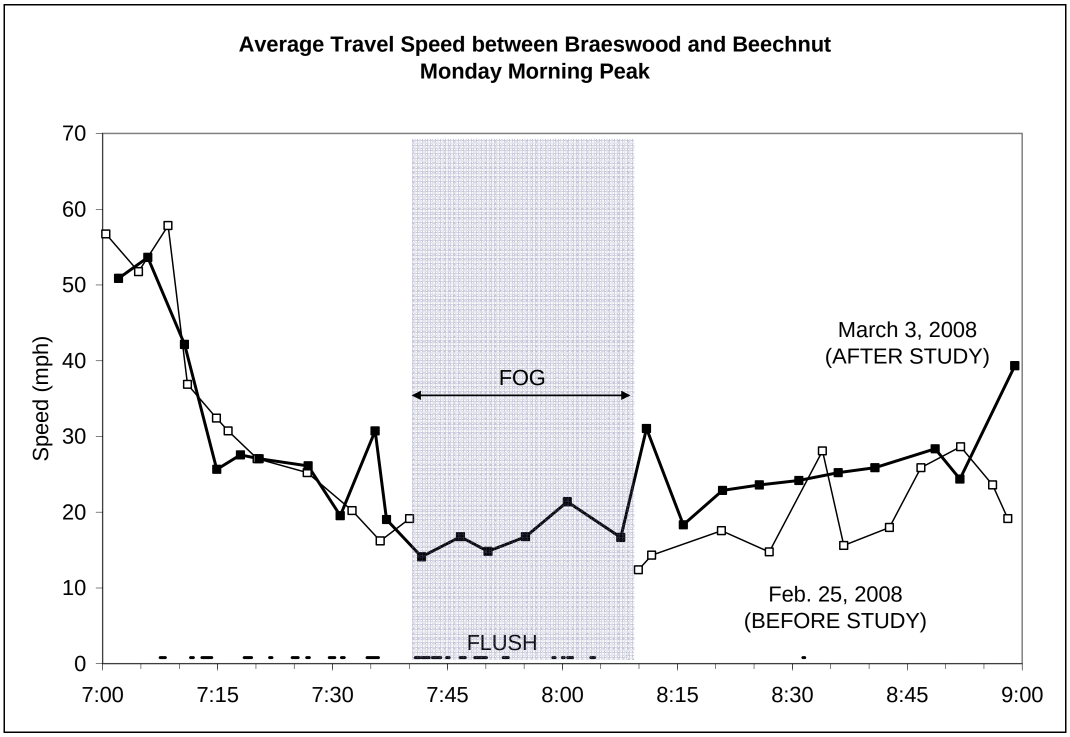


Figure 34. Travel Speeds (mph) — Monday Morning Peak.

Table 48. ANOVA of Travel Times without (TT-Before) and with (TT-After) Ramp Metering.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TT-Before	23	52.6825	2.290543	0.584771
TT-After	23	60.51111	2.630918	0.610896

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1.332329	1	1.332329	2.228597	0.142613	4.061706
Within Groups	26.30466	44	0.597833			
Total	27.63699	45				

Note: TT-Before: Travel time on February 25, 2008, 7 a.m. to 9 a.m.

TT-After: Travel time on March 3, 2008, 7 a.m. to 9 a.m.

Table 49. ANOVA of Travel Speeds without (v-Before) and with (v-After) Ramp Metering.

SUMMARY

Groups	Count	Sum	Average	Variance
v-Before	23	575.4465	25.01941	117.4991
v-After	23	488.7924	21.25185	82.09485

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	163.2373	1	163.2373	1.635694	0.207622	4.061706
Within Groups	4391.066	44	99.79695			
Total	4554.303	45				

Note: v-Before: Travel speeds on February 25, 2008, 7 a.m. to 9 a.m.

v-After: Travel speeds on March 3, 2008, 7 a.m. to 9 a.m.

Table 50. ANOVA of Travel Times without (TT-Before) and with (TT-After) Ramp Metering.

SUMMARY

Groups	Count	Sum	Average	Variance
TT-Before	19	43.45	2.286842	0.745242
TT-After	23	49.56667	2.155072	0.440522

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.18066	1	0.18066	0.312753	0.579114	4.084746
Within Groups	23.10584	40	0.577646			
Total	23.2865	41				

Note: TT-Before: Travel time on February 25, 2008, 7 a.m. to 9 a.m.

TT-After: Travel time on March 3, 2008, 7 a.m. to 9 a.m.

Table 51. ANOVA of Travel Speeds without (v-Before) and with (v-After) Ramp Metering.

SUMMARY

Groups	Count	Sum	Average	Variance
v-Before	19	484.1808	25.4832	155.0411
v-After	23	587.9646	25.56368	97.47082

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.067388	1	0.067388	0.000546	0.981471	4.08474
Within Groups	4935.097	40	123.3774			
Total	4935.165	41				

Note: v-Before: Travel speeds on February 25, 2008, 7 a.m. to 9 a.m.

v-After: Travel speeds on March 3, 2008, 7 a.m. to 9 a.m.

The time series plots suggest that traffic operations in terms of travel times and speeds improved only during the Monday morning peak period. However, the ANOVA results show that the improvement (i.e., reduction in travel time and increase in speed) was statistically not significant at the 95 percent confidence level.

CONCLUSIONS

From the field study, we conducted a before-after comparison of main lane traffic conditions before and after the deployment of ramp meters. The evaluation results indicated that the improvement in the MOEs were statistically significant only for Mondays. The differences in the MOEs on the other days of the week were not statistically significant at $\alpha = 0.05$. While the results suggested that the deployment of ramp meters did not provide substantial operational benefits at this location, the analysis of ramp meter operations using detector and signal status data logs revealed that a combination of heavy ramp demands and current flush policy used in Houston have significantly reduced the meter availability. The two different ramps studied had different results. For the Braeswood ramp, Monday was the only day that had higher meter availability during the peak-hour and thus also the only day that had some improvement in freeway traffic flow after the meter deployment. For the Beechnut ramp, the meter availability was less than 70 percent for all days except Friday. The analysis of tube data collected from the frontage road also showed that diversion increased after ramp metering deployment. However, due to the data quality issue, it is difficult to assess the accuracy of actual numbers (percentages) given the fact that the data from two adjacent tubes did not closely match in most cases. The analysis of video recording data indicated a slight safety improvement in terms of the number of conflicts as well as a marginal reduction in main lane travel times; however, the differences were not statistically significant.

From the field study, we identified certain conditions where ramp meter operations would be less effective and could potentially be considered for removal as follows:

- frequent flushes from a combination of heavy ramp demand (>1000 vph) and active flush mode, and
- peak-hour meter availability less than 70 percent.

CHAPTER 5: DEVELOPMENT OF CRITERIA AND GUIDELINES FOR INSTALLING, OPERATING, AND REMOVING RAMP CONTROL SIGNALS

CRITERIA FOR INSTALLING A RAMP CONTROL SIGNAL

Using the results of the simulations as well as the findings from the literature review, we developed a Ramp Control Signal Authorization Form. This form is shown in the operational guidelines contained in TxDOT Product 0-5294-P1. The form is modeled after TxDOT's current Traffic Signal Authorization Form, which is used to present the findings of a traffic signal warrant analysis for approval by the district engineer. By signing the authorization form, the TxDOT district engineer is signifying that one or more of the warrant conditions for installing a traffic signal have been met and the TxDOT district engineer is authorizing the use of funds to install a traffic signal at the studied location. The intent of the Ramp Control Signal Authorization Form is to provide TxDOT with a form that District Traffic Operations personnel can use to summarize for approval the criteria and conditions to justify the installation of a ramp control signal. The Ramp Control Signal Authorization Form contains the following:

- the name of the freeway where the ramp control signal will be located,
- the name of the cross-street entrance ramp on which the ramp control signal will be located,
- the direction of travel on the freeway,
- the control section and reference marker numbers of the freeway,
- the name of the city and/or county where the ramp control signal is to be installed,
- the name of the district where the ramp meter is to be installed,
- the date that the analysis was completed,
- the criteria and condition(s) that were met to justify the installation of the ramp control signal,
- a place or field to document any extenuating circumstances that might justify the installation of a ramp control signal,
- the signature and date of the district traffic section responsible for preparing and/or approving the authorization form, and
- the recommendation and approval signature of the district engineer.

Included on the authorization form are three sets of criteria the study team identified that could be used for justifying the installation of a ramp control signal at a location: traffic flow considerations, safety considerations, and other considerations.

Traffic Flow Considerations

The first set of criteria identified to justify the installation of a ramp control signal is traffic flow considerations. The *Texas Manual on Uniform Traffic Control Devices* (*TMUTCD*) (*37*) states that ramp control signals should be installed where flow entering the freeway routinely causes congestion to form on the freeway, and where operations of the freeway would be improved as a result of installing the control signal. As a result, we identified traffic flow conditions that may justify the installation of a ramp control signal:

1. Congestion routinely recurs in the merge area because the traffic demand on the freeway exceeds the capacity of the merge area.
2. The freeway regularly operates at speeds less than 50 mph for at least a half-hour period during the day (presumably during the peak period).
3. The ramp sustains a minimum flow rate of at least 300 vph during the peak periods.
4. The measured average hourly flow rates of traffic of the *two* rightmost freeway lanes exceed the thresholds established for different ramp acceleration lane lengths.
5. The combined hourly flow rates of the ramp plus the rightmost freeway lane volume exceed the thresholds established for different ramp acceleration lane lengths.

The first two criteria have been included because they are expressly identified in the *TMUTCD* as conditions where a ramp control signal may be beneficial. The criteria imply that the merge area is causing traffic on the freeway to break down, and that the breakdowns in freeway performance are severe enough and last for a long enough duration to cause a significant level of decline in freeway operations (Level of Service D or worse).

The third, fourth, and fifth criteria were developed as a result of simulation studies and review of the literature and are intended to reflect the minimum traffic conditions that should be present at a ramp location before a ramp control signal is installed. The fourth criterion is intended to imply that a ramp needs to have at least a minimum amount of traffic using it to justify the need for interrupting its flow. The literature and researchers' experience have shown that drivers have a tendency to violate the signal indications when cycle length exceeds 10 to

15 seconds (assuming a one-vehicle-per-green operating strategy). The maximum service flow rate that can be achieved using this cycle length is 360 vph to 240 vph. Therefore, the research team recommends a maximum cycle length of 12 seconds (2 seconds of green, followed by 10 seconds of clearance) when operating ramp control signals in a single-lane, one-vehicle-per-cycle service rate operating mode. This cycle length is equivalent to achieving a maximum service flow rate of 300 vph.

The fifth criterion implies that there must be a minimum amount of traffic that exists in the two rightmost lanes of the freeway (i.e., those most closely affected by the traffic entering the ramp). Field observations and simulation studies showed that under light volume conditions, through drivers had a tendency to vacate the rightmost lane to allow traffic entering the freeway to have their own lane. The tendency holds true as long as the traffic volumes averaged from the two rightmost lanes did not exceed 1600 vphpl (for entrance ramps that have relatively short acceleration lengths). As the average traffic volumes in these two lanes exceed 1600 vphpl, there are not enough gaps of sufficient size in the second lane from the right to allow drivers to vacate the rightmost lane without significantly altering their speed. As the length of the acceleration lane increases, the average threshold level of traffic in the two rightmost lanes increases. Figure 35 shows the minimum main lane volume thresholds for different ramp acceleration lane lengths.

The simulation results also showed that there was a threshold of entering ramp traffic and traffic in the rightmost lane of the freeway where installing a ramp control signal can result in improved performance of the freeway (in terms of average running speed of traffic). Below this threshold, no statistically significant difference existed between the average running speed of the freeway when the ramp control signal was active versus when it was not active. However, as the combination of ramp volume and traffic volumes in the rightmost lane exceeded these thresholds, the simulation results showed that a ramp control signal resulted in higher average main lane travel speeds than those achieved when a ramp control signal was not present. We used this relationship to define the thresholds shown in Figure 36.

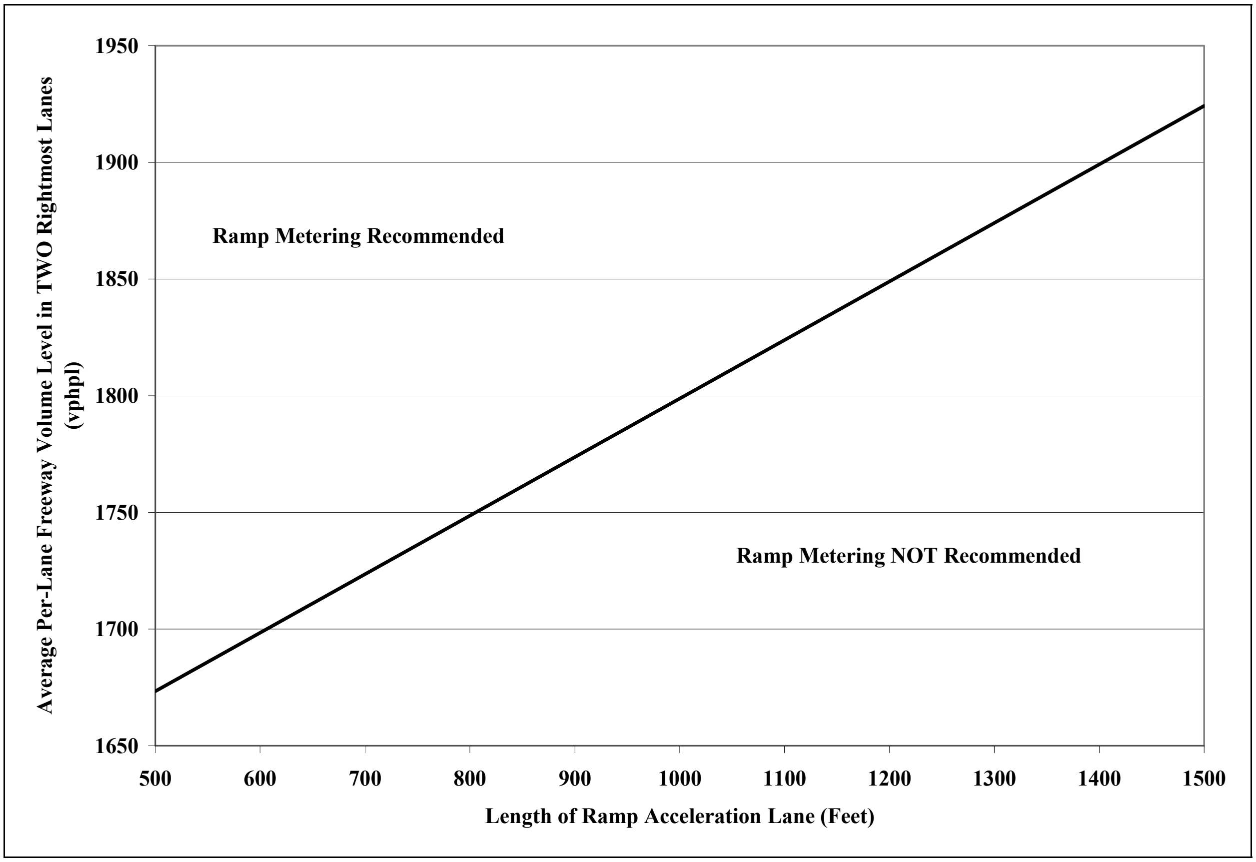


Figure 35. Freeway Main Lane Volume Thresholds (Average of Two Rightmost Lanes) for Installing Ramp Control Signals.

Safety Considerations

Another reason for installing a ramp control signal at a location might be to address a safety or collision situation that is occurring on the ramp. To address this need, we identified four criteria that could potentially be used to justify installing a control signal on a ramp. As discussed in the first criterion, one reason for installing a ramp control signal might be a higher than normal collision rate. Studies have shown that ramp control signals can reduce some types of collisions that occur in the merge area of ramps. If a ramp is experiencing a higher than typical collision rate in the merge area, then installing a ramp control signal might help reduce the collision rate.

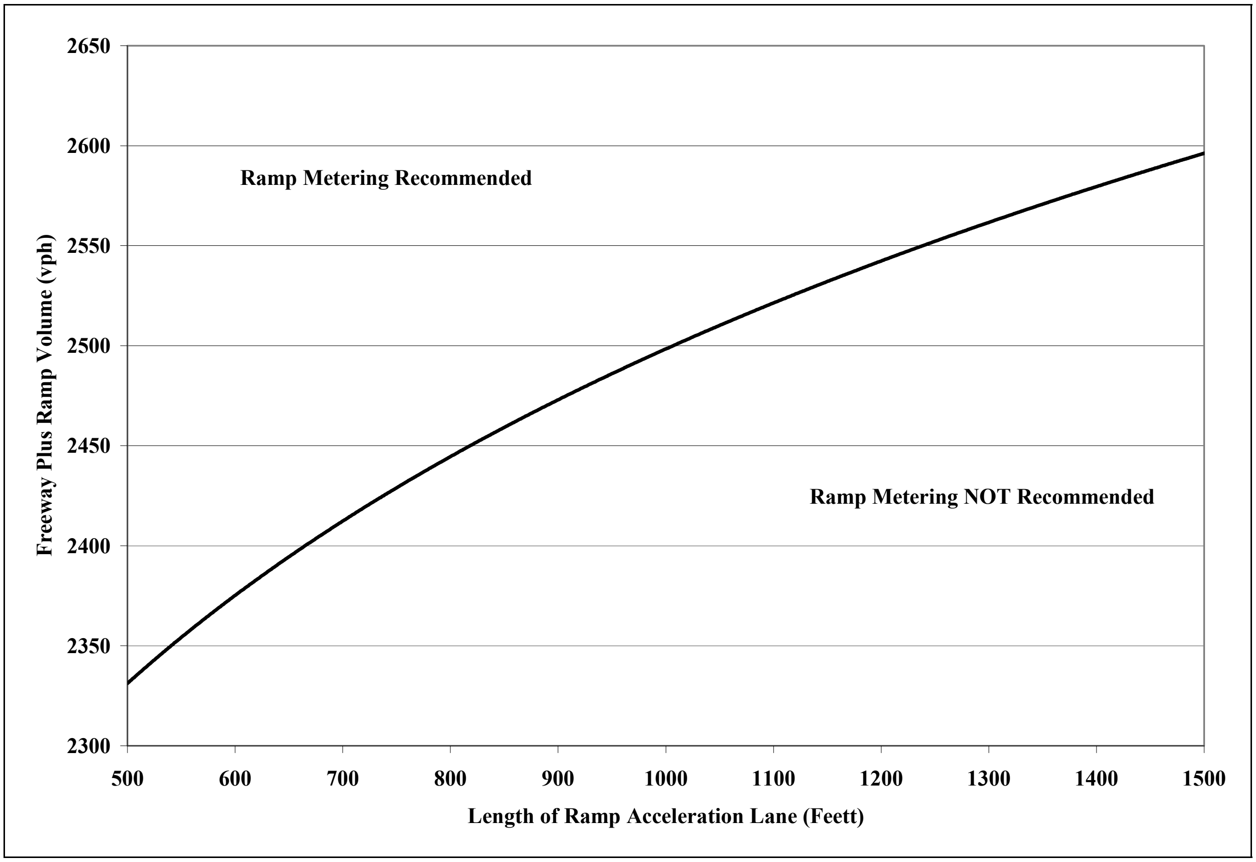


Figure 36. Combination of Ramp plus Freeway (Outside Lane Only) Volume Thresholds for Installing Ramp Control Signals.

The second criterion was derived from the *TMUTCD.* A ramp control signal may be justified if the primary cause of collisions in the merge area can be attributed to congestion. The idea is that installing a ramp meter would improve freeway performance, thereby potentially reducing collisions in the merge area.

The third safety-based warrant criterion was developed based on vehicle kinematics properties and the assumption that the interacting ramp and freeway traffic vehicles must be able to maintain a desirable time to collision (TTC) after the merge. A TTC value lower than a specified threshold indicates an unsafe merge condition at the ramp meter.

Figure 37 shows the merging interaction between ramp and freeway traffic. The ramp vehicle attempts to find the available gap in the freeway traffic stream to merge safely. The available gap or the average space headway in the freeway segment depends on the segment free-flow speed and prevailing traffic flow conditions. For a typical merging interaction, the ramp vehicle accelerates to reach the desired speed, which is usually the prevailing freeway speed. The freeway vehicle, on the other hand, either remains at the same speed or slightly decelerates to maintain comfortable time headway.

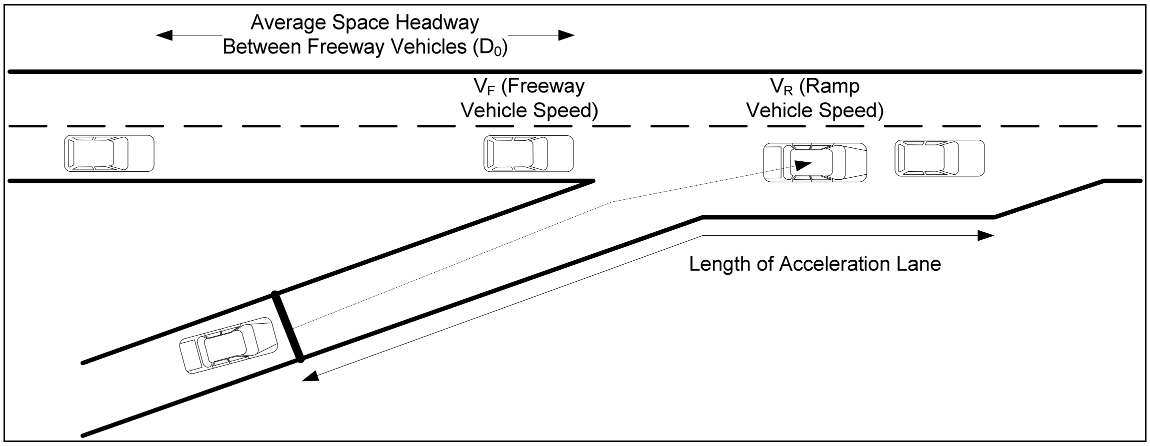


Figure 37. Ramp and Freeway Traffic Merging Interaction.

Under this interaction behavior, the worst-case scenario exists when the freeway vehicle continues at the current speed without any deceleration and the ramp vehicle slowly accelerates at a comfortable pace to keep up with the freeway speed. The worst-case scenario is defined by the moment at which the TTC between the two vehicles reaches the minimum. The TTC is the time remaining for the freeway vehicle to collide with the merging ramp vehicle if it were to continue at its current speed.

The objective of this analysis was to determine the speed that the ramp vehicle, under a specific freeway traffic condition, would have to achieve at the merge in order to prevent the TTC from dropping below the required threshold.

To define the interaction mathematically, the process starts from the moment when the ramp vehicle just merges into the freeway lane. This time point is defined as t = 0. The distance gained by both freeway and ramp vehicles can be expressed as:

$$
\begin{aligned}
S_F &= V_F t + \frac{1}{2} a_F t^2 \\
S_R &= V_R t + \frac{1}{2} a_R t^2
\end{aligned}
\tag{13}
$$

where S_F = distance gained by freeway vehicle over time t, V_F = freeway vehicle speed, a_F = freeway vehicle acceleration, S_R = distance gained by ramp vehicle over time t, V_R = ramp vehicle speed, and a_R = ramp vehicle acceleration.

When $S_F > S_R$, the space headway decreases. Define

$$\Delta S(t) = S_F - S_R ,$$

or equivalently

$$\Delta S(t) = (V_F - V_R)t + \frac{1}{2}(a_F - a_R)t^2 . \tag{14}$$

The minimum space headway between the two vehicles occurs when $\Delta S(t)$ is maximized; that is:

$$\frac{dS(t)}{d(t)} = 0 . \tag{15}$$

Solving Eq. (15) yields the time at which the space headway is the most critical; that is:

$$t_m = \frac{(V_F - V_R)}{(a_F - a_R)} . \tag{16}$$

The speed of the freeway vehicle at t_m is then equal to:

$$V_F(t_m) = V_F + a_F t_m . \tag{17}$$

Let D_0 be the average space headway between freeway vehicles. Now, assume that this is also the average space headway that the ramp vehicle will generally have available for the merge. The minimum space headway between the ramp and freeway vehicles will occur after the merge at t_m. Therefore, the minimum TTC between the freeway and ramp vehicles can be defined as:

$$TTC_{min} = \frac{D_0 - \Delta S(t_m)}{(V_F)(t_m)} . \tag{18}$$

It is reasonable to consider the case of nonaggressive freeway drivers; that is, $a_F \leq 0$. Under this assumption, the worst case took place when $a_F = 0$, and Eq. (18) becomes:

$$TTC_{min} = \frac{D_0 - (V_F - V_R) - \frac{1}{2}(a_F - a_R)t_m^2}{V_F}. \tag{19}$$

The values of D_0 depend on the freeway traffic conditions. As traffic volume increases, the freeway speed decreases. This relationship is described in detail in the *HCM* (*22*). For a basic freeway segment, the freeway speed is a function of freeway traffic volume (q_F) and free-flow speed (FFS) of a segment, or mathematically:

$$V_F = f(q_F, FFS) \tag{20}$$

where f is the *HCM* functions to relate the resulting freeway speed to the free-flow speed and the prevailing traffic volume of the segment.

Therefore, using Eq. (20), D_0 can be expressed as:

$$D_0 = 3600\frac{V_F}{q_F} = \frac{f(q_F, FFS)}{q_F}. \tag{21}$$

Substituting Eq. (16) and Eq. (21) into Eq. (19) gives:

$$TTC_{min} = \frac{3600\frac{V_F}{q_F} - \frac{1}{2}\frac{(V_F - V_R)^2}{a_R}}{V_F}. \tag{22}$$

Now, if the desired minimum TTC is specified in Eq. (22), solving for V_R gives the speed that the ramp vehicle would have to achieve to maintain the specified minimum TTC.

Since V_F is a function of q_F and FFS as described in Eq. (20), solving for V_R in Eq. (22) would require the following parameters:

- TTC_{min} — desired minimum TTC after the merge,
- FFS — free-flow speed of the segment,
- q_F — prevailing freeway traffic flow rate, and
- a_R — acceleration rate of the ramp vehicle after the merge.

We developed a spreadsheet using Microsoft Excel® to evaluate the speed requirement for the ramp vehicle at the merge under various scenarios. The Solver add-in in Microsoft Excel® was used to find the solutions to the equations used to derive the speed requirement. An example of the spreadsheet is shown in Table 52.

In this table, the free-flow speed was set at 75 mph, and freeway flow rates were varied from 1000 to 2200 pcphpl. The minimum TTC was fixed at 2.0 seconds, and the ramp vehicle acceleration was configured at 0.1 g or 3.22 feet per second squared. For this example, the maximum required speed for the ramp vehicle at the merge is 57.0 mph (shaded cell), which was observed when the flow rate was equal to 1800 pcphpl. The implication here is that, for a freeway segment with FFS = 75 mph, a ramp meter that has an acceleration length adequate for the ramp vehicle to reach 57.0 mph at the merge would be able to prevent the TTC between the ramp and freeway vehicles from dropping below the required threshold of 2.0 seconds regardless of freeway traffic conditions.

Table 52. Example of Spreadsheet for Calculating Ramp Speed Requirement.

FFS (mph)	q_F (vph)	V_F (mph)	V_R (mph)	V_F-V_R (mph)	V_F (fps)	V_R (fps)	a_F-a_R	D_0 (Feet)	t_m	$V_F(t_m)$	Δs_m	ttc
75	1000	75.0	47.9	27.1	110	70	-3.22	396	12.36	75.0	2.46.0	2.00
75	1100	75.0	49.9	25.1	110	73	-3.22	360	11.42	75.0	210.0	2.00
75	1200	75.0	51.8	23.2	110	76	-3.22	330	10.57	75.0	180.0	2.00
75	1300	74.9	53.4	21.5	110	78	-3.22	304	9.79	74.9	154.4	2.00
75	1400	74.7	54.8	19.9	110	80	-3.22	282	9.06	74.7	132.3	2.00
75	1500	74.2	55.8	18.4	109	82	-3.22	261	8.37	74.2	112.8	2.00
75	1600	73.5	56.6	16.9	108	83	-3.22	242	7.70	73.5	95.5	2.00
75	1700	72.4	57.0	15.5	106	84	-3.22	225	7.05	72.4	80.1	2.00
75	1800	71.0	57.0	14.1	104	84	-3.22	208	6.42	71.0	66.3	2.00
75	1900	69.3	56.6	12.7	102	83	-3.22	192	5.79	69.3	53.9	2.00
75	2000	67.1	55.7	11.3	98	82	-3.22	177	5.16	67.1	42.9	2.00
75	2100	64.4	54.4	10.0	94	80	-3.22	162	4.54	64.4	33.1	2.00
75	2200	61.2	52.7	8.6	90	77	-3.22	147	3.90	61.2	24.5	2.00

A similar analytical procedure was applied to different FFSs. The results can be displayed graphically as shown in Figure 38. Each curve represents the required merge speeds for varying flow rates at a specific FFS. The solid black line represents the maximum point observed in each curve, which is the minimum ramp speed requirement at the merge that a ramp vehicle must attain in order to satisfy a minimum TTC threshold regardless of traffic conditions.

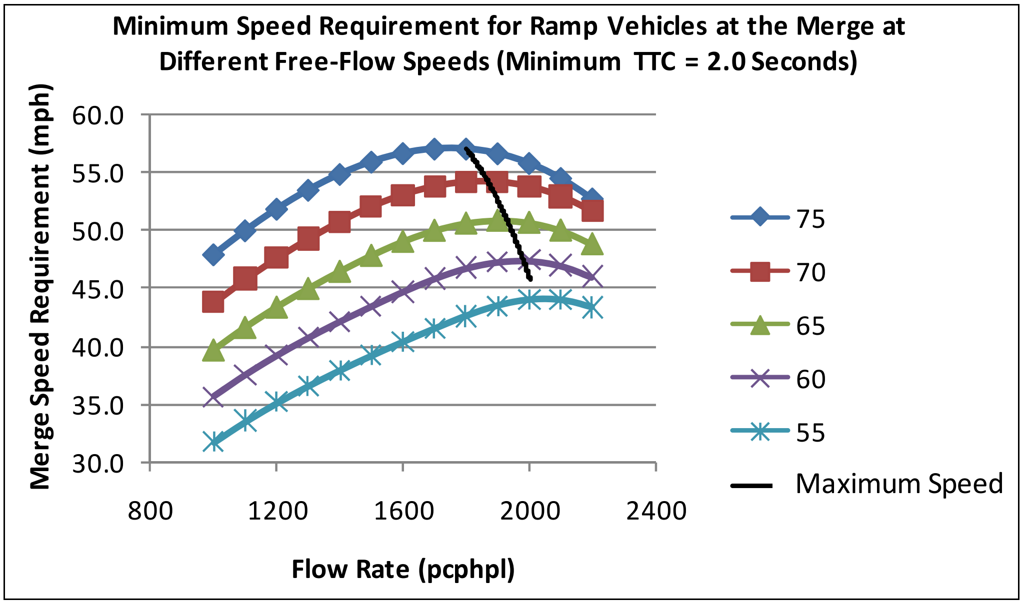


Figure 38. Example of Merge Speed Requirement (TTC = 2.0 seconds).

Through a similar analytical process, the research team analyzed the ramp speed requirements using a fixed ramp vehicle acceleration rate of 3.22 feet per second squared and the TTCs of 1.5, 1.75, and 2.0 seconds. The results are the recommendations that we provided in the safety-based warrant criteria of the TxDOT ramp controls signal installation criteria.

Figure 39 summarizes our recommendations from the analysis at TTCs of 1.5 to 2.0 seconds and an FFS of 55 to 75 mph. For example, if the free-flow speed of the freeway segment considered for ramp metering is 70 mph and the desired minimum TTC is 1.5 seconds, the minimum ramp speed requirement at the merge from the table would be 50.8 mph. This implies that, to maintain the minimum TTC of 1.5 seconds, a ramp must have a sufficient acceleration length for the ramp vehicle to start from zero speed at the stop line and reach at least 50.8 mph at the merge area.

Mininum Speed Requirement for Ramp Vehicles at the Merge			
Free-Flow Speed (mph)	Min Vr (mph)		
	Min TTC = 2.0	Min TTC = 1.75	Min TTC = 1.5
75	57.0	55.3	53.8
70	54.1	52.4	50.8
65	50.8	49.0	47.4
60	47.4	45.5	44.0
55	44.0	42.2	40.6

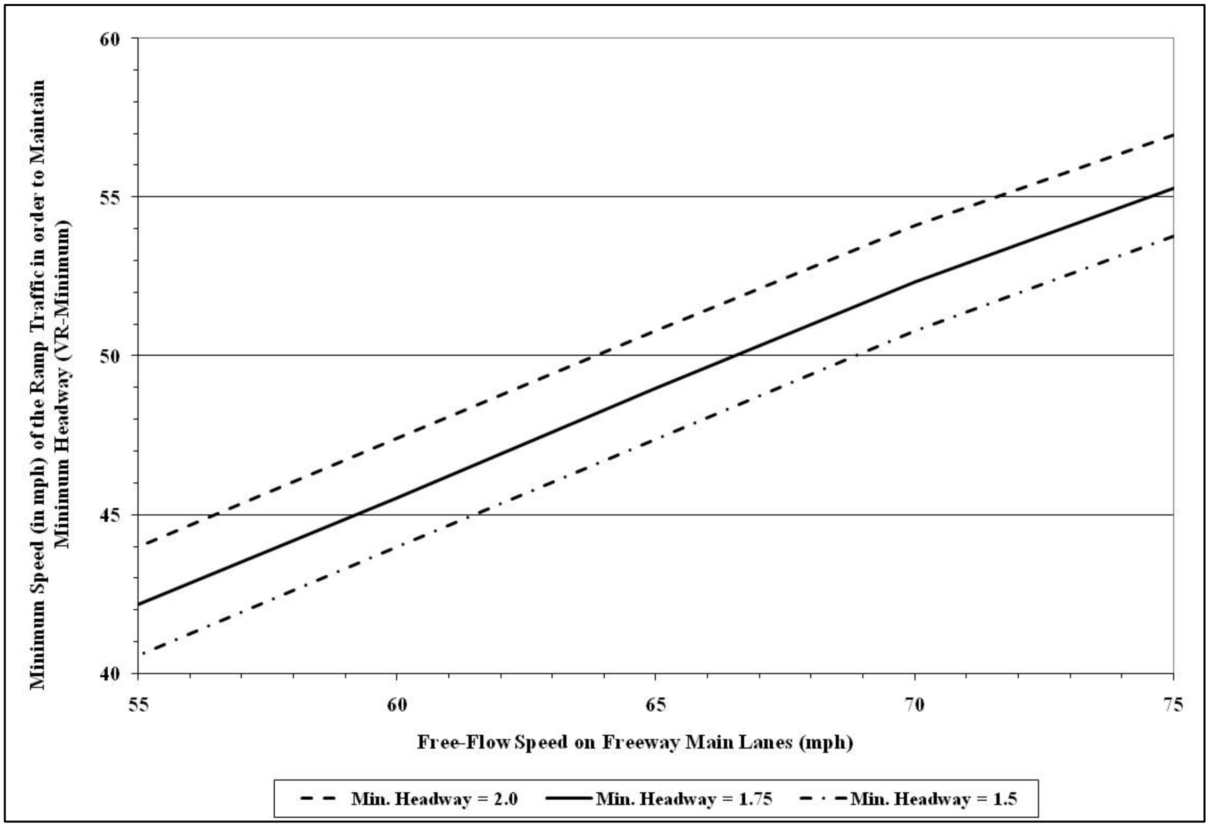


Figure 39. Speed Requirement for Ramp Vehicles at the Merge.

The fourth criterion addresses the concern of adequate storage space between the ramp control signal and the frontage road. One purpose of a ramp control signal is to break up platoons of traffic released from upstream signalized intersections. Because the arrival rate of traffic leaving these intersections is generally greater than the metering rate, queues can form at some ramp locations. If these queues become too long, they could potentially block traffic on the frontage road, thereby creating the potential for rear-end collisions on the frontage road. Figure 40 shows the storage length criterion. Adapted from the Chaudhary et al. (*32*), this criterion was included to give operations personnel an idea of the distance required to store vehicles behind the stop line of the ramp for various ramp demands and metering rates. If the available storage space is greater than or equal to the required storage space, then sufficient space exists for installing the ramp meter. If sufficient space does not exist to store the arriving demand, we recommend that the ramp control signal not be installed at this location.

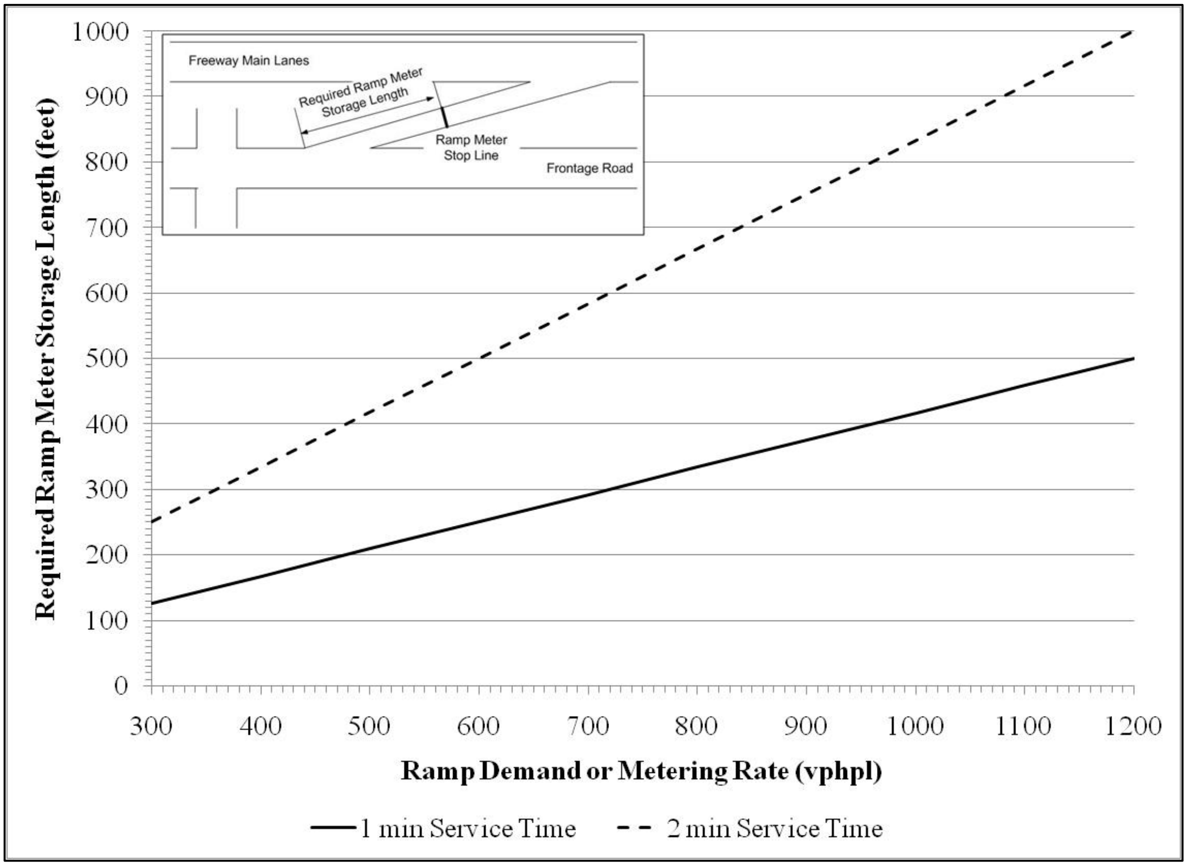


Figure 40. Required Length to Store Vehicles Waiting for Service at Ramp Control Signal (*32*).

Other Considerations

As with a traffic signal installation, other factors may exist that give a reason for (or against) installing a ramp control signal. The *TMUTCD* (*37*) suggests that one reason for installing a ramp control signal might be to address short-term sporadic traffic congestion that might develop as a result of traffic entering or leaving a special event venue. In this situation, the ramp control signals might be one element of a larger traffic management plan that would be implemented to address congestion problems caused by traffic demands at the venue. Another reason for justifying the installation of the ramp control signal at a location is that it is needed as part of a much larger series of ramp control signals that are designed to operate the system, even though the ramp may not totally satisfy the traffic flow or safety criteria by itself. This criterion is equivalent to the system warrant that exists for traffic signal systems.

Situations exist where the negative impacts of installing a ramp control signal may outweigh the benefits to be derived for freeway traffic. When considering whether or not to install a ramp control signal, TxDOT may want to consider these factors. For example, one potential impact of a ramp control signal is that it encourages some drivers to divert to alternate routes. TxDOT may not want to install a ramp control signal if the traffic conditions on the adjacent arterial street cannot accommodate the diverted demand or if traffic is likely to divert through neighborhoods or past sensitive areas (such as schools) to get to these alternate routes.

Another reason for not installing a ramp control signal is the impact that it might have on the environment. While ramp control signals have the potential to reduce vehicle emissions and fuel consumption on the freeway, these reductions are offset by increases in emissions and fuel consumption for vehicles waiting to enter from the ramp. Generally, vehicles accelerating from a stop consume more fuel and emit more pollutants than vehicles that are already moving. Careful consideration should be given to whether ramp control signals are justified when traffic on the freeway is operating at or close to free-flow speeds.

Equity is often cited as an argument against installing ramp control signals. Equity issues arise from the perception that ramp control signals favor suburban motorists who make longer trips than those who live in the immediate area of the ramp, who make shorter trips. The perception is based on the assumption that individuals already on the freeway are not delayed by the ramp control signal. Issues of equity tend to be more pronounced in areas that are en route to a core destination (such as a central business district) where those entering the freeway closer to the destination have proportionally unfair commutes when comparing travel time against travel distance. Strategies that have been employed to address equity issues include the following:

- Initially operate the ramp control signal in the outbound direction to eliminate the city-suburban equity problem.
- Implement more restrictive metering rates farther away from the central business district.

Process for Approving Ramp Control Signal Installation

Figure 41 shows a suggested process for approving the installation of a ramp control signal. This process is modeled after the process used to approve the installation of a traffic control signal. The District Traffic Operations section initiates the study for installing a ramp control signal. The reason for studying a location could be the result of an internally generated need or a request from an external source (another public agency or a citizen). The next step in the process is to conduct an engineering investigation to examine if the conditions and criteria are met for installing the ramp control signal. The District Traffic Operations section completes the Ramp Control Signal Authorization Form and sends the form to the district engineer for approval. If the district engineer approves the form, signed copies of the form are sent to the Traffic Operations Division for record retention. Another copy of the form is forwarded to the District Advance Planning section, which initiates the preparation of the plans, specifications, and estimates (PSE) for installing the ramp control signal. The PSE are submitted to the Traffic Operations Division for review and comment.

Data Requirements for Completing Ramp Control Signal Authorization Form

The decision to install a ramp control signal should be based on actual, measured traffic and geometric conditions. While it may be appropriate to install the infrastructure (conduit, pull boxes, communications, etc.) to support ramp control signals in new freeway construction or reconstruction, the decision to install and operate ramp control signals should not be based on future or projected traffic conditions.

Geometric Conditions

The following information about the geometry of the freeway-ramp merge area is needed to complete an assessment of the need for a ramp control signal:

- the number of lanes on the freeway section upstream and downstream of the proposed ramp control signal location,
- the number and width of the ramp,
- the length of the acceleration lane of the ramp merge area (measured from the nose of the gore area to the end of the acceleration lane),
- the grade of the ramp approaching the freeway merge area,

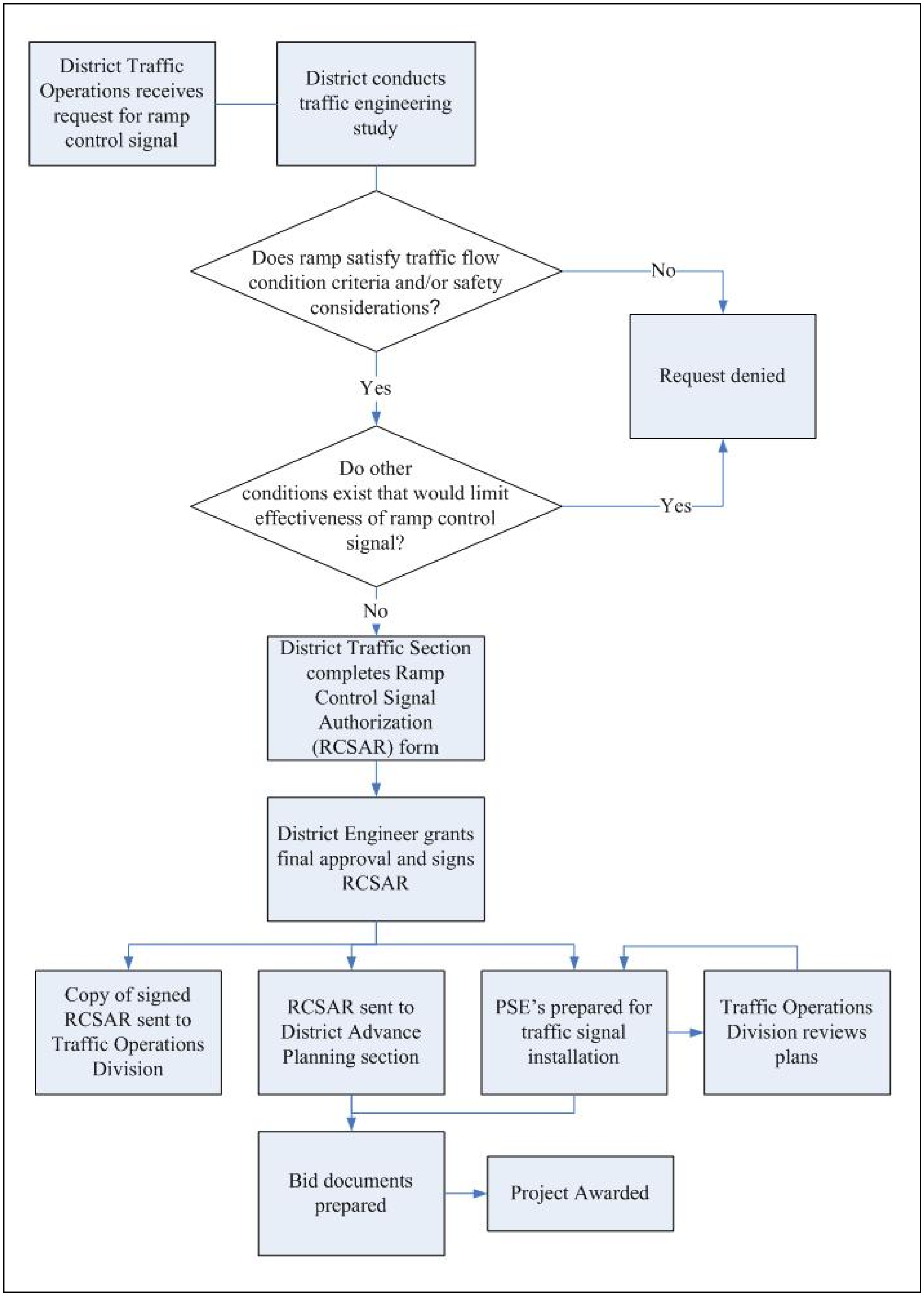


Figure 41. Recommended Process for Approving Installation of New Ramp Control Signal.

- the length of the ramp (measured from the beginning of the ramp on the frontage road to the gore of the area on the freeway),
- the distance from the upstream arterial conflict point (either the intersection or the U-turn bay) to the beginning of the entrance ramp,
- the presence of any sight distance restrictions (trees, buses, retaining walls, bridge columns, etc.), and
- the free-flow and prevailing speed of both the traffic on the ramp and on the freeway.

Vehicle Count Information

The traffic count should include the number of vehicles in each lane of the freeway upstream of the ramp location and the number of vehicles entering the freeway on the ramp. Ideally, a full week's worth of data (Monday through Friday) should be collected, but at a minimum, traffic count data from both the freeway and the ramp should be obtained from three consecutive, "representative days." Furthermore, under ideal conditions, data should be collected for 24 hours during each data collection period, but at a minimum, traffic counts should be made from at least 1 hour before the a.m. peak period to 1 hour after the p.m. peak period. Traffic count data should be recorded for each quarter hour (i.e., 15-minute interval) for the duration of the count. While it is not essential to quantify the number of heavy vehicles on both the freeway and entrance ramp, it is important to note whether a significant proportion of both the freeway and the ramp traffic streams can be classified as heavy vehicles.

Whenever possible, traffic count data should be collected from "representative days." A representative day is one in which traffic conditions generally reflect a typical day on the freeway. Generally speaking, a representative day is normally an average, mid-week day. Whenever possible, data should be collected on days free of unusual traffic events, such as incidents or collisions. (Note: Incidents conditions upstream or downstream of the study location can significantly alter freeway counts in the study location. Incidents on adjacent facilities can also significantly alter typical travel patterns on a freeway. It is critical that the individual doing the analysis have a clear understanding of the presence and impacts of any incident) In addition to incident-free data, avoid using traffic count data that include any of the following conditions:

- when weather has a significant impact on traffic operations,
- near major traffic generators or retail areas during major traffic events or holidays,

- near major school holidays (such as spring, fall, and winter breaks or summer months), and
- federal or state holidays.

Collision (or Crash) Information

Crash information in the immediate vicinity of the ramp location should be obtained for a minimum of one year and preferably three years prior to the study period. Crash information can be obtained from traditional TxDOT sources. In those locations where accident and collision information is routinely collected as part of the routine logging of incident information, these logs can be used as a substitute for actual collision records.

REMOVAL OF RAMP CONTROL SIGNAL

Changing traffic patterns over time can eliminate the need for a ramp control signal. Often, reconstruction of the freeway increases capacity and improves traffic operations so that ramp control signals are no longer necessary.

Removal Criteria

Neither the *TMUTCD* (*37*) or *MUTCD* (*5*) provides specific criteria that can be used to determine if and when to remove a ramp control signal. As in the case of an intersection traffic signal, engineering judgment should be used. Removal of a ramp control signal should be considered when one or more of the following situations exist:

- if the freeway is reconstructed so that the ramp is the beginning of a new freeway lane,
- when traffic demand on the ramp no longer exceeds the minimum volume threshold for installing a ramp meter (300 vph),
- when the rate of crashes in the merge area exceeds the mean crash rate of other ramps that use ramp control signals,
- if a substantial increase in rear-end crash rates is observed for vehicles on the frontage road,
- when the meter availability during the peak operating hours is less than 70 percent,

- when the prevailing speed of the freeway exceeds 50 mph or greater throughout the entire day (a result of reconstruction of the freeway),
- when the annual cost of operating and maintaining a ramp control signal exceeds the estimated benefits,
- when delays to the ramp traffic exceed the threshold established by the district engineer (Note: The Houston District's policy is that delays cannot exceed 2 minutes. In Minneapolis, this threshold is set to 4 minutes.), and
- when driver noncompliance reaches an unacceptable level and increased enforcement activities have failed to correct noncompliance issues.

TTI developed a Ramp Control Signal Removal Authorization Form similar to the Ramp Control Signal Authorization Form. This form lists the criteria that researchers have identified for removing a ramp control signal. As with the Ramp Control Signal Authorization Form, the Ramp Control Signal Removal Authorization Form should be completed by the District Transportation Operations section after conducting an engineering investigation of the ramp in question. The form should then be submitted to the district engineer for his or her approval. After the district engineer signs the form, a copy of the completed and signed form should be sent to the Traffic Operations Division for record retention.

Process for Removing Ramp Control Signals

When removing a ramp control signal, we recommend that TxDOT adopt the following:

- An information sign should be installed indicating that the ramp meter will be removed. It is recommended that the sign be in place at least two weeks prior and two weeks after removal of the ramp meter. This sign should replace the "RAMP METERED WHEN FLASHING" sign. An additional sign may be placed near the ramp control signal heads.
- Ramp control signal heads should either be bagged or pointed away from the entering ramp traffic for the two-week period after the meters have been deactivated.
- If, after a period of non-operation, the ramp merge area operation and safety are acceptable, the signal heads, signs, and ramp control signal controller can be removed from the field.

- If the ramp control signal is to be removed as part of a reconstruction project, it is recommended that the in-ground infrastructure (conduit and pull-boxes for cable runs and controller cabinet, and traffic sensors for the freeway) be reinstalled as part of the construction activities. It is not recommended that loop detectors or other traffic sensors for the ramp be installed as part of the reconstruction because exposure to the weather and traffic may cause these sensors to fail before a ramp control signal is needed.

OPERATIONAL GUIDELINES

Researchers were tasked with developing guidelines that TxDOT could use in the decision-making process for installing, removing, and operating ramp control signals. Originally, it was envisioned that these guidelines would be written as a standalone research report; however, over the course of this research project, the research team, in conjunction with the TxDOT Project Advisory Panel, determined that it would be better if the guidelines were written as a chapter that could be inserted into TxDOT's current *Traffic Signals Manual*. The guidelines contain the following sections:

- an introduction that outlines the purpose and benefits of ramp control signals;
- a section that describes who has the authority to install and/or remove a ramp control signal, and the process for securing approval;
- a section that contains the criteria that can be used to justify the installation of a ramp control signal;
- a section that contains a description of the different modes of operating ramp control signals, including single-lane single-entry mode, single-lane bulk-entry mode, and dual-lane operations;
- a section on the basic operating parameters and fundamentals of a ramp control signal, including setting the metering ramp rates, queue management strategies, startup and shutdown procedures, etc.;
- a section on the criteria and processes for removing a ramp control signal;
- a section that describes special operations that might occur at a ramp control signal, including transit or HOV bypass lanes, and operations during incident conditions;

- a section on measuring and monitoring the performance of ramp control signals, including performance measures, assessment approaches, and ongoing effectiveness monitoring;
- a section that discusses the importance of enforcements and provides guidelines that can be used in the design of a ramp meter installation to support enforcement activities; and
- a section on the maintenance of ramp control signals, include checklist items to be incorporated into a preventative maintenance program for ramp control signals.

The guidelines also contain the Ramp Control Signal Authorization Form and the Ramp Control Signal Removal Authorization Form.

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APPENDIX A:
RESULTS OF VISSIM® SIMULATION COMPARING THE EFFECTS OF USING A RAMP CONTROL SIGNAL ON FREEWAY PERFORMANCE

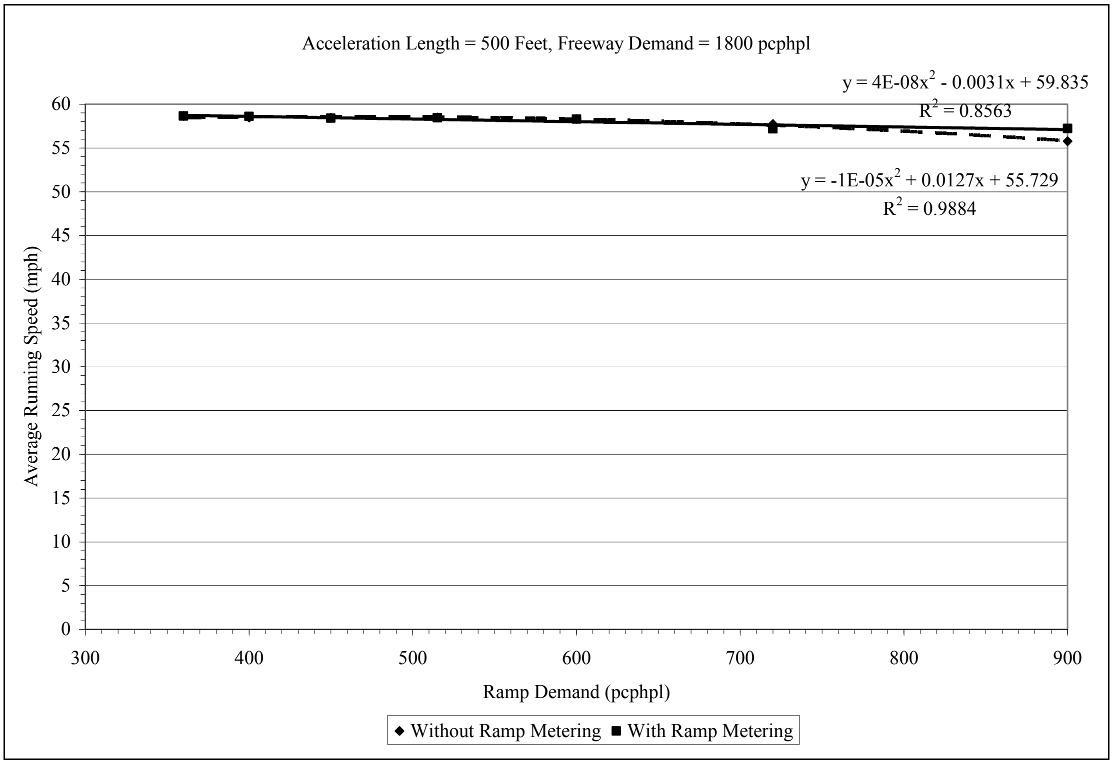

Figure A-1. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 1800 pcphpl Freeway Demand

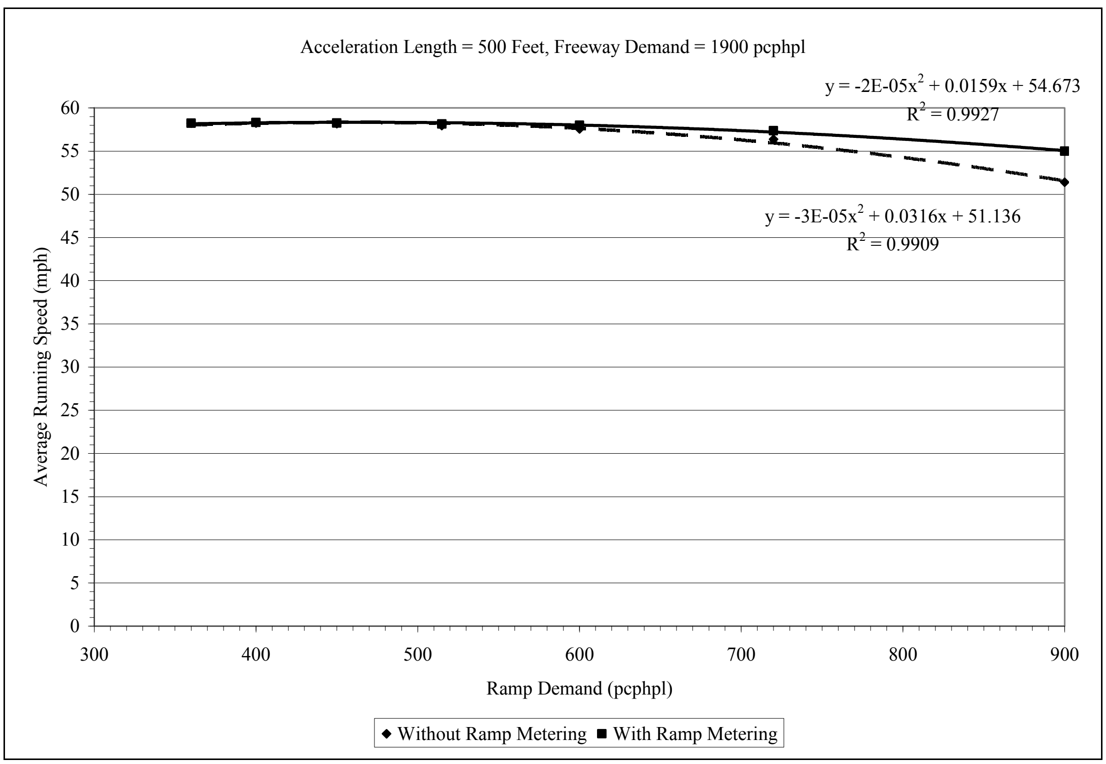

Figure A-2. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 1900 pcphpl Freeway Demand

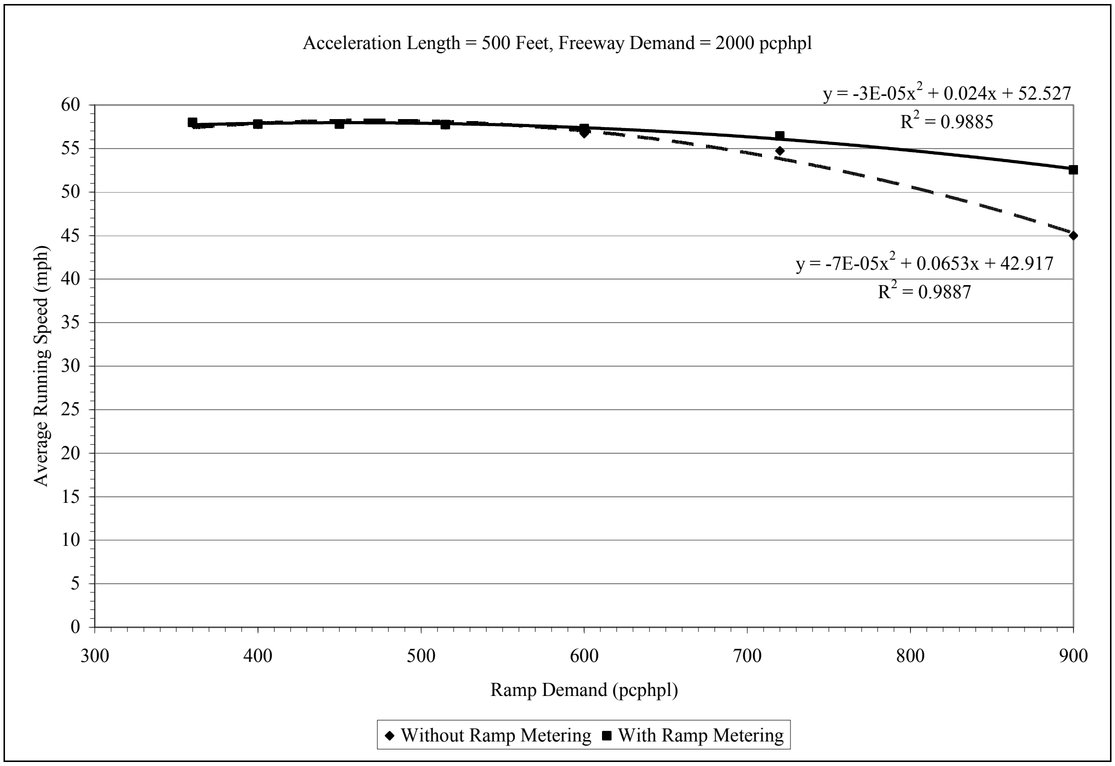

Figure A-3. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 2000 pcphpl Freeway Demand

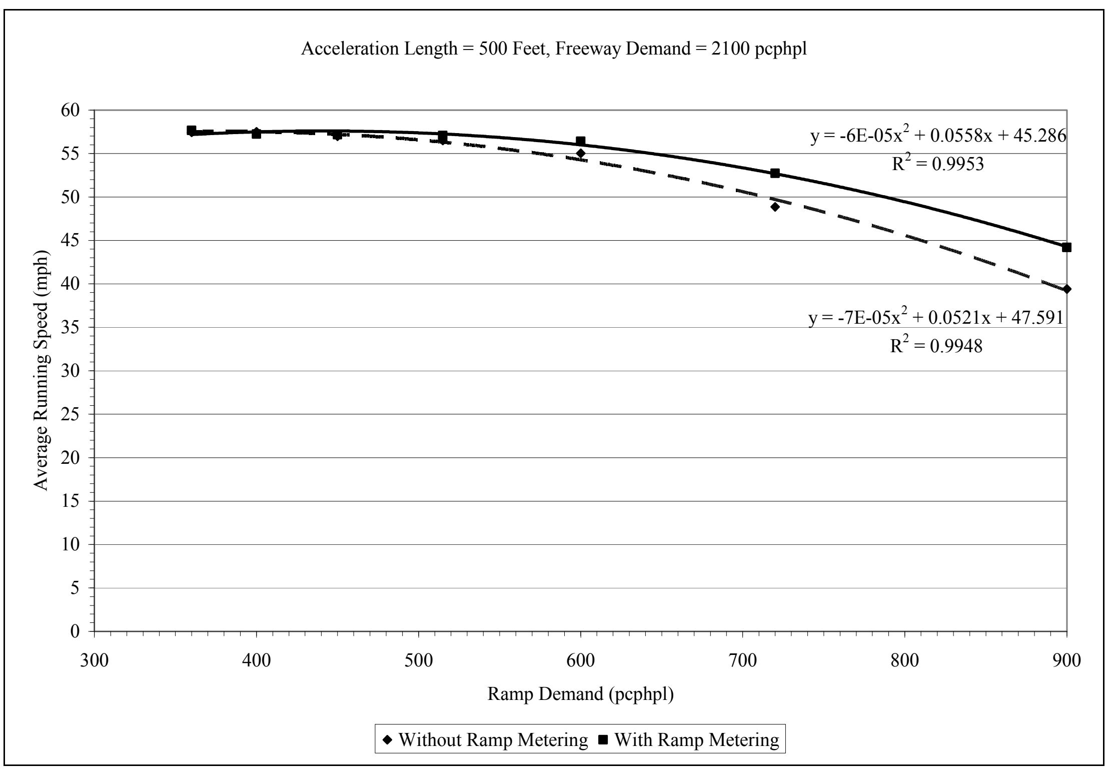

Figure A-4. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 2100 pcphpl Freeway Demand

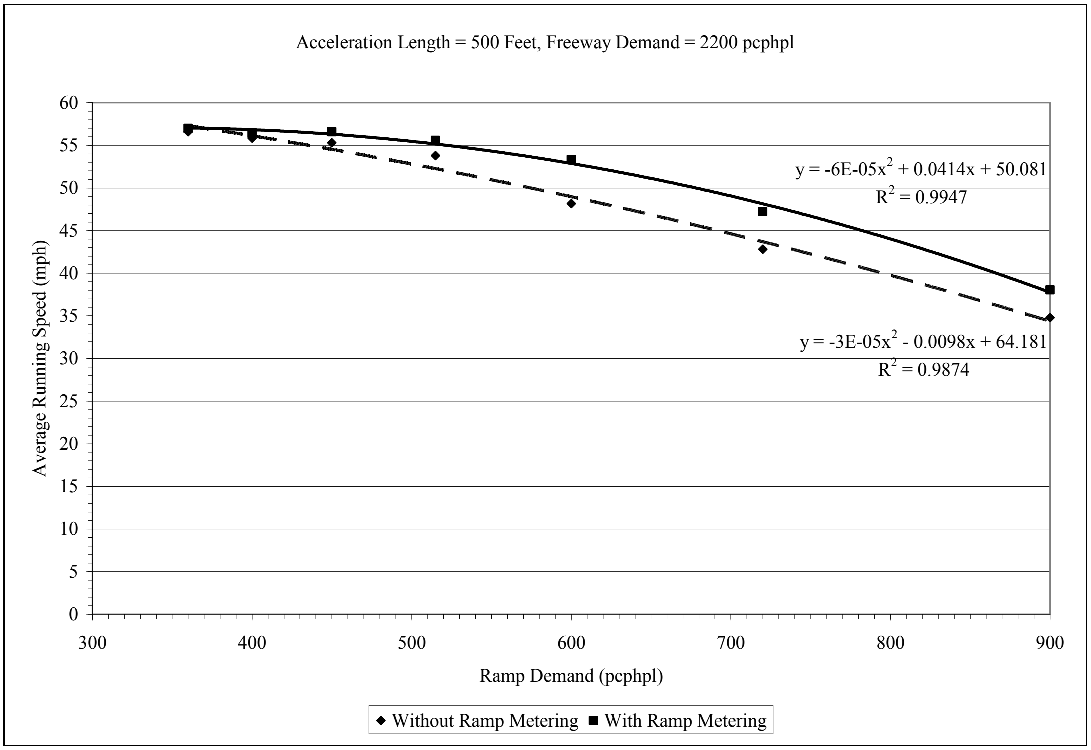

Figure A-5. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 2200 pcphpl Freeway Demand

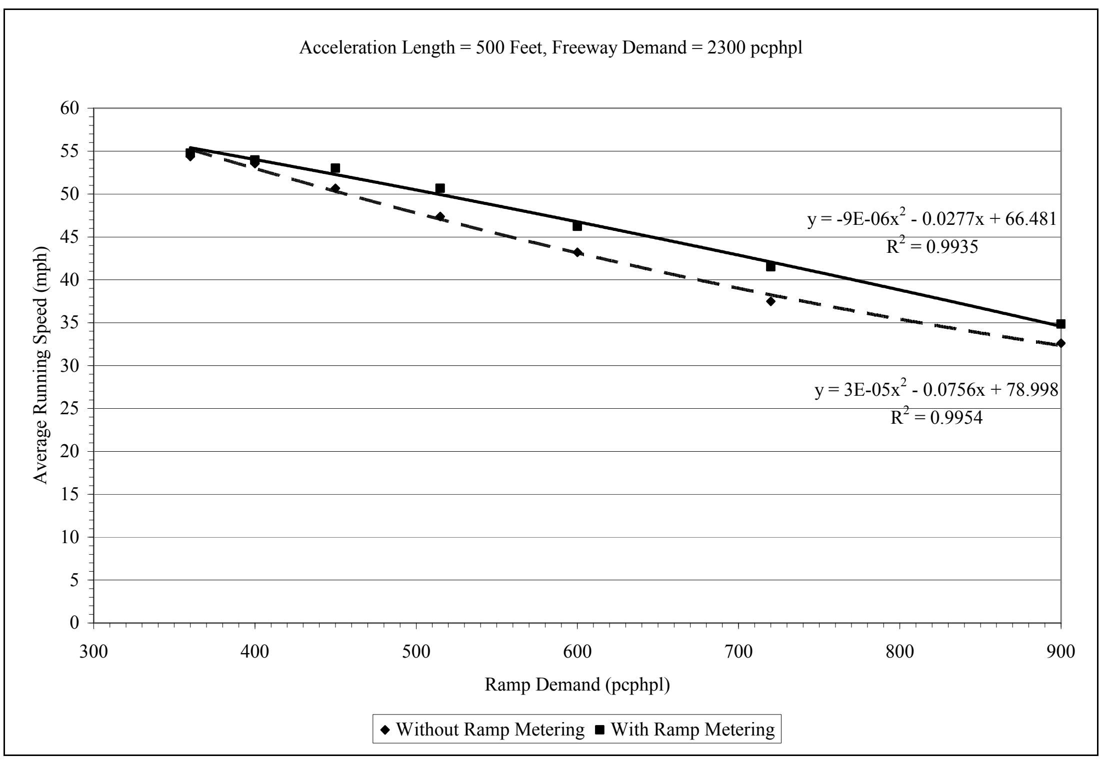

Figure A-6. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 2300 pcphpl Freeway Demand

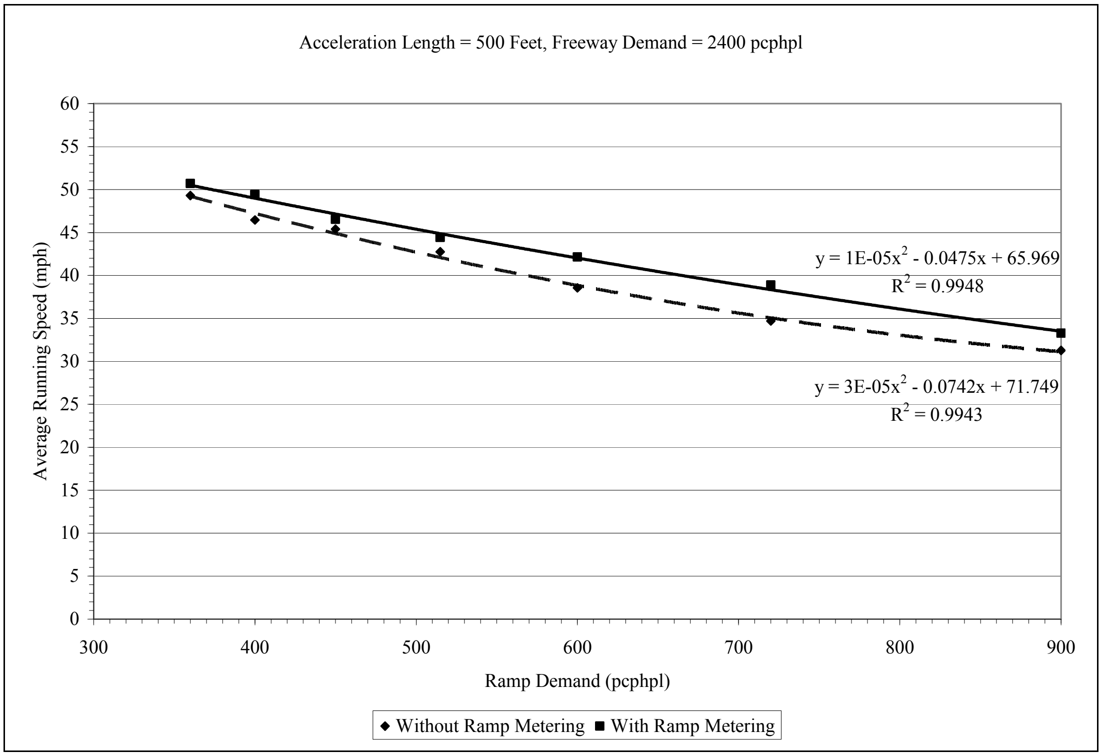

Figure A-7. Comparison of Average Running Speed with and without Ramp Metering, 500-Foot Acceleration Lane, 2400 pcphpl Freeway Demand

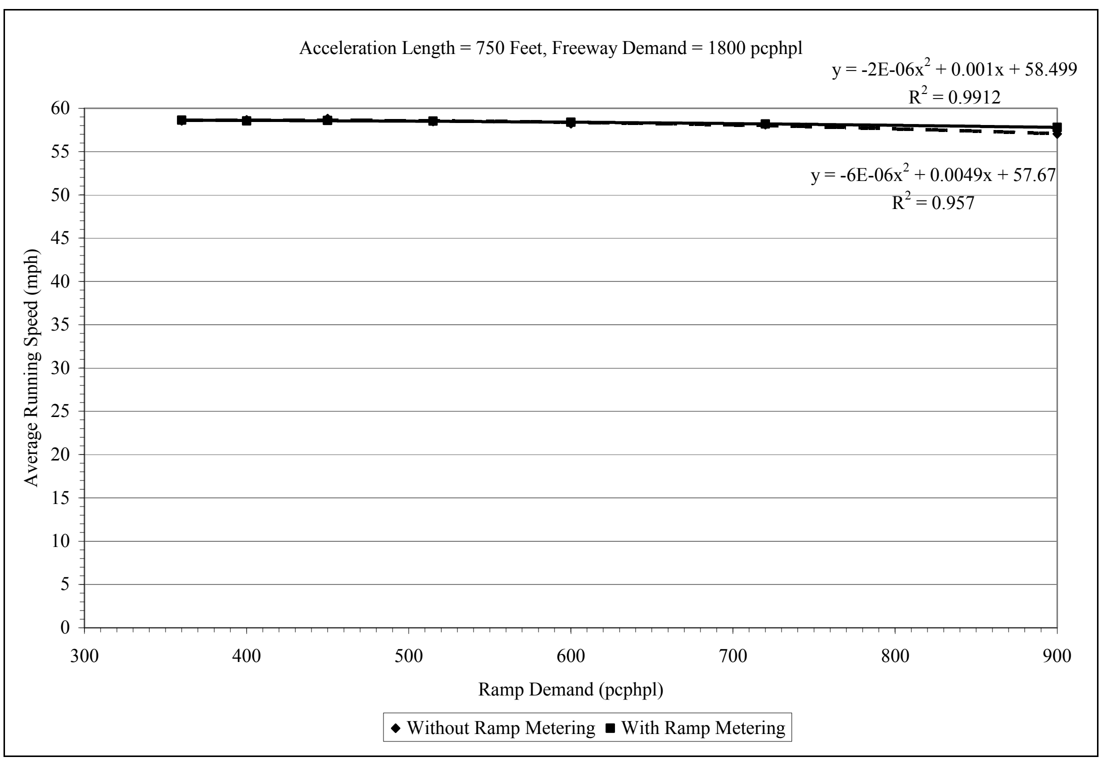

Figure A-8. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 1800 pcphpl Freeway Demand

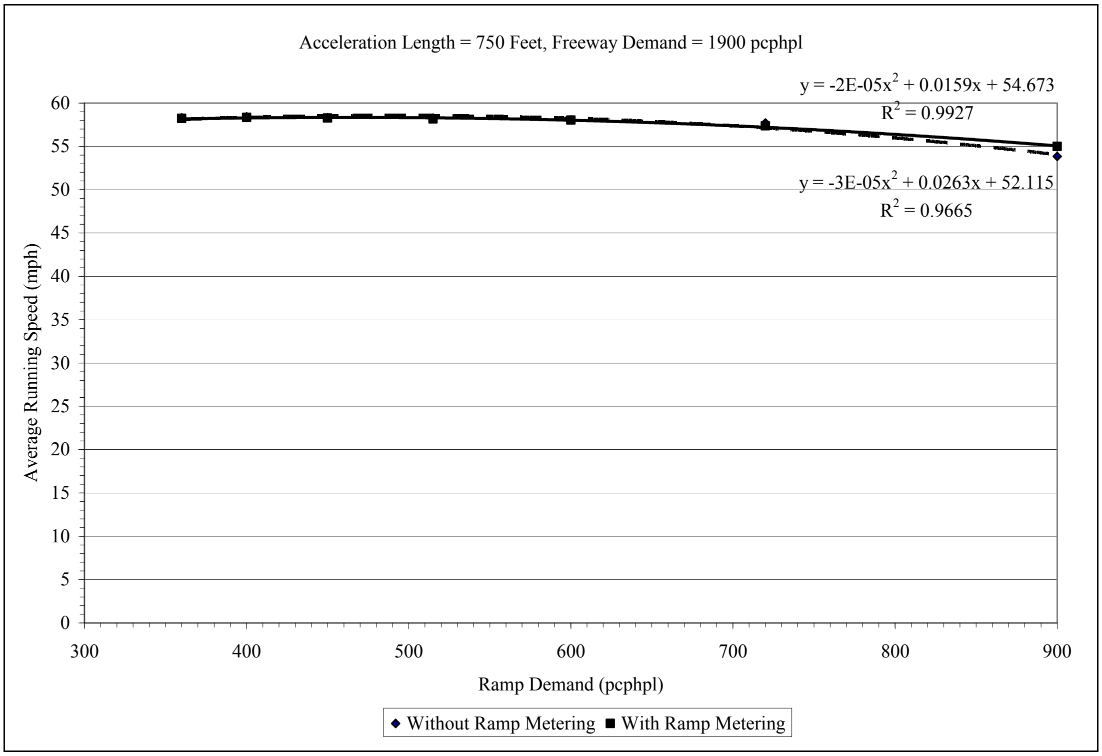

Figure A-9. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 1900 pcphpl Freeway Demand

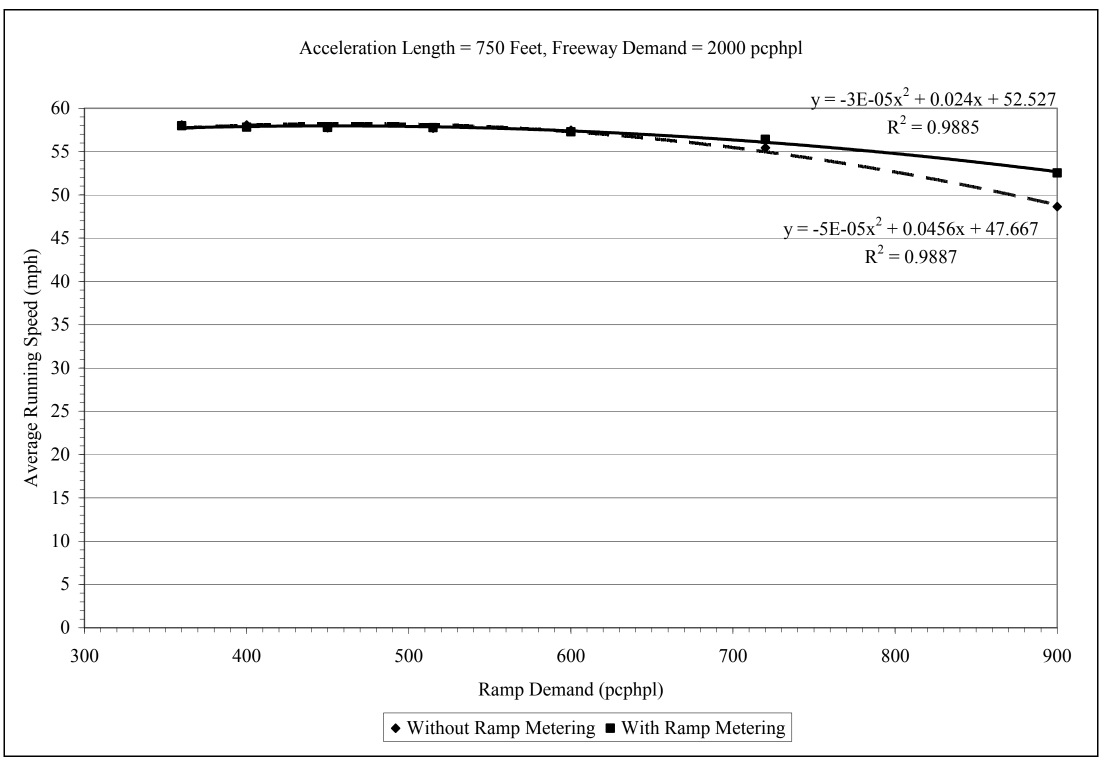

Figure A-10. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 2000 pcphpl Freeway Demand

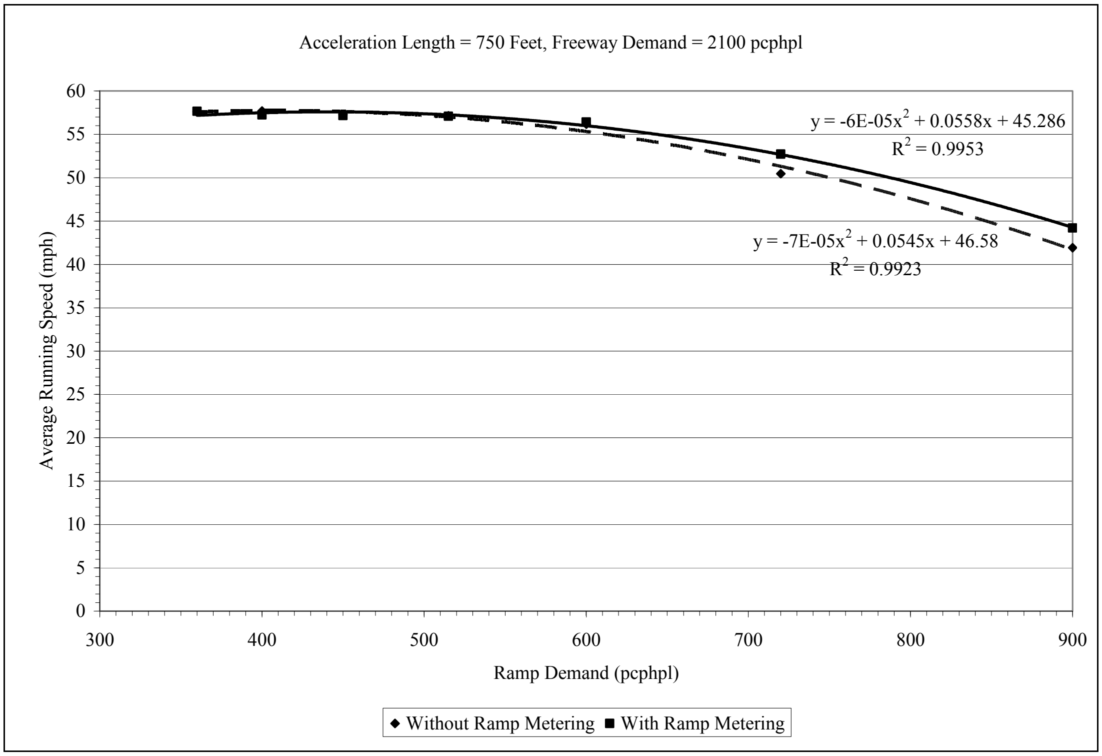

Figure A-11. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 2100 pcphpl Freeway Demand

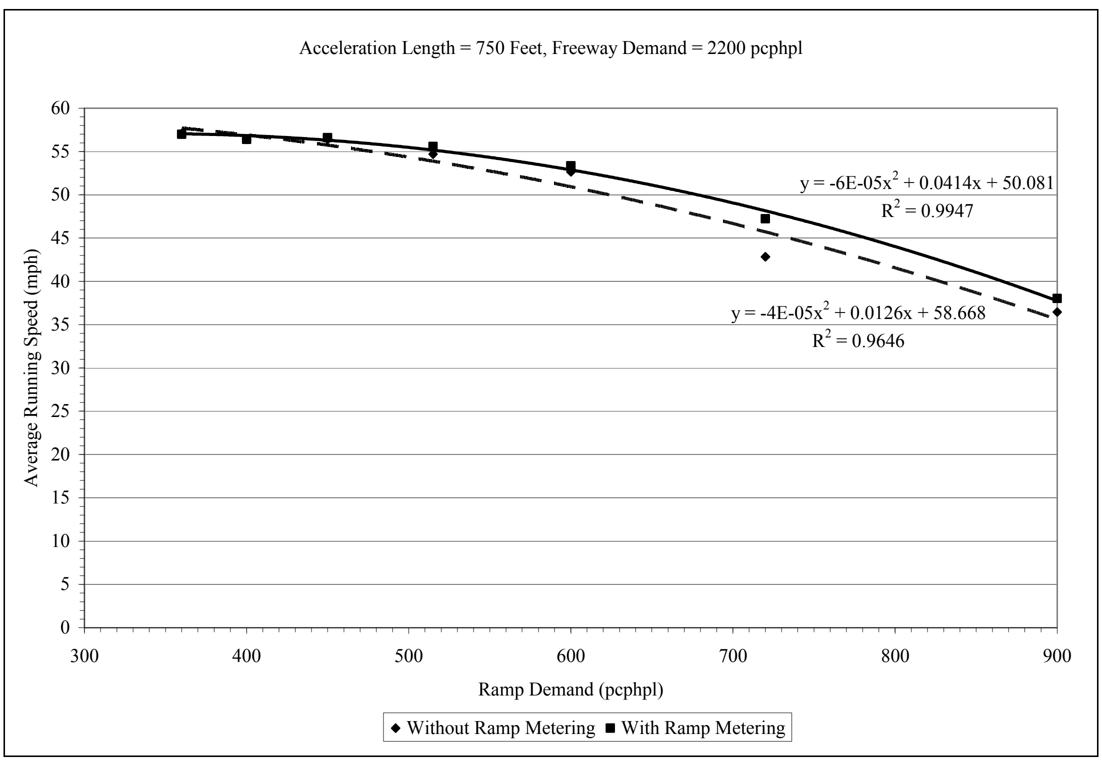

Figure A-12. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 2200 pcphpl Freeway Demand

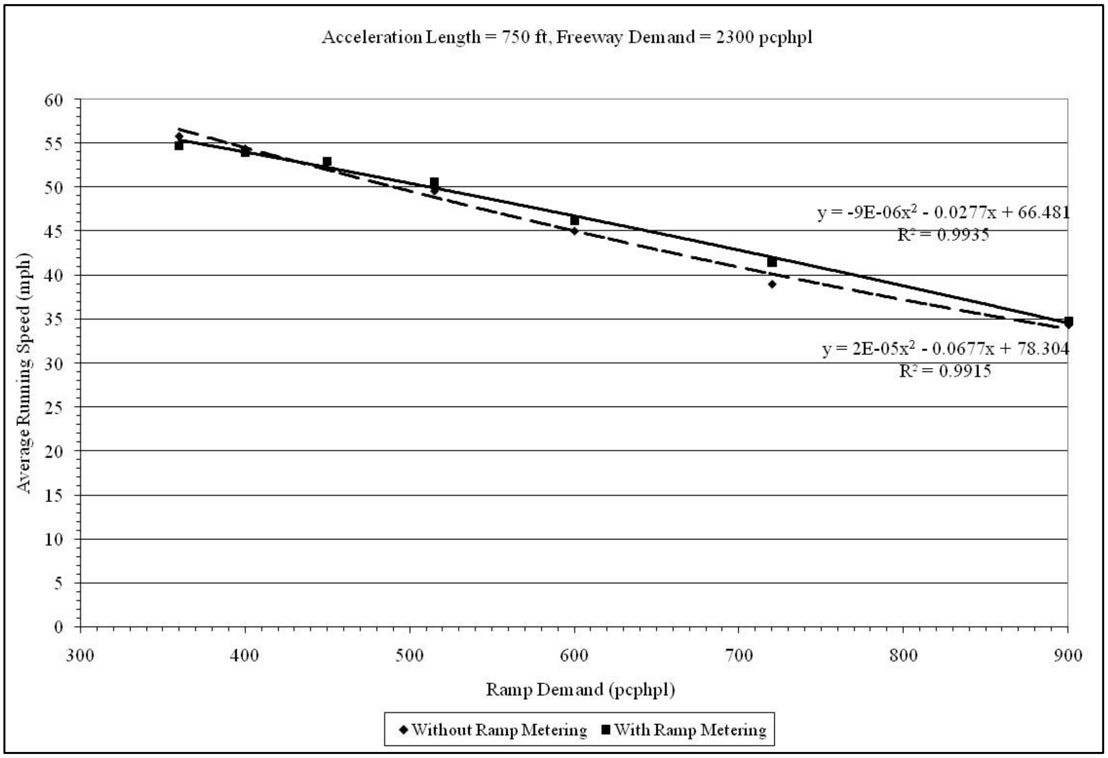

Figure A-13. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 2300 pcphpl Freeway Demand

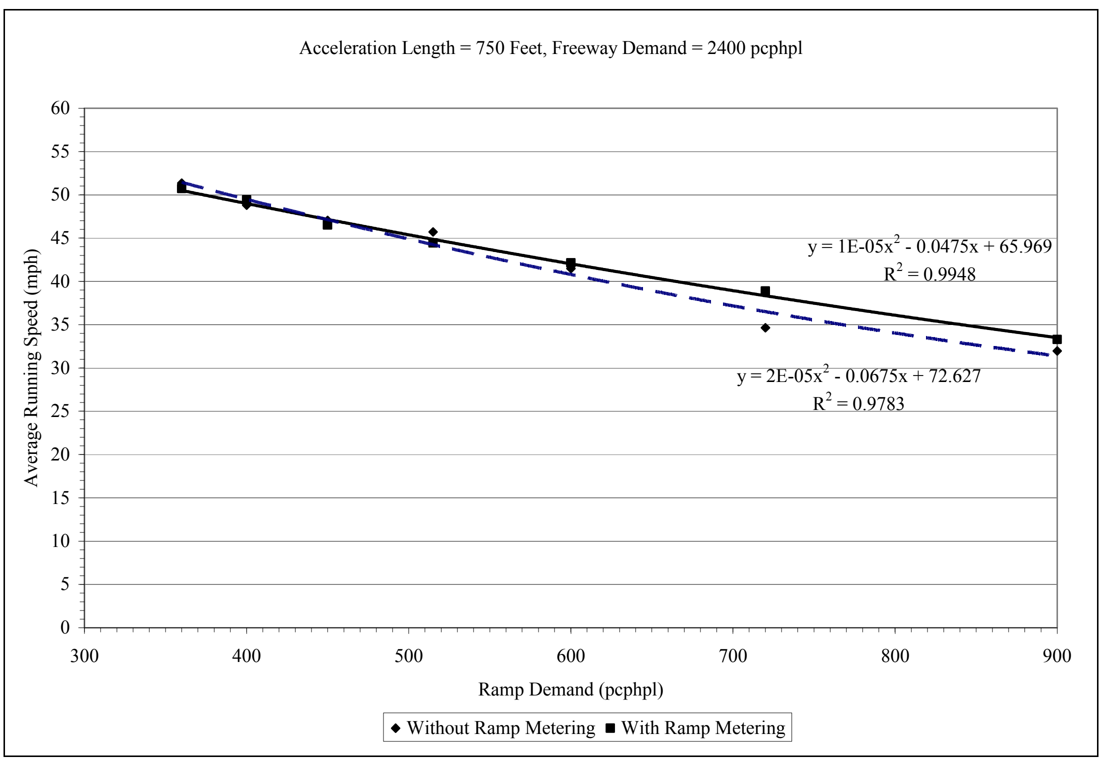

Figure A- 14. Comparison of Average Running Speed with and without Ramp Metering, 750-Foot Acceleration Lane, 2400 pcphpl Freeway Demand

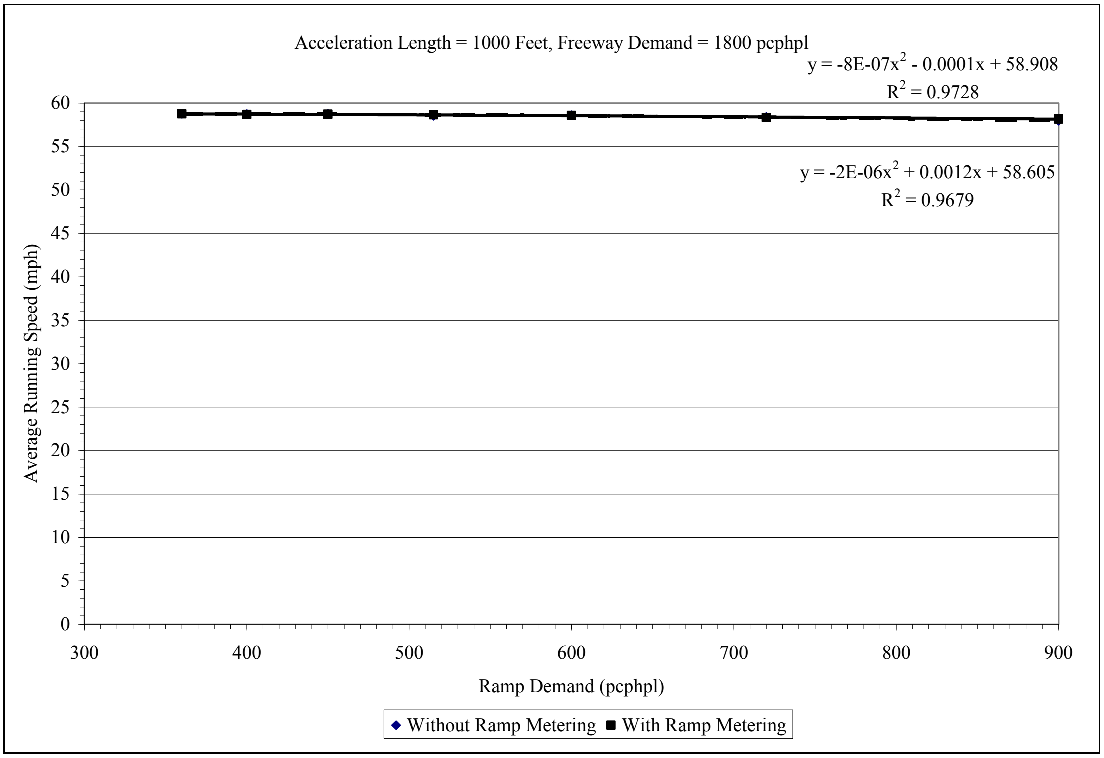

Figure A-15. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 1800 pcphpl Freeway Demand

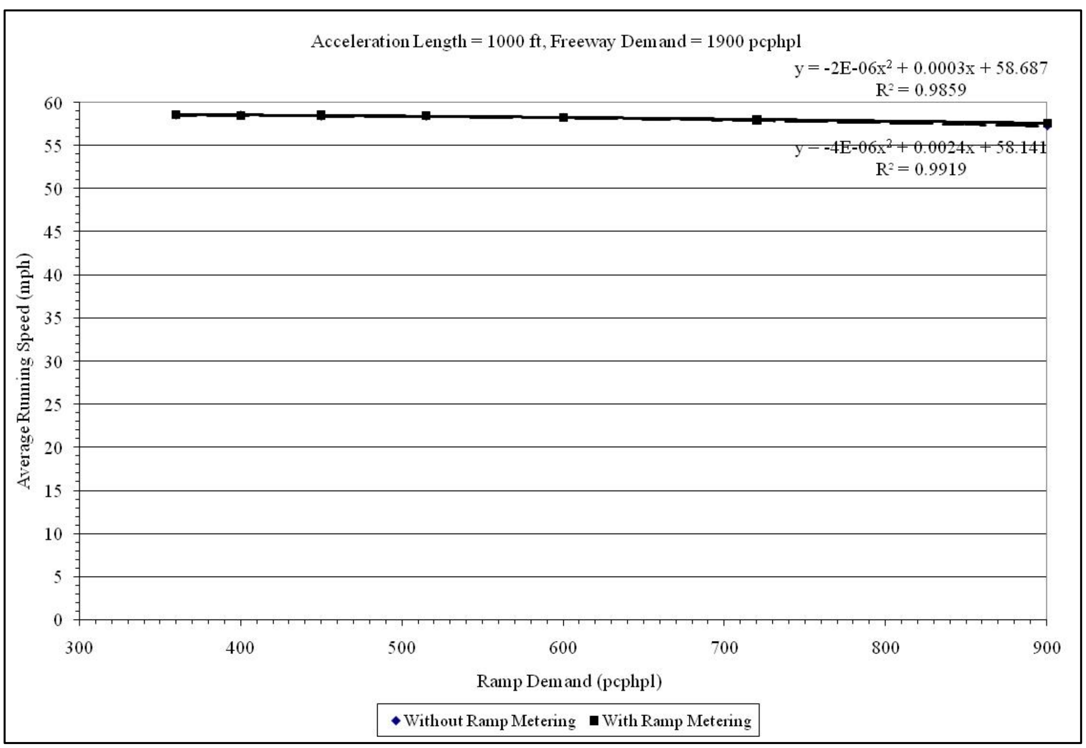

Figure A-16. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 1900 pcphpl Freeway Demand

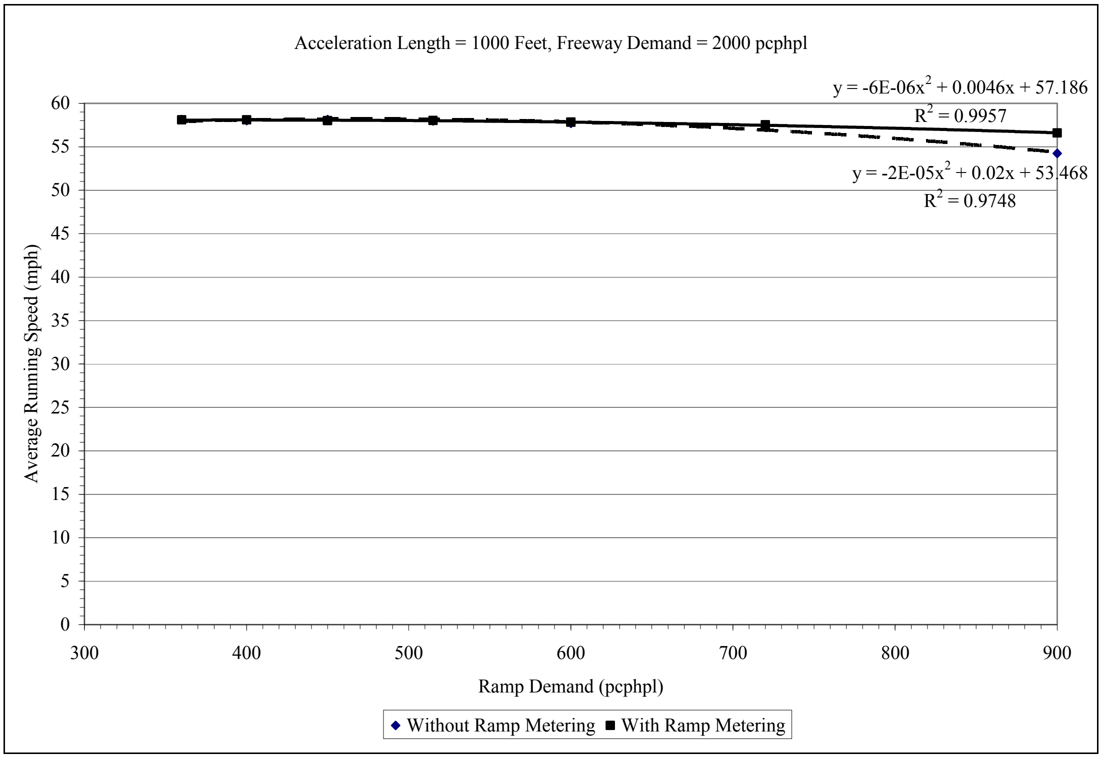

Figure A-17. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 2000 pcphpl Freeway Demand

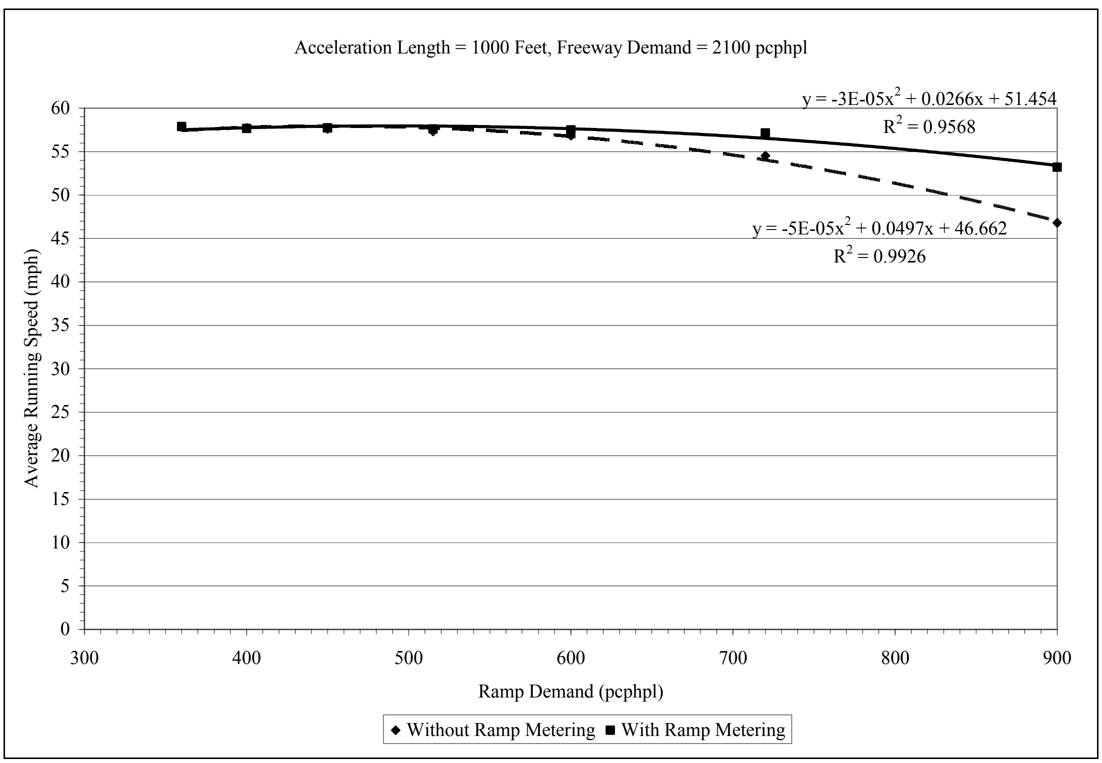

Figure A-18. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 2100 pcphpl Freeway Demand

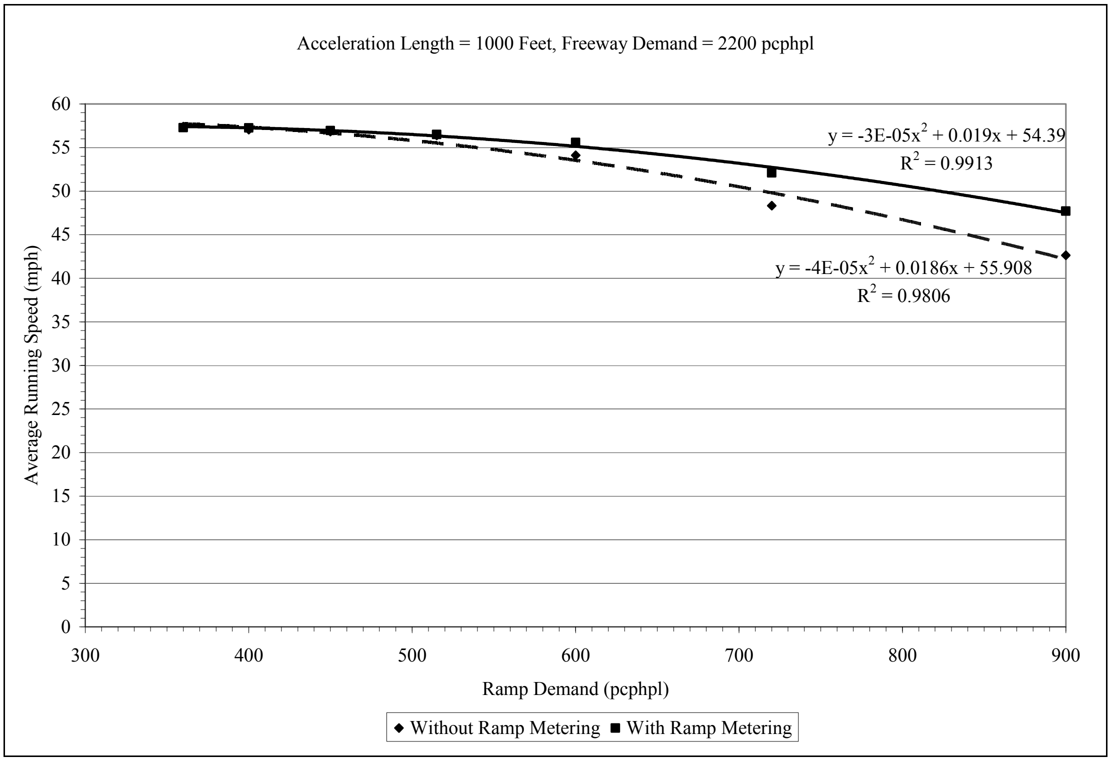

Figure A-19. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 2200 pcphpl Freeway Demand

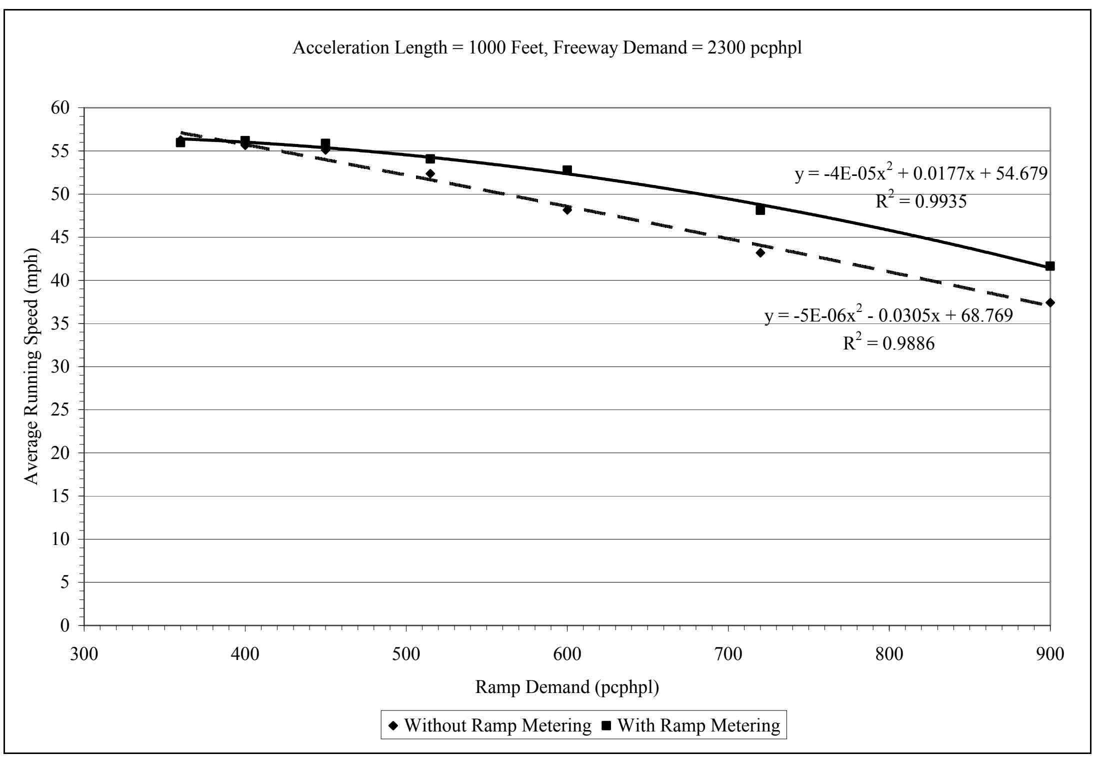

Figure A-20. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 2300 pcphpl Freeway Demand

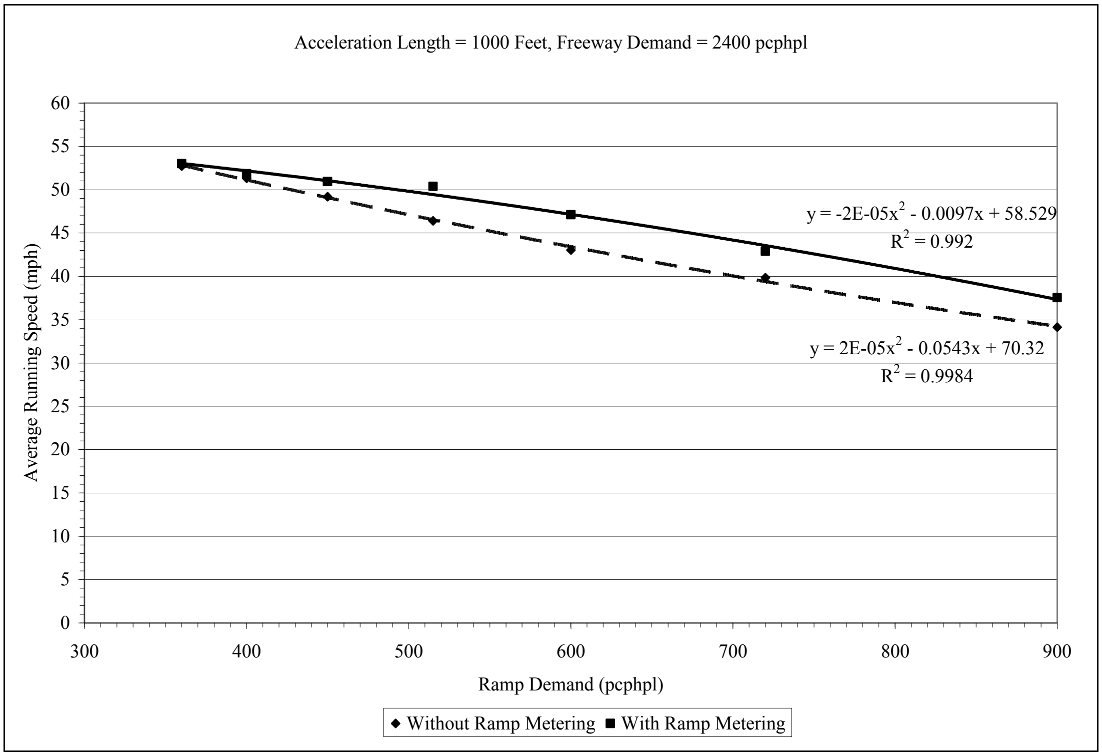

Figure A-21. Comparison of Average Running Speed with and without Ramp Metering, 1000-Foot Acceleration Lane, 2400 pcphpl Freeway Demand

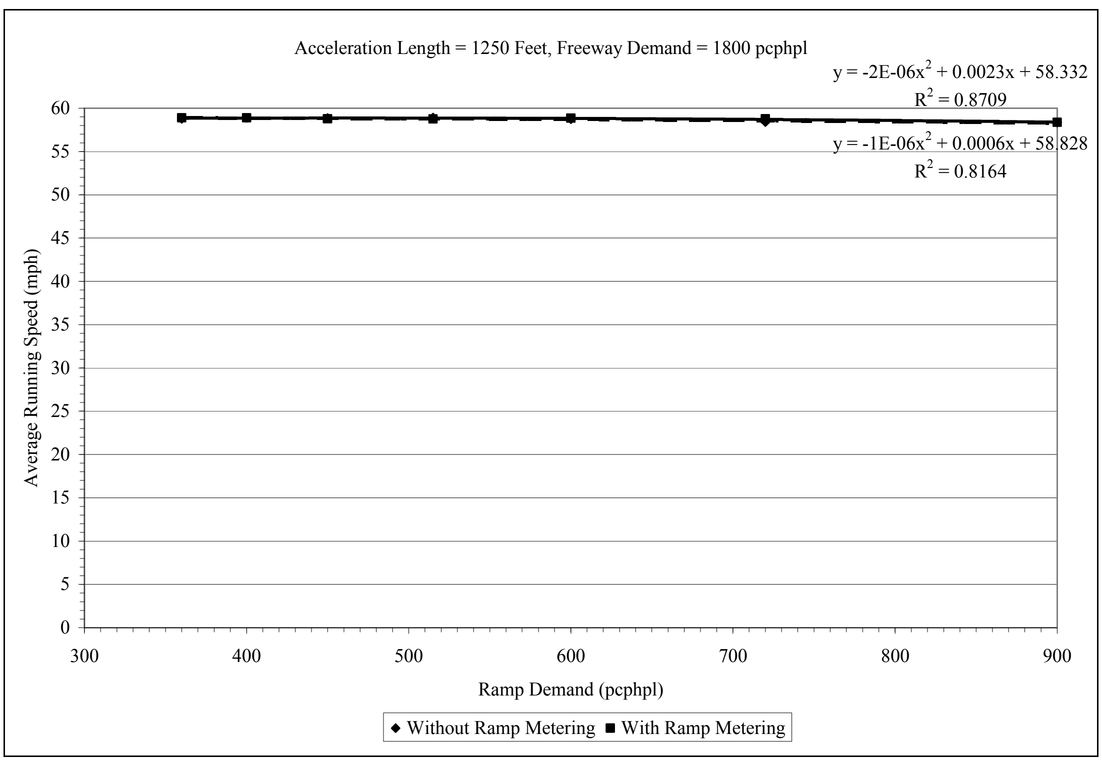

Figure A-22. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 1800 pcphpl Freeway Demand

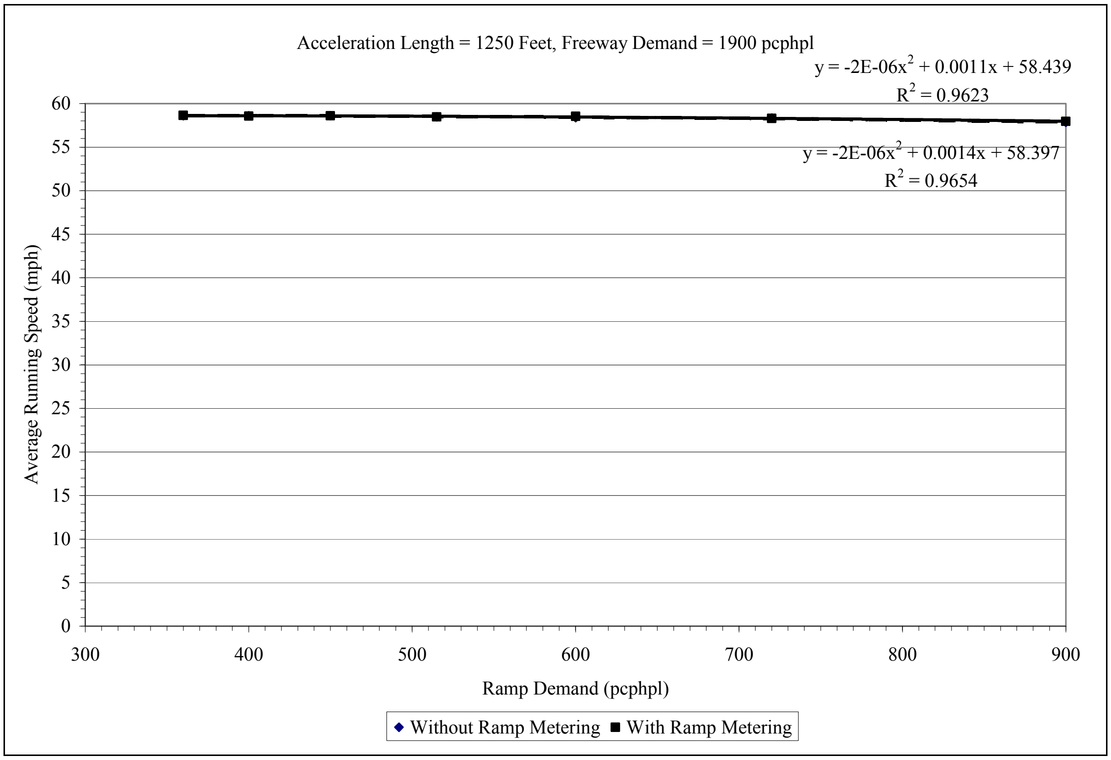

Figure A-23. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 1900 pcphpl Freeway Demand

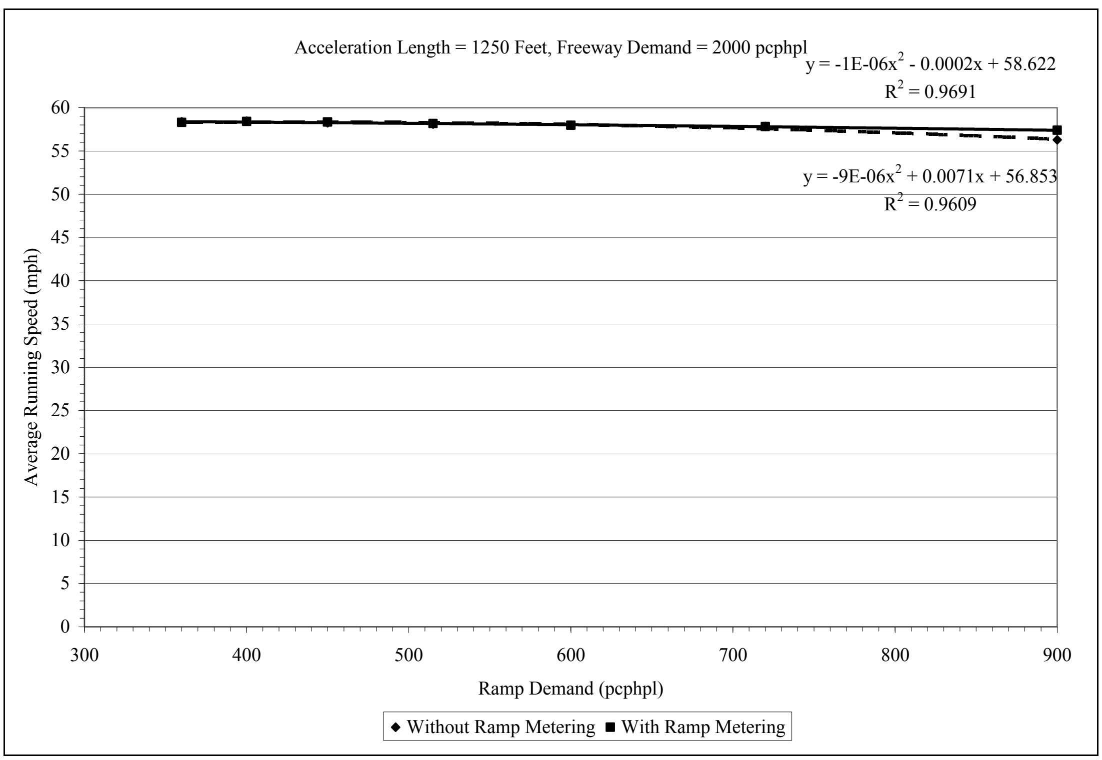

Figure A-24. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 2000 pcphpl Freeway Demand

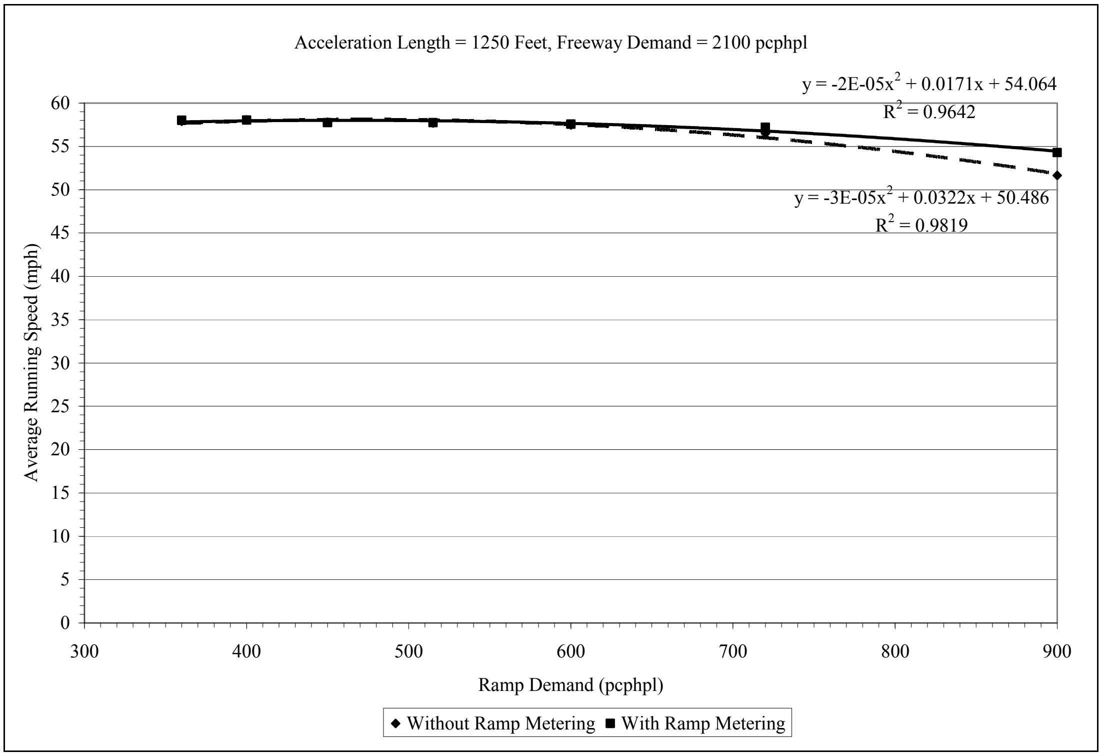

Figure A-25. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 2100 pcphpl Freeway Demand

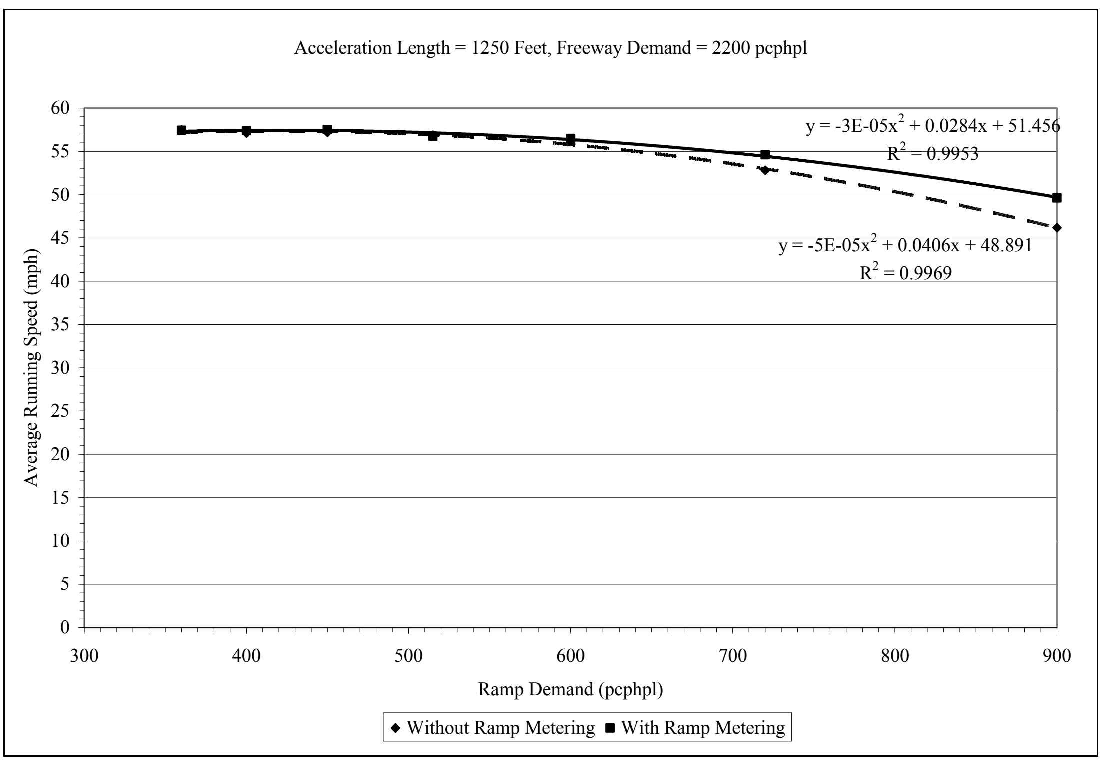

Figure A-26. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 2200 pcphpl Freeway Demand

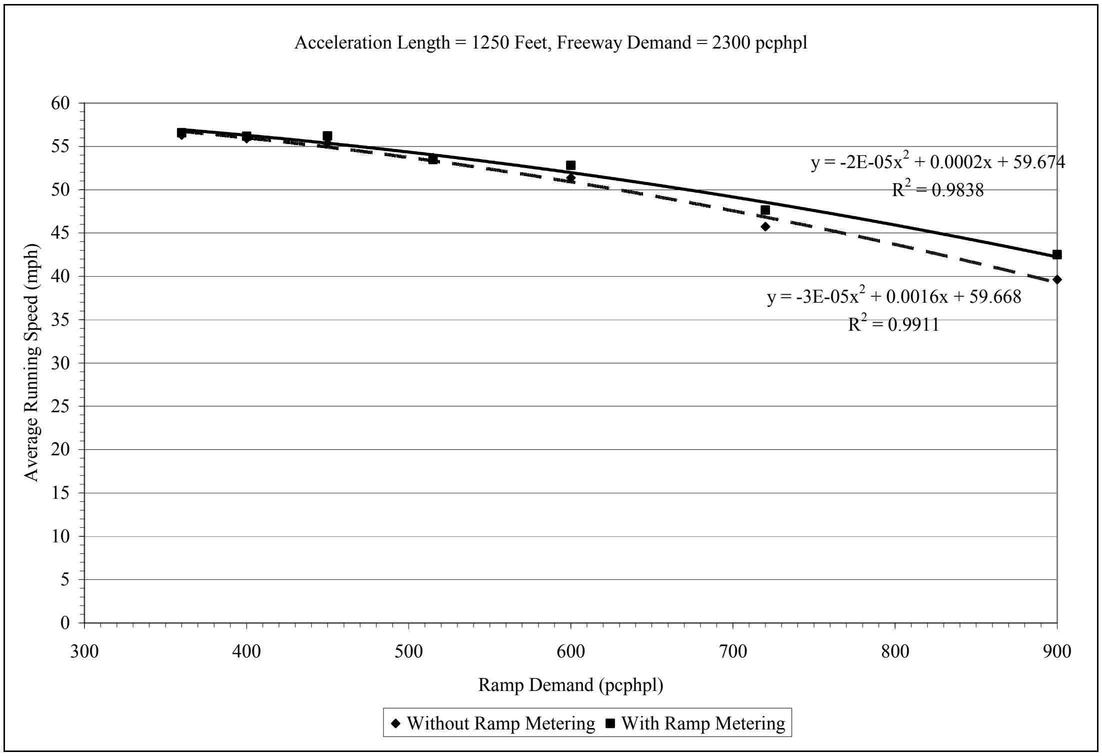

Figure A-27. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 2300 pcphpl Freeway Demand

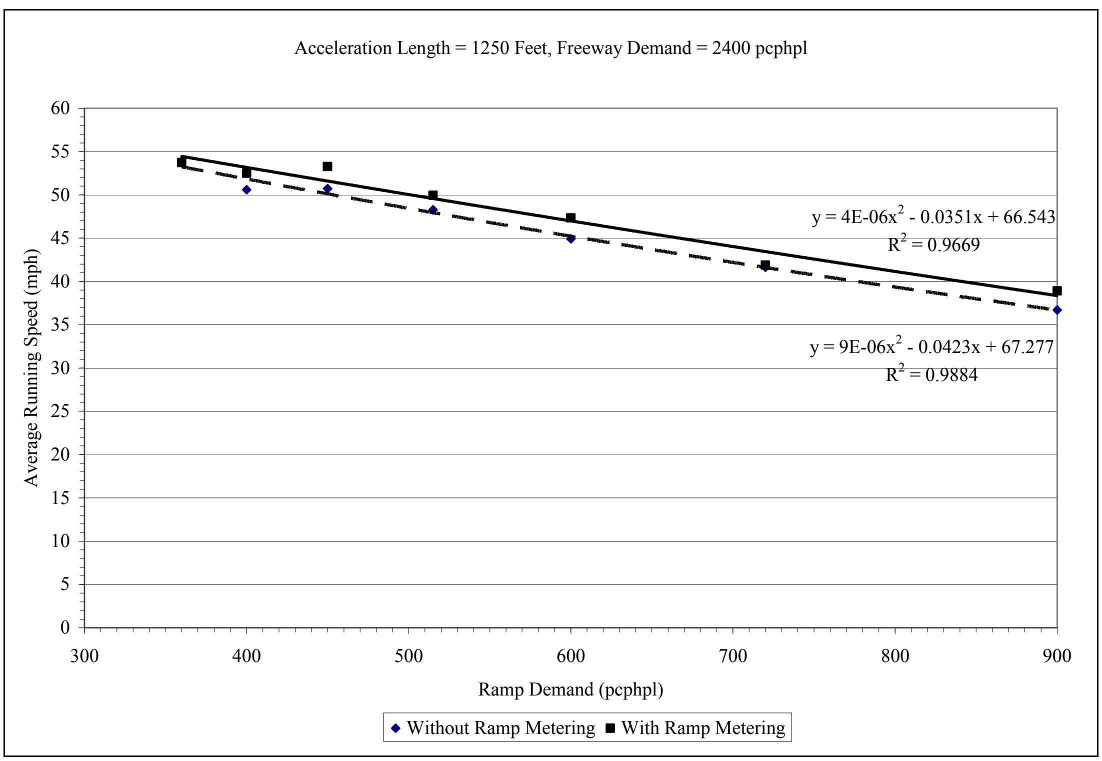

Figure A-28. Comparison of Average Running Speed with and without Ramp Metering, 1250-Foot Acceleration Lane, 2400 pcphpl Freeway Demand

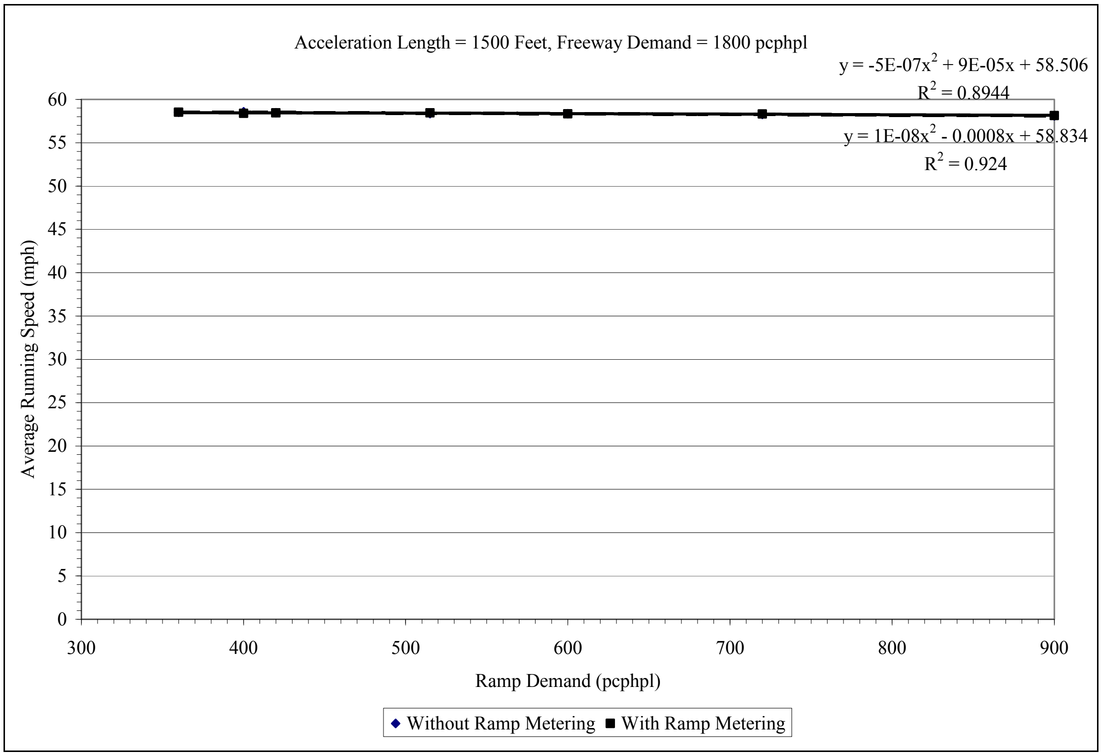

Figure A-29. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 1800 pcphpl Freeway Demand

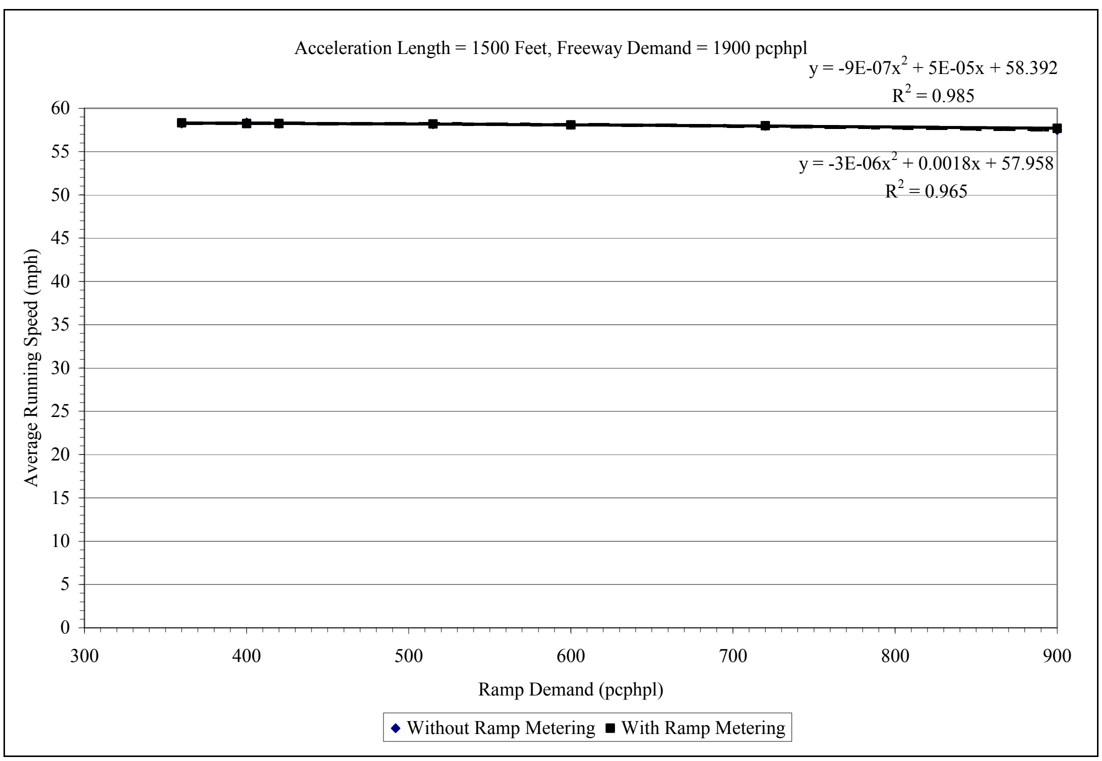

Figure A-30. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 1900 pcphpl Freeway Demand

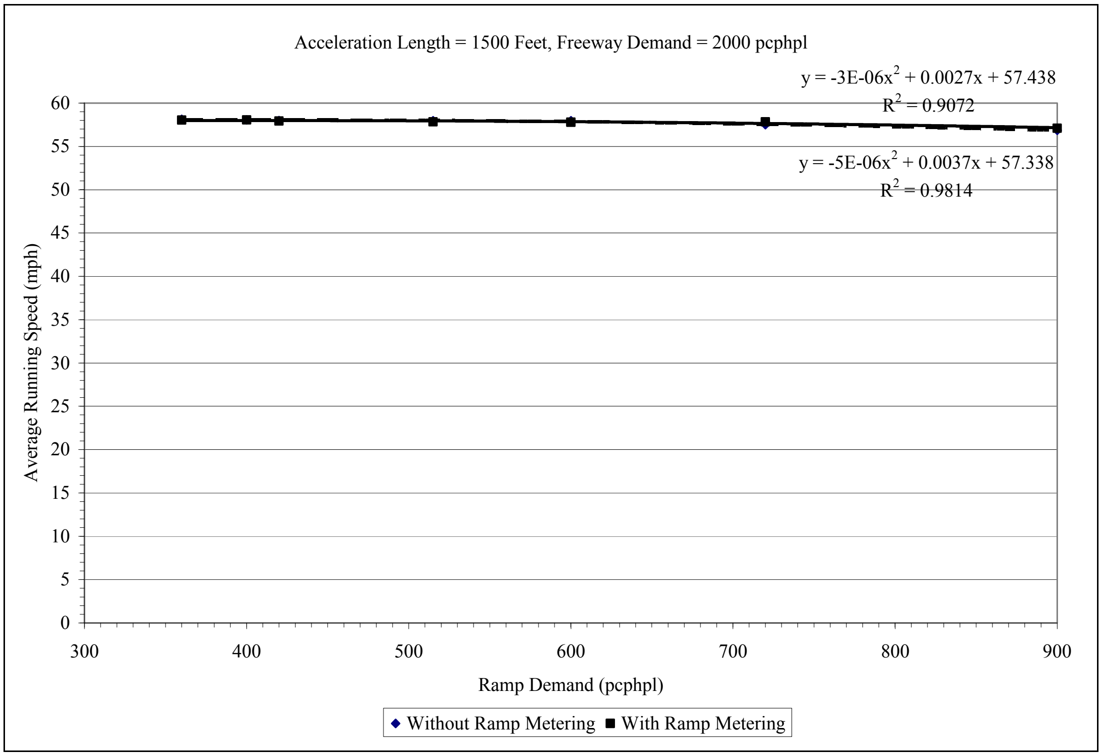

Figure A-31. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 2000 pcphpl Freeway Demand

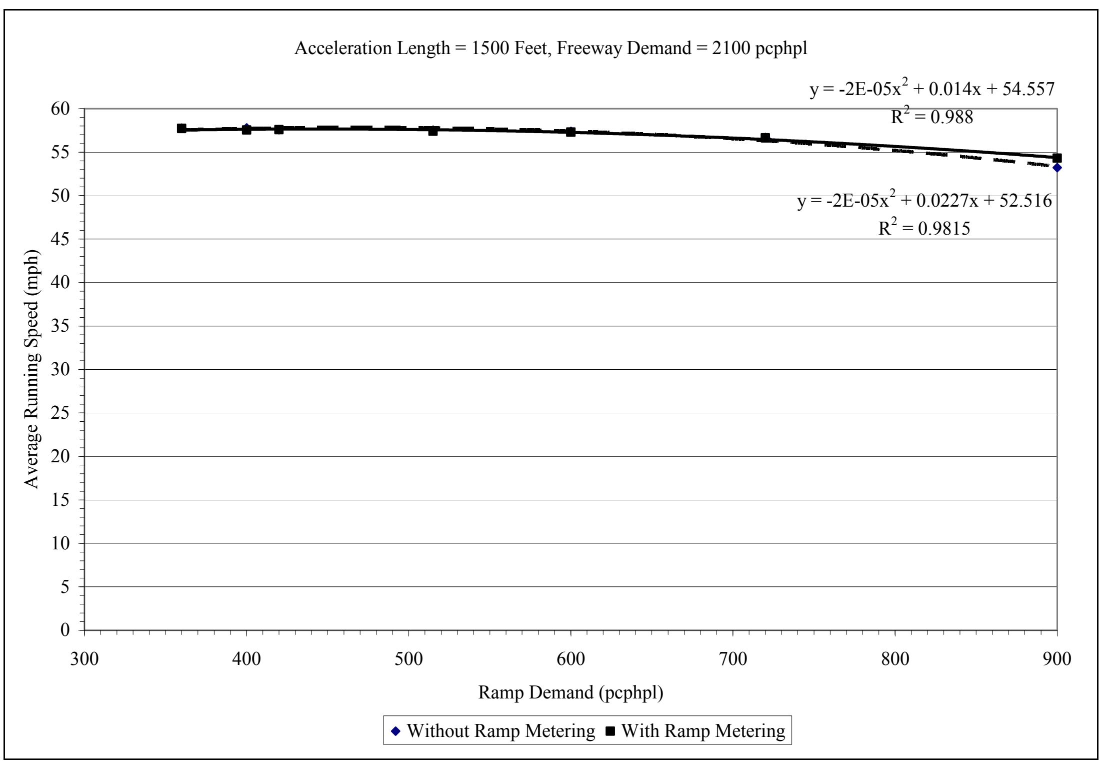

Figure A-32. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 2100 pcphpl Freeway Demand

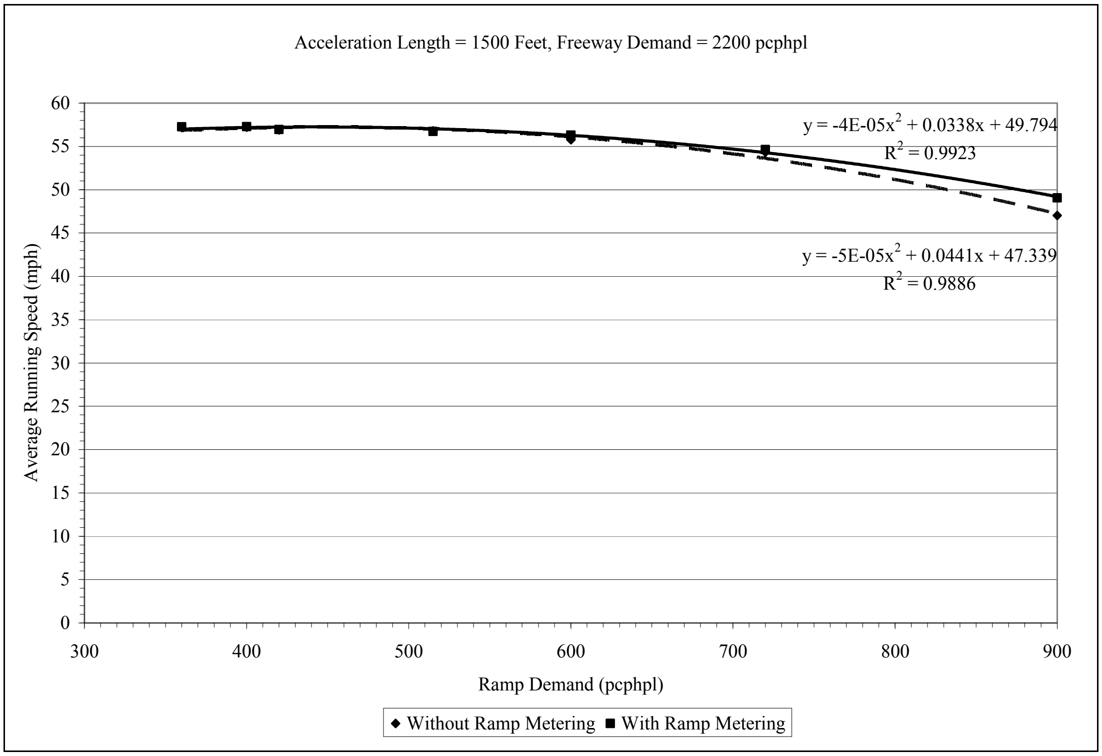

Figure A-33. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 2200 pcphpl Freeway Demand

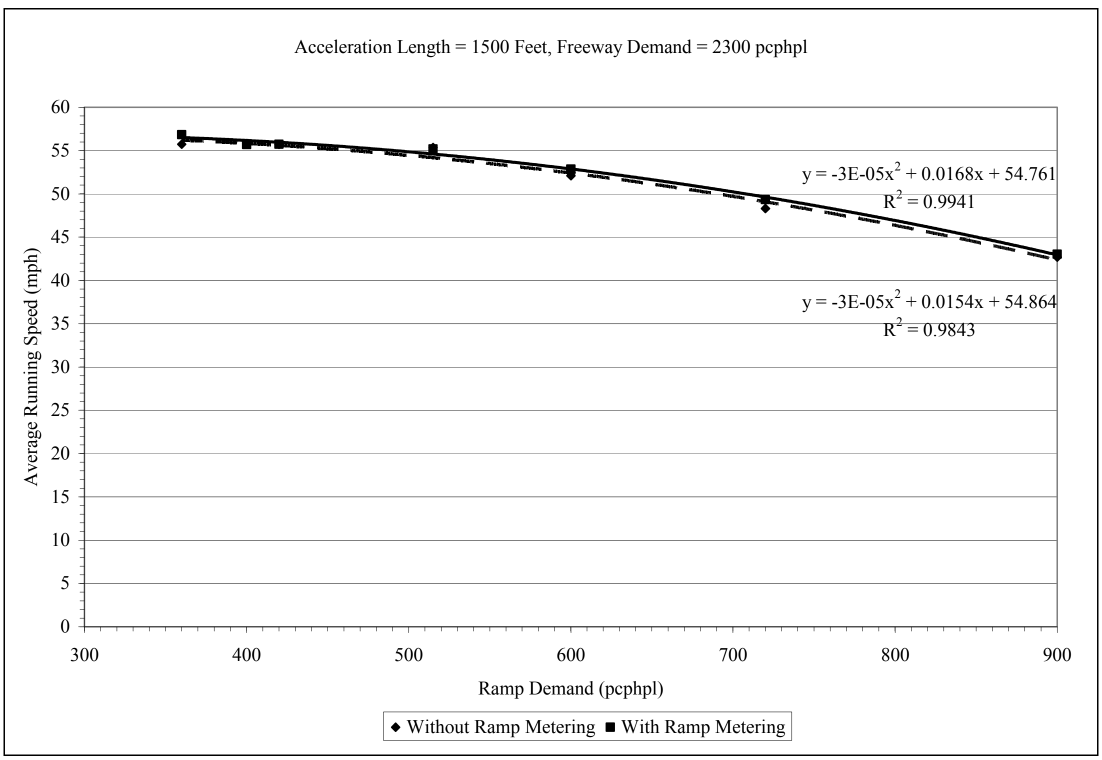

Figure A-34. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 2300 pcphpl Freeway Demand

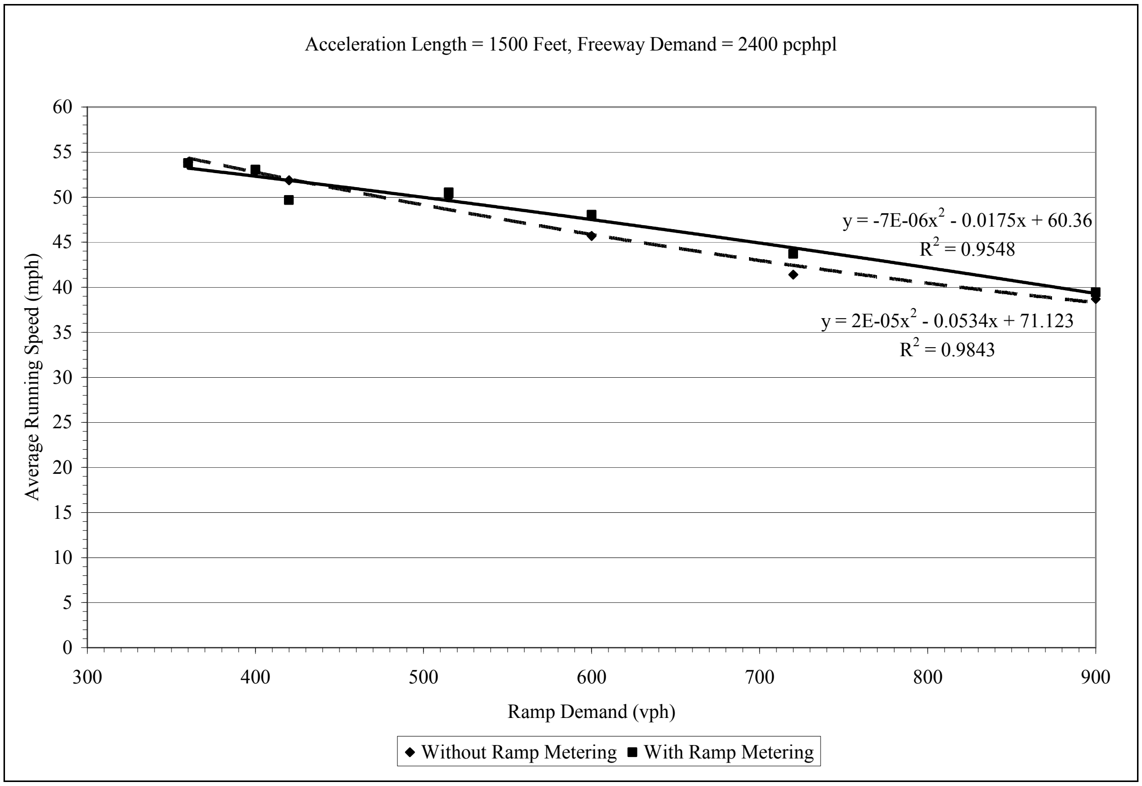

Figure A-35. Comparison of Average Running Speed with and without Ramp Metering, 1500-Foot Acceleration Lane, 2400 pcphpl Freeway Demand

APPENDIX B:
RESULTS OF STATISTICAL COMPARISON OF THE EFFECTS OF USING A RAMP CONTROL SIGNAL ON AVERAGE RUNNING SPEED

Table B-1. Comparison of Average Freeway Running Speed with and without Ramp Metering — 500-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
1800	360	10	58.6	58.6	0.0	18	-0.01	0.996	No
	400	9	58.5	58.6	0.1	17	-1.45	0.1644	No
	450	8	58.5	58.4	-0.1	18	0.96	0.3495	No
	515	7	58.5	58.4	0.0	18	0.53	0.6005	No
	600	6	58.3	58.3	0.0	18	0.38	0.7074	No
	720	5	57.7	57.2	-0.5	9.27	0.61	0.5569	No
	900	*4*	*55.8*	*57.2*	*1.5*	*10.7*	*-2.67*	*0.0221*	*Yes*
1900	360	10	58.2	58.2	0.0	18	0.01	0.9896	No
	400	9	58.3	58.3	0.1	18	-0.82	0.4225	No
	450	8	58.2	58.3	0.1	18	-0.51	0.6131	No
	515	7	58.0	58.2	0.2	18	-1.95	0.0681	No
	600	*6*	*57.6*	*58.0*	*0.5*	*18*	*-2.27*	*0.036*	*Yes*
	720	*5*	*56.4*	*57.4*	*1.0*	*11*	*-2.67*	*0.022*	*Yes*
	900	*4*	*51.4*	*55.0*	*3.6*	*18*	*-2.67*	*0.0155*	*Yes*
2000	360	10	57.9	58.0	0.1	18	-0.71	0.4839	No
	400	9	57.8	57.8	0.0	18	-0.17	0.8661	No
	450	8	57.8	57.8	0.0	18	0.49	0.6333	No
	515	7	57.7	57.8	0.0	18	-0.9	0.681	No
	600	*6*	*56.7*	*57.3*	*0.6*	*11.5*	*-2.99*	*0.0117*	*Yes*
	720	*5*	*54.7*	*56.4*	*1.7*	*11.5*	*-2.4*	*0.0295*	*Yes*
	900	*4*	*45.0*	*52.5*	*7.6*	*18*	*-4.27*	*0.0005*	*Yes*
2100	*360*	*10*	*57.4*	*57.7*	*0.2*	*12.8*	*-2.32*	*0.032*	*Yes*
	400	*9*	*57.5*	*57.2*	*-0.3*	*18*	*-1.22*	*0.2386*	*Yes*
	450	8	57.0	57.2	0.2	18	-4.79	0.0004	No
	515	*7*	*56.5*	*57.1*	*0.6*	*12.1*	*-3.21*	*0.0075*	*Yes*
	600	*6*	*55.0*	*56.4*	*1.4*	*18*	*-4.76*	*0.0002*	*Yes*
	720	*5*	*48.9*	*52.7*	*3.9*	*12.3*	*-3.69*	*0.0017*	*Yes*
	900	*4*	*39.4*	*44.2*	*4.8*	*18*	*-5.08*	*<0.0001*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-1. Comparison of Average Freeway Running Speed with and without Ramp Metering — 500-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
2200	*360*	*10*	*56.6*	*57.0*	*0.4*	*18*	*-2.32*	*0.032*	*Yes*
	400	9	55.8	56.4	0.6	18	-1.22	0.2386	No
	450	*8*	*55.3*	*56.6*	*1.3*	*12.5*	*-4.79*	*0.0004*	*Yes*
	515	*7*	*53.8*	*55.6*	*1.8*	*11.8*	*-3.21*	*0.0075*	*Yes*
	600	*6*	*48.2*	*53.3*	*5.2*	*18*	*-4.76*	*0.0002*	*Yes*
	720	*5*	*42.8*	*47.2*	*4.4*	*18*	*-3.69*	*0.0017*	*Yes*
	900	*4*	*34.8*	*38.0*	*3.3*	*18*	*-5.08*	*<0.0001*	*Yes*
2300	360	10	54.4	54.8	0.4	18	-0.51	0.6144	No
	400	9	53.5	54.0	0.4	18	-0.65	0.5269	No
	450	*8*	*50.7*	*53.0*	*2.3*	*18*	*-2.62*	*0.0174*	*Yes*
	515	*7*	*47.4*	*50.7*	*3.3*	*18*	*-2.19*	*0.0422*	*Yes*
	600	*6*	*43.2*	*46.2*	*3.0*	*18*	*-2.69*	*0.0148*	*Yes*
	720	*5*	*37.5*	*41.5*	*4.0*	*18*	*-5.79*	*<0.0001*	*Yes*
	900	*4*	*32.6*	*34.8*	*2.2*	*18*	*-3.01*	*0.0076*	*Yes*
2400	360	10	49.3	50.7	1.4	18	-1.28	0.2167	No
	400	*9*	*46.5*	*49.4*	*2.9*	*18*	*-2.29*	*0.0344*	*Yes*
	450	8	54.4	46.5	1.1	13.1	-1.11	0.2868	No
	515	7	42.7	44.4	1.7	18	-1.91	0.0723	No
	600	*6*	*38.6*	*42.2*	*3.6*	*18*	*-3.87*	*0.0011*	*Yes*
	720	*5*	*34.7*	*38.9*	*4.2*	*18*	*-5.24*	*<0.0001*	*Yes*
	900	*4*	*31.3*	*33.3*	*2.0*	*18*	*-3.09*	*0.0063*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-2. Comparison of Average Freeway Running Speed with and without Ramp Metering — 750-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
1800	360	10	58.5	58.6	0.1	18	-1.28	0.2184	No
	400	9	58.7	58.5	-0.1	17	1.49	0.1541	No
	450	8	58.8	58.6	-0.2	18	-0.79	0.4408	No
	515	7	58.5	58.5	0.0	18	-0.25	0.8084	No
	600	6	58.2	58.4	0.2	18	-1.8	0.089	No
	720	5	58.1	58.2	0.1	18	-0.98	0.3411	No
	900	*4*	*57.0*	*57.8*	*0.7*	*10.5*	*-2.97*	*0.0133*	*Yes*
1900	360	10	58.3	58.4	0.0	18	-0.32	0.7758	No
	400	9	58.4	58.4	0.0	18	0.5	0.6232	No
	450	8	58.3	58.2	-0.1	18	1.46	0.1616	No
	515	7	58.3	58.2	-0.1	18	0.81	0.4301	No
	600	6	58.1	58.1	0.1	12.7	-0.63	0.5386	No
	720	5	57.7	57.9	0.2	18	-1.52	0.1468	No
	900	*4*	*58.4*	*57.1*	*3.3*	*9.38*	*-3.81*	*0.0038*	*Yes*
2000	*360*	*10*	*58.1*	*57.9*	*-0.2*	*18*	*2.31*	*0.033*	*Yes*
	400	9	58.1	58.0	-0.1	18	1.14	0.2673	No
	450	*8*	*57.7*	*57.9*	*0.2*	*18*	*-2.36*	*0.0295*	*Yes*
	515	7	57.7	57.6	-0.1	18	0.57	0.579	No
	600	6	57.5	57.6	0.2	10.3	-1.19	0.2601	No
	720	*5*	*55.4*	*57.1*	*1.7*	*9.58*	*-3.22*	*0.0096*	*Yes*
	900	*4*	*48.6*	*55.6*	*7.0*	*9.49*	*-4.44*	*0.0014*	*Yes*
2100	360	10	57.6	57.8	0.2	18	-1.98	0.0632	No
	400	9	57.7	57.6	-0.1	18	0.39	0.6982	No
	450	*8*	*57.3*	*57.6*	*0.3*	*18*	*-2.49*	*0.0228*	*Yes*
	515	7	57.2	57.4	0.3	18	-1.95	0.0663	No
	600	6	56.2	57.1	0.9	9.31	-2.05	0.07	No
	720	*5*	*50.5*	*56.2*	*5.7*	*11.22*	*-12.89*	*<0.0001*	*Yes*
	900	*4*	*41.9*	*51.2*	*9.3*	*18*	*-6.39*	*<0.0001*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-2. Comparison of Average Freeway Running Speed with and without Ramp Metering — 750-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
2200	360	10	57.1	57.1	0.0	18	0.08	0.9339	No
	400	9	56.4	57.1	0.7	10.5	-1.86	0.0904	No
	450	8	56.4	56.8	0.4	18	-1.58	0.1317	No
	515	*7*	*54.7*	*56.3*	*1.6*	*12*	*-3.56*	*0.0039*	*Yes*
	600	*6*	*52.6*	*55.4*	*2.8*	*18*	*-3.89*	*0.0011*	*Yes*
	720	*5*	*42.8*	*52.0*	*9.1*	*18*	*-9.91*	*<0.0001*	*Yes*
	900	*4*	*36.5*	*45.3*	*8.8*	*18*	*-7.08*	*<0.0001*	*Yes*
2300	360	10	55.8	55.9	0.1	13.2	-0.24	0.8148	No
	400	*9*	*54.4*	*55.8*	*1.4*	*18*	-2.56	*0.0198*	*Yes*
	450	8	52.8	54.5	1.7	18	-1.59	0.1287	No
	515	*7*	*49.6*	*52.4*	*2.8*	*18*	*-2.44*	*0.0253*	*Yes*
	600	*6*	*45.0*	*49.5*	*4.5*	*18*	*-4.45*	*0.0003*	*Yes*
	720	*5*	*38.9*	*45.7*	*6.8*	*18*	*-6.21*	*<0.0001*	*Yes*
	900	*4*	*34.3*	*40.0*	*5.7*	*18*	*-6.00*	*<0.0001*	*Yes*
2400	*360*	*10*	*51.3*	*53.4*	*2.1*	*18*	*-2.61*	*0.0178*	*Yes*
	400	9	48.8	51.4	2.6	18	-1.83	0.0837	No
	450	*8*	*47.0*	*50.9*	*3.8*	*18*	*-3.84*	*0.0012*	*Yes*
	515	7	45.7	47.5	1.8	18	-1.35	0.1926	No
	600	*6*	*41.5*	*45.1*	*3.6*	*12.5*	*-3.73*	*0.0027*	*Yes*
	720	*5*	*34.6*	*42.2*	*7.5*	*18*	*-13.8*	*<0.0001*	*Yes*
	900	*4*	*32.0*	*35.8*	*3.9*	*18*	*-6.53*	*<0.0001*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-3. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1000-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
1800	360	10	58.8	58.8	0.0	18	0.08	0.9392	No
	400	9	58.7	58.7	-0.1	17	0.71	0.4862	No
	450	8	58.8	58.7	0.0	18	0.42	0.6789	No
	515	7	58.5	58.6	0.1	18	-1.16	0.2607	No
	600	6	58.6	58.6	0.0	18	0.25	0.8080	No
	720	5	58.4	58.3	-0.1	18	0.59	0.5597	No
	900	4	58.0	58.2	0.2	18	-1.46	0.1627	No
1900	360	10	58.5	58.6	0.0	18	-0.62	0.5421	No
	400	9	58.6	58.5	-0.1	13.2	0.89	0.3897	No
	450	*8*	*58.4*	*58.5*	*0.1*	*18*	*-2.23*	*0.0387*	*Yes*
	515	7	58.4	58.4	0.0	18	-0.53	0.6042	No
	600	6	58.3	58.2	0.0	18	0.3	0.7646	No
	720	5	57.9	58.0	0.1	17	-0.55	0.5895	No
	900	4	57.3	57.6	0.3	11.8	-1.45	0.1730	No
2000	360	10	58.1	58.1	0.0	18	0.32	0.7527	No
	400	9	58.0	58.1	0.1	18	-1.18	0.2532	No
	450	8	58.1	58.0	-0.1	18	1.96	0.0659	No
	515	7	58.0	58.0	0.0	18	-0.37	0.7145	No
	600	6	57.7	57.8	0.1	18	-1.21	0.2438	No
	720	5	57.3	57.5	0.2	18	-0.92	0.3716	No
	900	*4*	*54.2*	*56.6*	*2.4*	*13*	*-3.06*	*0.0092*	*Yes*
2100	360	10	57.8	57.9	0.0	18	-0.23	0.8204	No
	400	9	57.7	57.6	-0.1	18	0.6	0.5549	No
	450	8	57.6	57.7	0.1	18	-1.17	0.2560	No
	515	*7*	*57.3*	*57.6*	*0.3*	*18*	*-2.22*	*0.0397*	*Yes*
	600	*6*	*56.8*	*57.5*	*0.7*	*10.5*	*-3.35*	*0.0069*	*Yes*
	720	*5*	*54.5*	*57.1*	*2.6*	*10*	*-3.63*	*0.0046*	*Yes*
	900	*4*	*46.8*	*53.2*	*6.4*	*18*	*-5.96*	*<0.0001*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-3. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1000-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
2200	360	10	57.4	57.3	-0.1	18	0.98	0.3396	No
	400	9	57.0	57.2	0.2	18	-1.21	0.2404	No
	450	8	56.8	56.9	0.1	18	-0.38	0.7056	No
	515	7	56.4	56.5	0.1	18	-0.44	0.6661	No
	600	6	54.1	55.6	1.5	18	-2.06	0.0543	No
	720	*5*	*48.3*	*52.1*	3.8	*18*	*-4.68*	*0.0002*	*Yes*
	900	*4*	*42.6*	*47.7*	5.1	*18*	*-3.92*	*0.0010*	*Yes*
2300	360	10	56.3	55.9	-0.3	18	1.01	0.3264	No
	400	9	55.6	56.2	0.5	11.1	-1.26	0.2347	No
	450	8	55.1	55.9	0.8	18	-1.46	0.1627	No
	515	7	52.4	54.1	1.7	18	-1.79	0.0899	No
	600	*6*	*48.2*	*52.8*	*4.6*	*18*	*-4.42*	*0.0003*	*Yes*
	720	*5*	*43.2*	*48.1*	*4.9*	*18*	*-3.54*	*0.0023*	*Yes*
	900	*4*	*37.4*	*41.6*	*4.2*	*18*	*-10.51*	*<0.0001*	*Yes*
2400	360	10	52.7	53.0	0.3	18	-0.25	0.806	No
	400	9	51.3	51.8	0.5	11.7	-0.44	0.6645	No
	450	8	49.2	50.9	1.8	12.3	-2.1	0.0571	No
	515	*7*	*46.4*	*50.4*	*4.0*	*18*	*-5.7*	*<0.0001*	*Yes*
	600	*6*	*43.0*	*47.1*	*4.1*	*18*	*-3.54*	*0.0023*	*Yes*
	720	*5*	*39.8*	*42.9*	*3.1*	*18*	*-4.44*	*0.0003*	*Yes*
	900	*4*	*34.1*	*37.6*	*3.4*	*18*	*-5.75*	*<0.0001*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-4. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1250-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
1800	360	10	58.8	58.9	0.01	18	-0.24	0.8096	No
	400	9	58.9	58.9	0.0	17	-0.23	0.8201	No
	450	8	58.9	58.8	-0.1	18	1.13	0.2724	No
	515	7	58.9	58.8	-0.1	18	1.61	0.1243	No
	600	*6*	*58.7*	*58.9*	*0.1*	*18*	*-2.68*	*0.0152*	*Yes*
	720	*5*	*58.4*	*58.8*	*0.4*	*18*	*-3.52*	*0.0025*	*Yes*
	900	4	58.3	58.4	0.0	18	-0.25	0.8092	No
1900	360	10	58.6	58.6	0.0	18	-0.35	0.7340	No
	400	9	58.6	58.6	0.0	18	0.34	0.7360	No
	450	8	58.6	58.6	0.0	18	0.19	0.8487	No
	515	7	58.5	58.5	0.0	18	-0.09	0.9304	No
	600	6	58.4	58.5	0.1	18	-1.39	0.1809	No
	720	5	58.3	58.3	0.0	18	0.37	0.7132	No
	900	4	57.9	58.0	0.1	18	-0.93	0.3668	No
2000	360	10	58.4	58.3	-0.1	18	0.65	0.5252	No
	400	9	58.4	58.4	0.0	18	0.46	0.6537	No
	450	8	58.2	58.3	0.1	18	-1.15	0.2636	No
	515	7	58.1	58.2	0.1	18	-0.51	0.6180	No
	600	6	58.0	58.0	0.0	18	0.06	0.9498	No
	720	5	57.8	57.8	0.0	18	0.08	0.9396	No
	900	*4*	*56.3*	*57.4*	*1.1*	*18*	*-2.60*	*0.0179*	*Yes*
2100	360	10	57.9	58.0	0.1	18	-2.00	0.0605	No
	400	9	58.0	58.0	0.0	18	0.09	0.9273	No
	450	8	57.8	57.8	0.0	18	0.39	0.6985	No
	515	7	57.7	57.8	0.1	18	-0.40	0.6938	No
	600	6	57.5	57.6	0.1	18	-0.48	0.6372	No
	720	*5*	*56.5*	*57.2*	0.7	*18*	*-2.37*	*0.0290*	*Yes*
	900	*4*	*51.7*	*54.3*	2.6	*18*	*-2.43*	*0.0256*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-4. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1250-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
2200	360	10	57.5	57.4	0.0	18	0.21	0.8348	No
	400	9	57.1	57.4	0.3	18	-1.38	0.1853	No
	450	8	57.2	57.5	0.3	18	-1.79	0.0910	No
	515	7	56.9	56.8	-0.1	18	0.58	0.5696	No
	600	6	56.1	56.5	0.4	18	-0.85	0.4041	No
	720	*5*	*52.8*	*54.6*	*1.8*	*18*	*-2.2*	*0.0412*	*Yes*
	900	*4*	*46.2*	*49.6*	*3.4*	*18*	*-2.5*	*0.0264*	*Yes*
2300	360	10	56.3	56.6	0.3	18	-0.97	0.3429	No
	400	9	55.9	56.2	0.3	9.84	-0.48	0.6423	No
	450	8	55.4	56.2	0.8	18	-1.85	0.0805	No
	515	7	53.7	53.5	-0.2	18	0.22	0.8260	No
	600	6	51.4	52.8	1.4	18	-1.09	0.2896	No
	720	*5*	*45.7*	*47.6*	*1.9*	*18*	*-2.32*	*0.0323*	*Yes*
	900	*4*	*39.6*	*42.5*	*2.9*	*13*	*-2.65*	*0.0198*	*Yes*
2400	360	10	53.8	53.7	-0.1	18	0.1	0.9233	No
	400	9	50.6	52.5	1.9	18	-1.76	0.0961	No
	450	*8*	*50.7*	*53.3*	*2.6*	*18*	*-2.72*	*0.0141*	*Yes*
	515	*7*	*48.3*	*49.9*	*1.7*	*18*	*-2.14*	*0.0465*	*Yes*
	600	*6*	*44.9*	*47.3*	*2.4*	*18*	*-2.19*	*0.0422*	*Yes*
	720	5	41.6	41.9	0.2	18	-0.33	0.7444	No
	900	*4*	*36.7*	*38.9*	*2.2*	*18*	*-3.58*	*0.0021*	*Yes*

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-5. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1500-Foot Ramp Acceleration Lane Length.

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
1800	360	10	58.5	58.5	0.0	18	-0.02	0.9839	No
	400	*9*	*58.6*	*58.4*	*-0.2*	*18*	*2.73*	*0.0142*	*Yes*
	450	8	58.5	58.5	0.0	18	0.4	0.6950	No
	515	7	58.4	58.5	0.1	18	-1.48	0.1565	No
	600	6	58.4	58.3	0.0	18	0.49	0.6310	No
	720	5	58.3	58.3	0.0	18	-0.42	0.6815	No
	900	4	58.1	58.1	0.0	18	-0.71	0.4872	No
1900	360	10	58.2	58.3	0.1	18	-1.11	0.2797	No
	400	9	58.4	58.2	-0.1	18	1.43	0.1685	No
	450	8	58.2	58.2	0.0	18	-0.36	0.7194	No
	515	7	58.1	58.2	0.1	18	-0.82	0.4246	No
	600	6	58.1	58.1	0.0	18	0.62	0.5405	No
	720	5	57.9	58.0	0.0	18	-0.31	0.7592	No
	900	4	57.5	57.7	0.2	18	-1.6	0.1274	No
2000	360	10	58.1	58.0	-0.1	18	1.23	0.2354	No
	400	9	58.1	58.0	0.0	18	0.08	0.9348	No
	450	8	58.0	57.9	-0.1	18	0.53	0.6019	No
	515	7	58.0	57.8	-0.1	18	1.46	0.1619	No
	600	6	58.0	57.8	-0.2	18	1.95	0.0666	No
	720	*5*	*57.5*	*57.8*	*0.3*	*18*	*-2.70*	*0.0148*	*Yes*
	900	4	56.9	57.1	0.3	18	-1.05	0.3067	No
2100	360	10	57.8	57.7	0.1	18	0.39	0.6989	No
	400	*9*	*57.8*	*57.5*	*-0.2*	*18*	*3.55*	*0.0023*	*Yes*
	450	8	57.6	57.6	0.0	18	-0.18	0.9341	No
	515	7	57.5	57.4	-0.1	18	0.98	0.3388	No
	600	6	57.4	57.3	-0.1	18	1.00	0.3310	No
	720	5	56.7	56.6	0.0	18	0.13	0.8975	No
	900	4	53.2	54.3	1.1	18	-1.06	0.3014	No

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

Table B-5. Comparison of Average Freeway Running Speed with and without Ramp Metering — 1500-Foot Ramp Acceleration Lane Length (Continued).

Freeway Demand (pcphpl)	Ramp Demand (pcphpl)	Meter Cycle Length (Seconds)	Average Running Speed (mph)			Results of t-Test Procedure			
			Without Ramp Metering	With Ramp Metering	Difference in Running Speed	Degrees of Freedom	t-Value	Probability > |t|	Statistically Significant?
2200	360	10	57.2	57.3	0.1	18	-0.46	0.6515	No
	400	9	57.2	57.3	0.1	18	-0.37	0.7130	No
	450	8	56.9	56.9	0.0	18	-0.16	0.8761	No
	515	7	56.8	56.7	-0.1	18	0.24	0.8160	No
	600	6	55.8	56.3	0.5	18	-1.07	0.2972	No
	720	5	54.3	54.6	0.3	18	-0.39	0.7002	No
	900	4	47.0	49.1	2.0	18	-1.46	0.1617	No
2300	*360*	*10*	*55.7*	*56.8*	*1.1*	*12.1*	*-4.05*	*0.0162*	*Yes*
	400	9	55.8	55.7	-0.1	18	0.22	0.8277	No
	450	8	55.7	55.7	0.0	18	-0.05	0.9643	No
	515	7	55.4	55.2	-0.1	18	0.3	0.7711	No
	600	6	52.1	52.9	0.8	18	-0.70	0.4909	No
	720	5	48.3	49.3	1.0	18	0.65	0.5212	No
	900	4	42.7	43.0	0.4	18	-0.49	0.6321	No
2400	360	10	53.9	53.8	-0.1	18	0.14	0.8901	No
	400	9	52.8	53.1	0.2	18	-0.33	0.7453	No
	450	8	51.9	49.7	-2.2	18	2.09	0.0509	No
	515	7	50.0	50.5	0.5	18	-0.5	0.6260	No
	600	6	*45.7*	*48.0*	*2.3*	*18*	*-2.22*	*0.0393*	*Yes*
	720	5	*41.4*	*43.7*	*2.3*	*18*	*-2.60*	*0.0100*	*Yes*
	900	4	38.7	39.5	0.8	18	1.14	0.2710	No

Note: Values shown in italics indicate statistically significant values at 95% confidence level.

APPENDIX C:
85TH PERCENTILE QUEUE STATISTICS

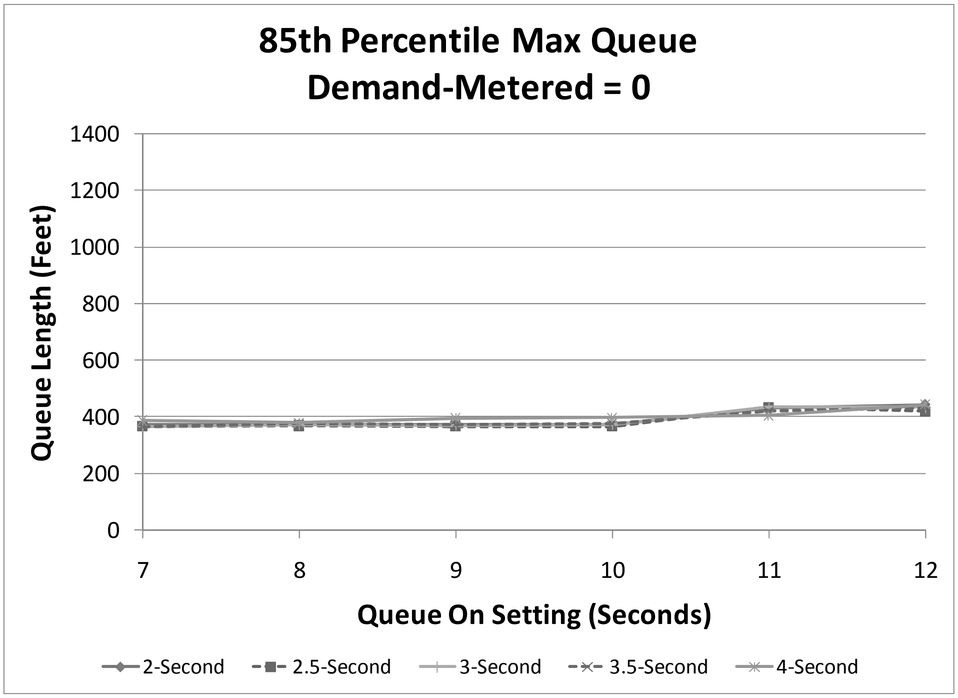

Figure C-1. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 0 Vehicles

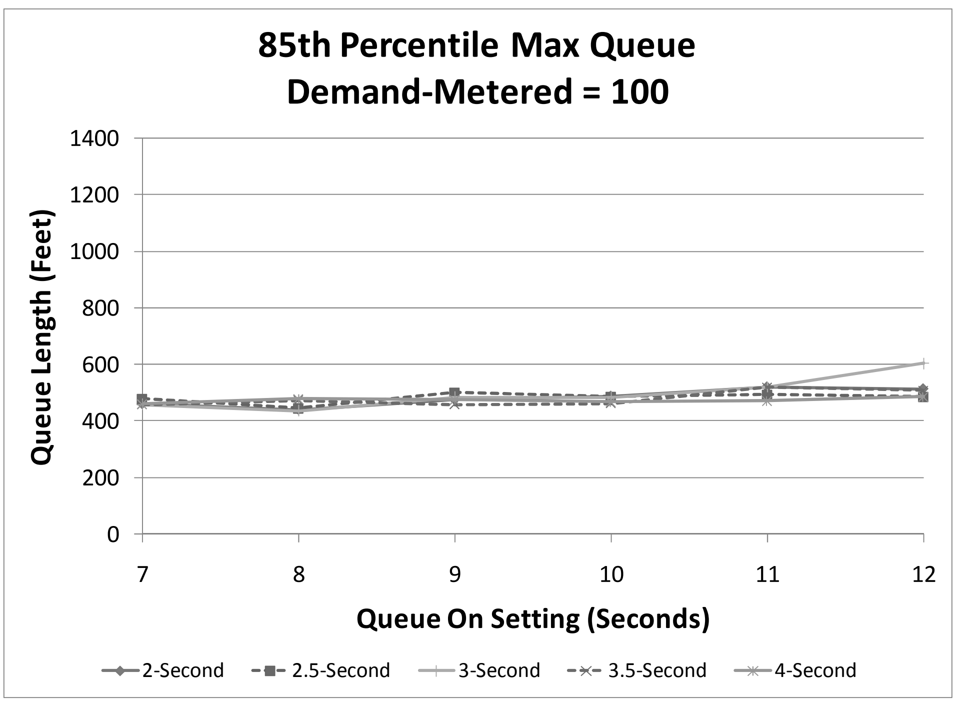

Figure C-2. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 100 Vehicles

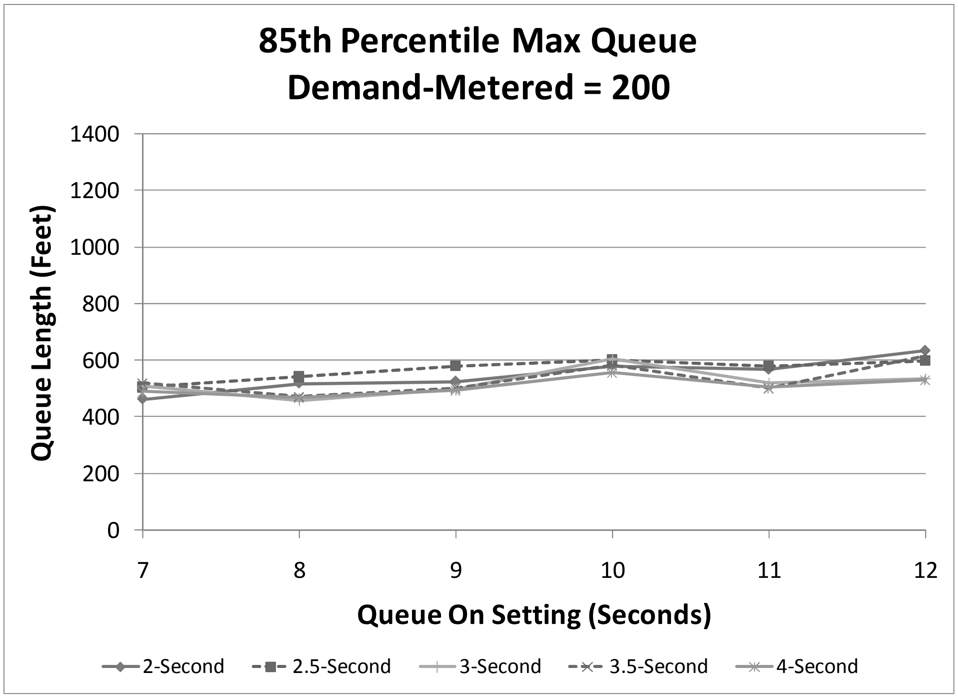

Figure C-3. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 200 Vehicles

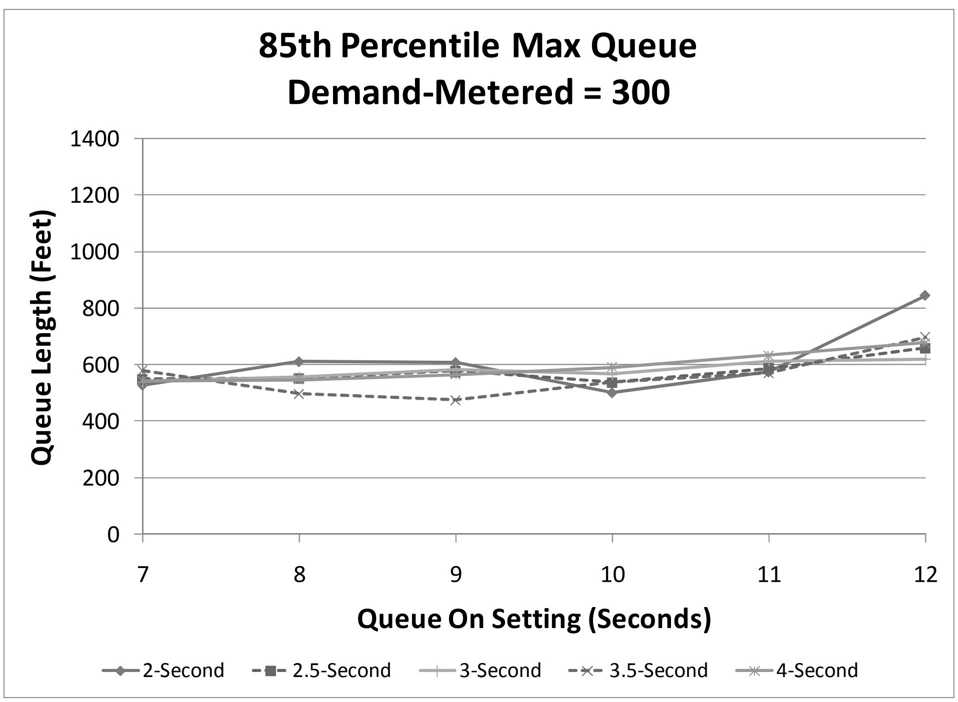

Figure C-4. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 300 Vehicles

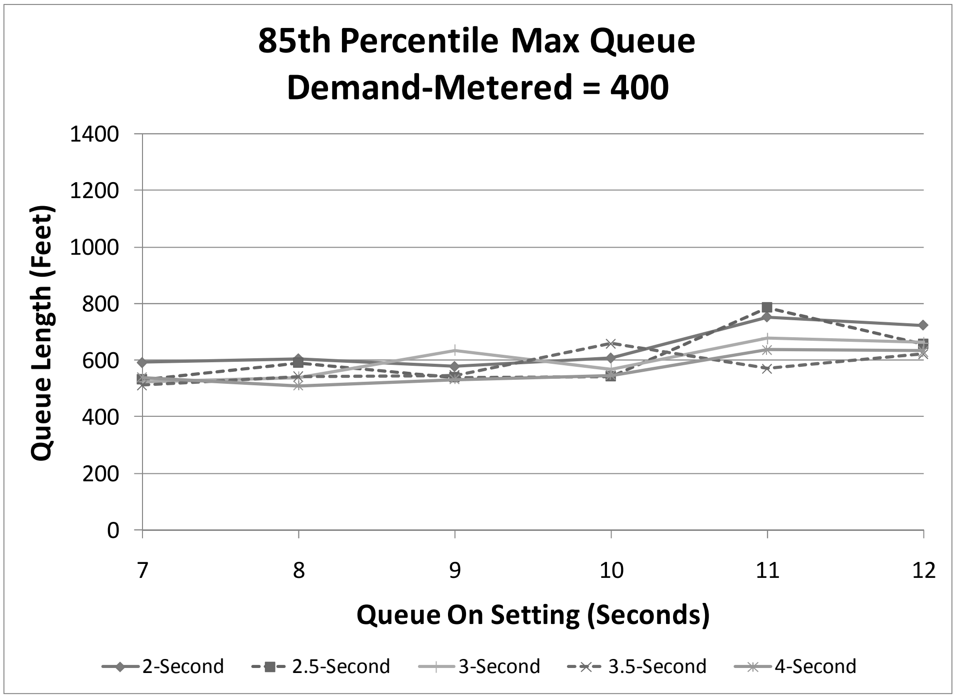

Figure C-5. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 400 Vehicles

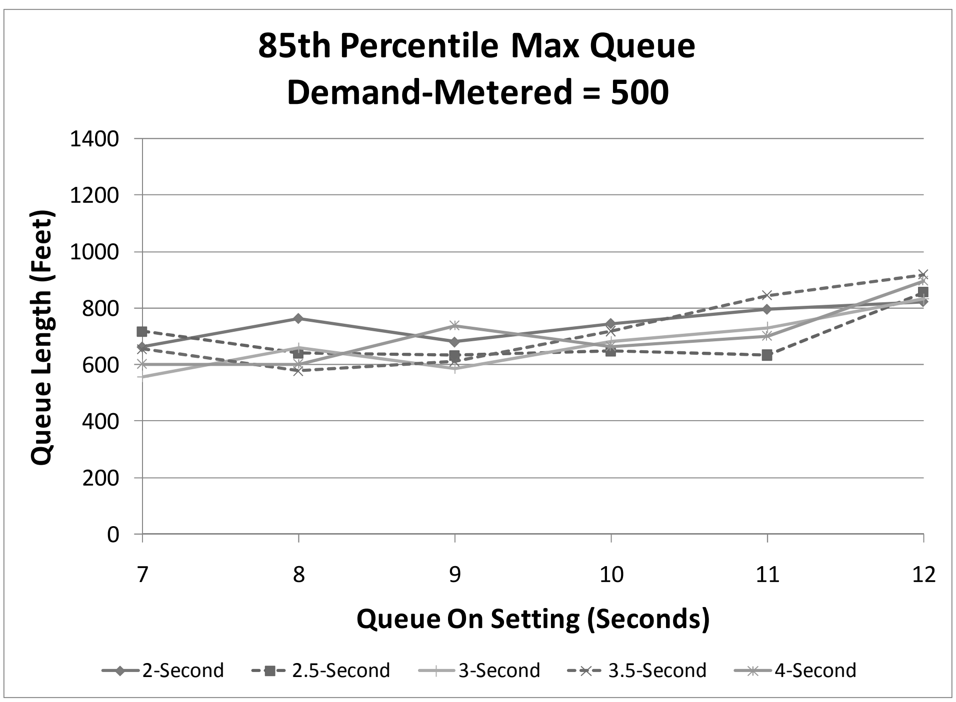

Figure C-6. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 500 Vehicles

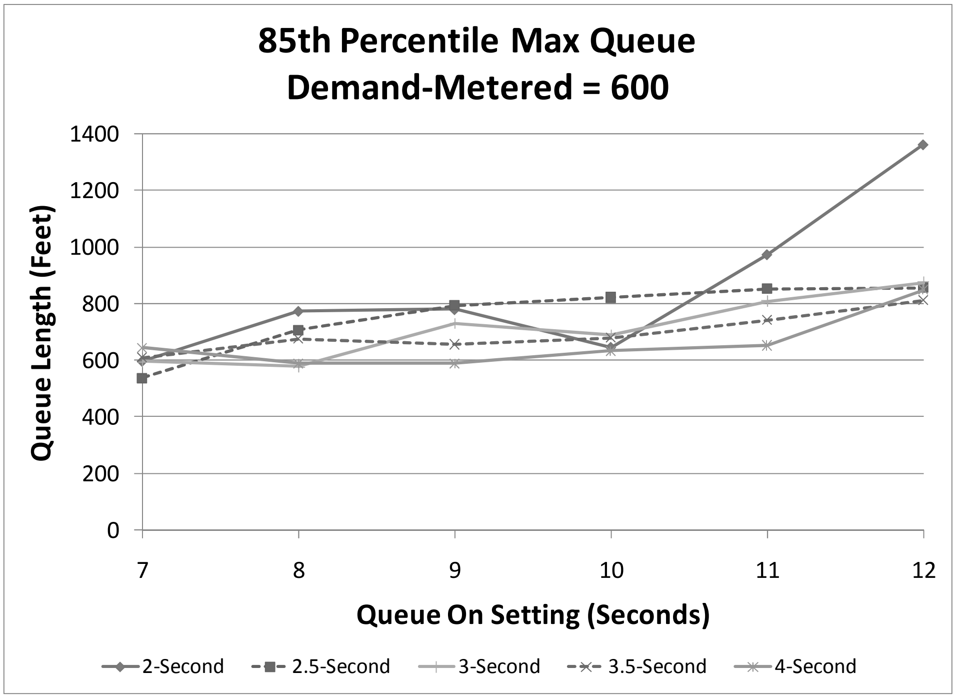

Figure C-7. Maximum Queue Length For Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 600 Vehicles

APPENDIX D:
METER AVAILABILITY

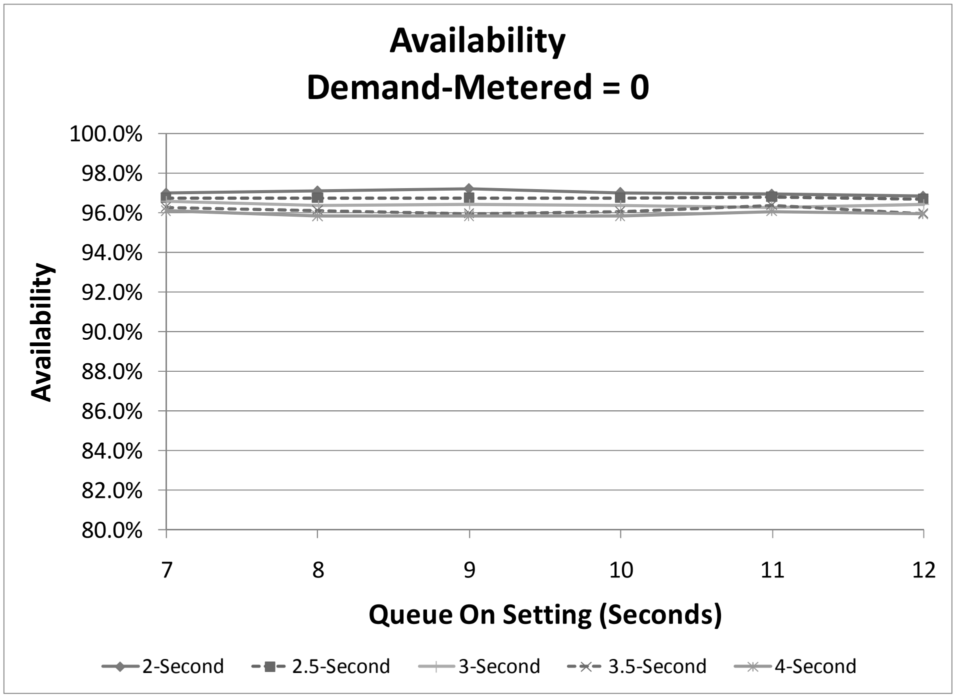

Figure D-1. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 0 Vehicles

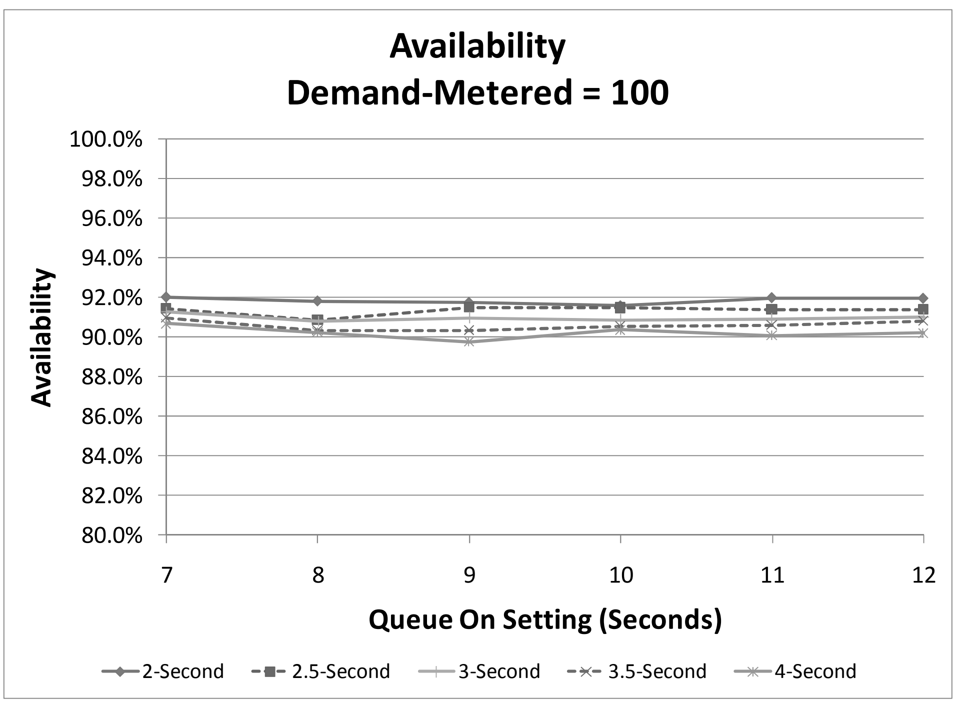

Figure D-2. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 100 Vehicles

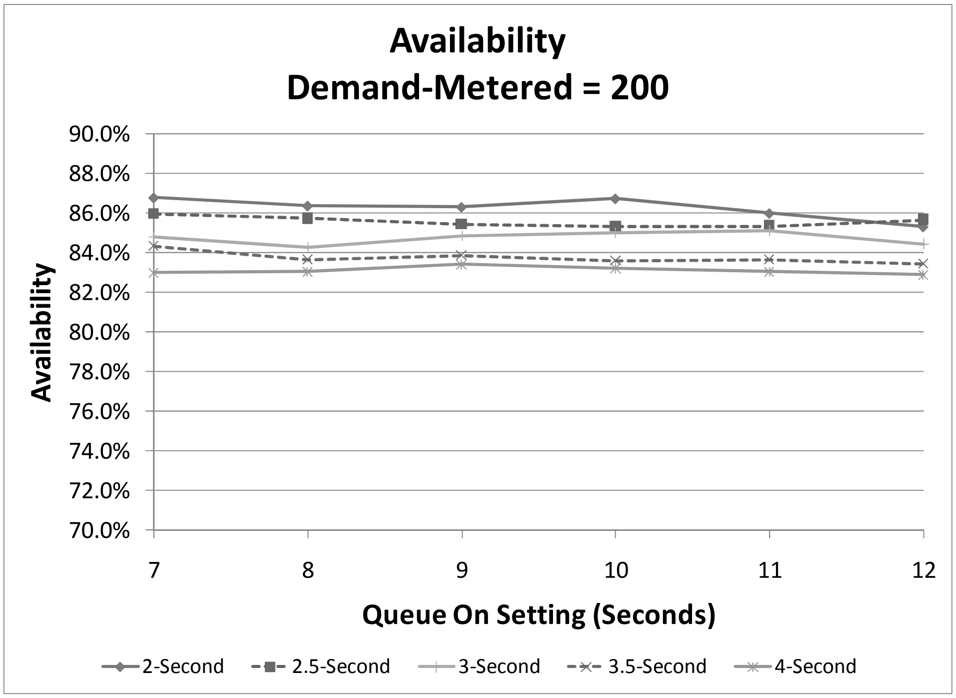

Figure D-3. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 200 Vehicles

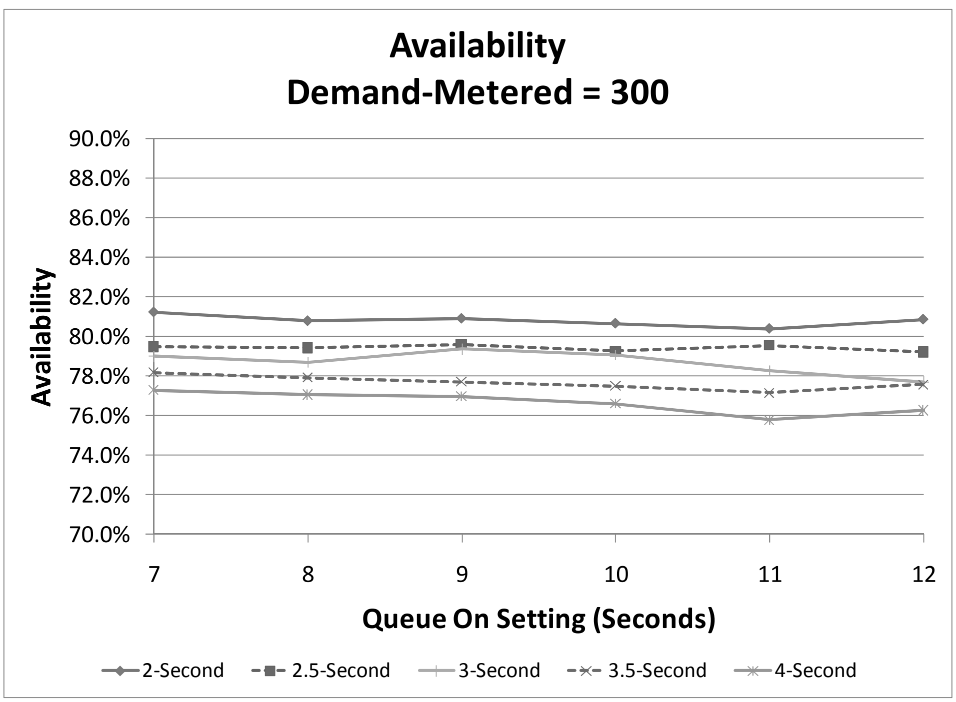

Figure D-4. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 300 Vehicles

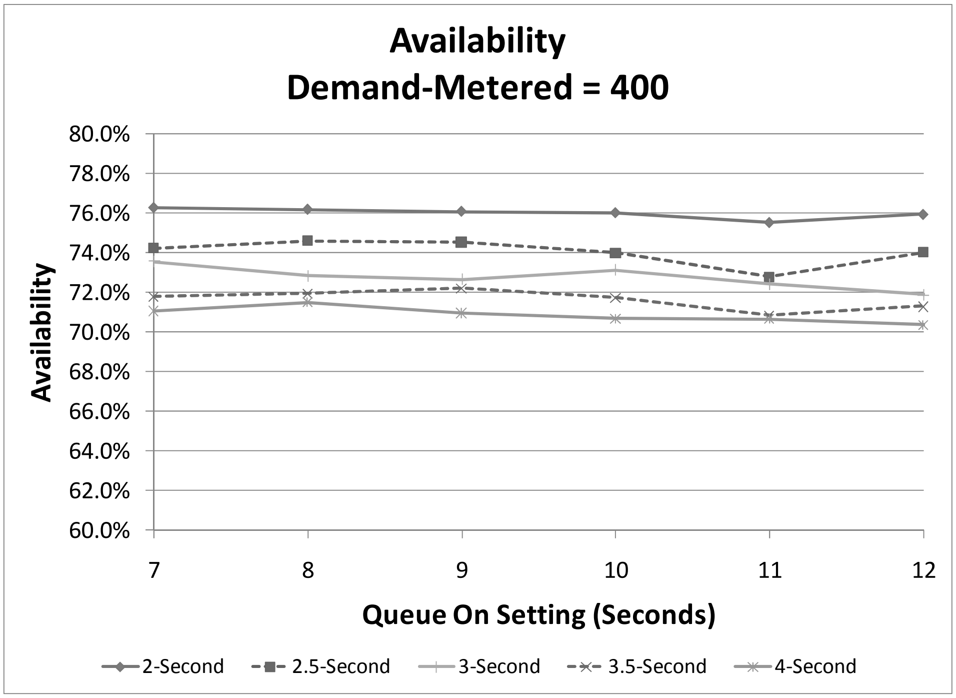

Figure D-5. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 400 Vehicles

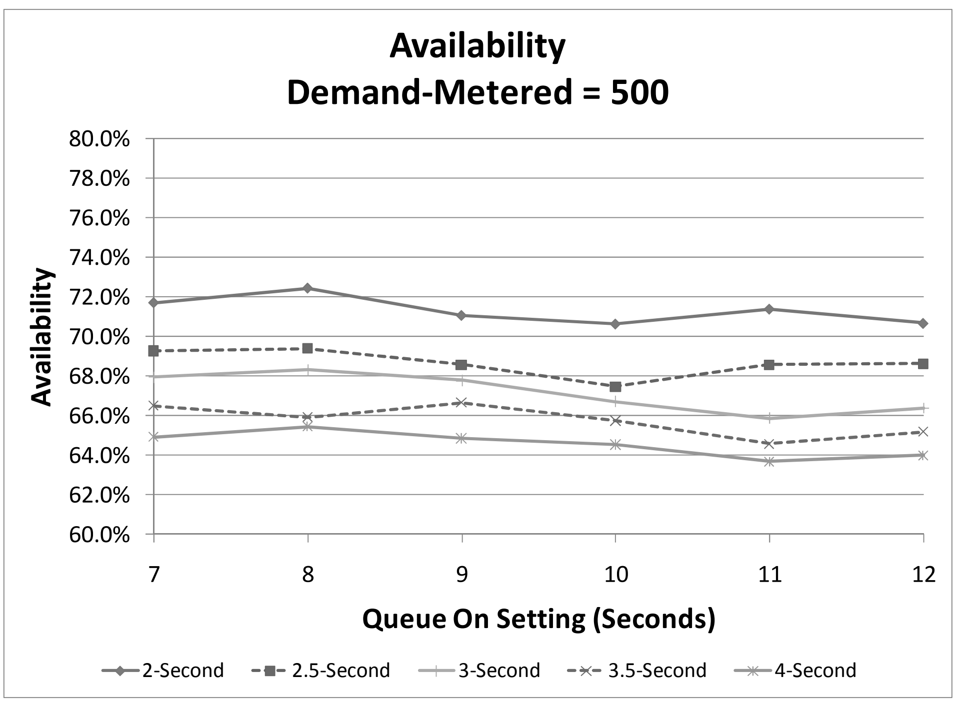

Figure D-6. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 500 Vehicles

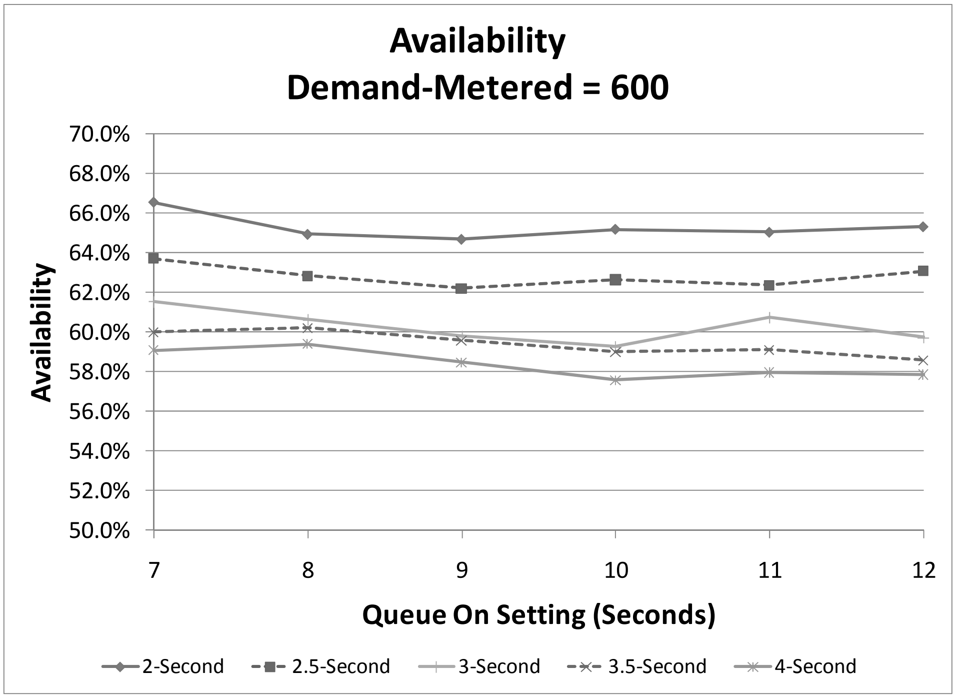

Figure D-7. Ramp Control Signal Availability for Different Queue-On Detector Settings: Difference in Demand minus Metered Volume = 600 Vehicles