Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-05/0-4629-1		

4. Title and Subtitle	5. Report Date
RAMP METERING ALGORITHMS AND APPROACHES FOR TEXAS	September 2004 Resubmitted: December 2004
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Nadeem A. Chaudhary, Zongzhong Tian, Carroll J. Messer, and Chi-Leung Chu	Report 0-4629-1

9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Project 0-4629

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	Technical Report: September 2003 – August 2004
	14. Sponsoring Agency Code

15. Supplementary Notes

Project performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.
Project Title: Evaluation of Ramp Metering Algorithms
URL: http://tti.tamu.edu/documents/0-4629-1.pdf

16. Abstract

The primary objective of this project was to compare ramp metering algorithms and develop guidelines for improving ramp metering operations in Texas. As part of this research project, researchers collected data at several sites in Houston, Texas. Data analysis showed that many congested freeways are facing heavy ramp demand, and require significant changes in existing ramp metering operations if ramp metering continues to be used as part of freeway traffic management. Furthermore, researchers used computer simulation to compare the effectiveness of ALINEA with queue flush with the existing strategy of metering at the maximum rate with queue flushing. Researchers found that ALINEA does not provide any benefits when queue flushing is permitted. Under heavy demand conditions such as those in Houston, the current strategy to meter at the fastest rate remains the most beneficial. However, this strategy also provides limited benefits. Finally, researchers developed guidelines and recommendations for current and future ramp metering operations in Texas. This report documents the research results.

17. Key Words	18. Distribution Statement
Ramp Meters, Algorithms, Operational Guidelines, Hardware-in-the-Loop Simulation, Simulation, Optimization	No restrictions. This document is available to the public through NTIS: National Technical Information Service Springfield, Virginia 22161 http://www.ntis.gov

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	94	

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

RAMP METERING ALGORITHMS AND APPROACHES FOR TEXAS

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DISCLAIMER

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ACKNOWLEDGMENTS

The research team conducted this project under a cooperative program between the Texas Transportation Institute (TTI), the University of Houston (UH), the Texas Department of Transportation (TxDOT), and the U.S. Department of Transportation, Federal Highway Administration. Mr. John Gaynor was the TxDOT project director for this research project. His assistance is acknowledged and appreciated. Dr. Lawrence Schulze from the Department of Industrial Engineering at UH was in charge of the data collection task in this project. Mr. Jason Lejeune and Mr. Yogesh Bhutani of UH were other members of the UH research team. Mr. Darrell W. Borchardt of TTI Houston provided additional data for use in this project. We acknowledge and thank all these individuals for their support in this project.

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CHAPTER 1:
INTRODUCTION

In Texas, the current use of ramp meters (flow signals) began in Houston in the mid 1990s. The operation of flow signals in Houston received favorable response from the motoring public due to the following two factors:

1. a policy of not allowing more than 2 minutes of delay to on-ramp vehicles, and
2. an extensive media campaign entitled “Go with the Flow” [1].

In the following years, the number of metered ramps rapidly grew. Initially, all controllers in Houston were programmed to provide pretimed operation at single-lane on-ramps. All these meters initially provided for the discharge of one vehicle per green. Later on, one dual-lane meter was added and platoon (bulk) metering was implemented at several single-lane ramps experiencing heavy traffic demand [2, 3].

In the mid 1990s, TxDOT initiated a series of research and construction projects to install an advanced ramp metering system at five on-ramps in Arlington, Texas [4]. The intended purpose of the Arlington system was to provide a real-life testbed for evaluating advanced ramp metering strategies. This system has center-to-field communication capabilities and is equipped to implement the full range of metering strategies based on the current Texas ramp metering specifications. The Arlington system has remained unchanged since it became operational in 1999. All of these meters provide single-lane one-car-per-green metering.

Although the Arlington ramp metering system remains the same, the system in Houston continues to grow at a steady rate. In recent years, Houston has begun implementing traffic responsive control based on freeway conditions. As this evolution occurs, TxDOT is striving to further improve ramp metering operation, including the current traffic responsive operation. As the ramp metering system in Houston matured, several questions arose. These questions include:

1. Should meters begin operation earlier and run all day long?
2. Should freeway speed be below 50 mph before a meter is activated?
3. Should platoon metering be used when an exit ramp immediately precedes an entrance ramp?
4. Can the maximum wait period for entering vehicles be increased from 2 minutes?
5. Do extra queue detectors aide or hinder ramp metering operation?
6. Can a predictive algorithm be used to start ramp meters before the freeway breaks down?
7. In evaluating algorithms, are the maintenance and operating costs required to keep the system running known?
8. Should enforcement level be considered when setting ramp meter strategy in high violation areas?
9. Can good operations be expected when a single ramp meter is added to a new corridor?
10. What to do with ramps without proper geometrics?
11. Should traffic signal timing be set to hold traffic a little longer and release at a rate that the ramp meter timing can handle?

Researchers addressed some of these questions in a recent project whose objective was to develop operational design guidelines for use in Texas [5, 6]. This research project has been initiated by TxDOT to address some of the remaining questions.

PROJECT OBJECTIVES

The primary objective of this project is to use computer simulation to evaluate the performance of the most promising advanced ramp metering algorithms being used elsewhere with the current operation in Texas. The specific sub-objectives are to:

- Develop a simulation testbed for evaluating advanced ramp metering strategies.
- Calibrate testbed using data from selected sites in Houston.
- Establish benchmarks for evaluating various strategies.
- Compare selected ramp metering algorithms.
- Provide recommendations for field testing and implementation of promising strategies.

A secondary objective of this project is to develop guidelines and procedures for assessing the performance of a system of on-ramps. A tertiary objective of this project is to provide controller training that will allow TxDOT staff to better utilize the features of this controller.

SCOPE OF PROJECT

The scope of this research project is limited to:

- field data collection to assess existing conditions at several congested locations in Houston, and
- in lab research, development, and testing of algorithms and procedures.

This project will make recommendations for future field testing of selected algorithms but will not conduct a field evaluation of such algorithms. Field data collection sites will be selected based on recommendations of the TxDOT advisory panel.

WORK CONDUCTED IN THIS PROJECT

To satisfy the objectives of this project and address issues identified by TxDOT staff, researchers conducted the following major tasks:

- reviewed literature to assess the state of technology and practice,
- met with TxDOT staff to identify the most pressing needs,
- selected a promising algorithm and compared its performance with the existing ramp metering operation in Texas,
- collected data to assess conditions at several congested locations in Houston. These data were provided to TxDOT Houston in a report prepared by UH,
- developed an improved version of RAMBO II optimization program [7],
- provided ramp controller training to TxDOT staff, and
- developed guidelines for installing and operating meters on existing ramps in Texas.

ORGANIZATION OF THIS REPORT

In addition to this chapter, this report contains five additional chapters providing details of work conducted and results obtained. Chapter 2 provides a review of current state of practice and existing technology. Chapter 3 provides a detailed overview of ramp metering operations in Texas. Chapter 4 provides a description of the revised version of RAMBO II produced in this project. Chapter 5 provides the results of simulation to evaluate existing isolated ramp metering operation with ALINEA. Finally, Chapter 6 provides guidelines for improved ramp metering operation in Texas.

In addition, the report contains two appendices. Appendix A contains VAP code used to simulate various metering strategies using VISSIM. Appendix B provides results of simulation in graphical form.

CHAPTER 2:
BACKGROUND

PURPOSE OF RAMP METERING

Ramp meters (also called Flow Signals) are traffic signals that control traffic at entrances to freeways [5, 6, 8]. Ramp meters are installed to address three primary operational objectives:

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

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

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

When properly installed, ramp metering has the potential to achieve the following benefits:

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

Furthermore, ramp metering can provide significant benefits even if a subset of its objectives is satisfied. In this regard the third objective is equally important. Figure 1 illustrates the freeway breakdown phenomenon recently observed by Persaud et al. [9]. The following points should be noted:

- As traffic flow increases, average speeds may decrease but generally remain in the vicinity of free-flow speeds.
- For a short period just before breakdown, flow may be as high as 2600 vehicles per hour (vph). This region is marked by a shaded box.
- At breakdown, there is a drastic reduction in flow and speed. Vehicle speeds may even reach zero just upstream of the bottleneck. A queue condition forms.

- As the queue of vehicles discharges from the bottleneck, speeds start to increase and the freeway capacity stabilizes at the breakdown capacity level of 2100 to 2200 vph.

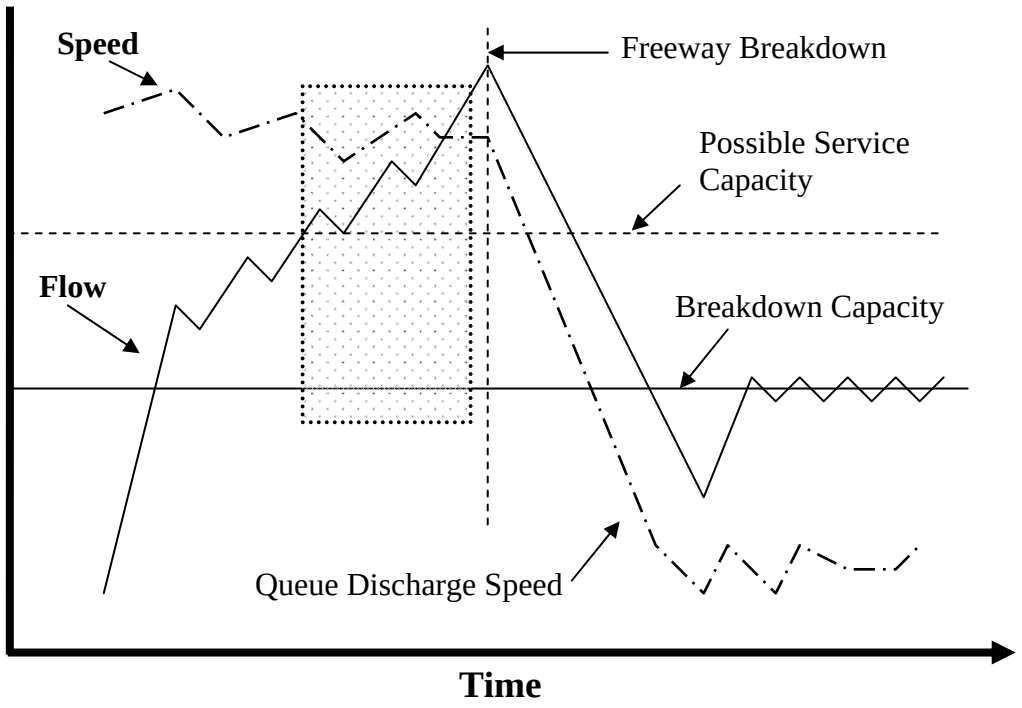


Figure 1. Freeway Breakdown Phenomenon.

This two-capacity phenomenon often occurs at freeway entrance ramps where platoons of vehicles trying to enter the congested freeway create a bottleneck. The end result is a reduction in service capacity. In addition, the shockwave created by a sudden drop in speed may travel for many miles upstream causing unsafe conditions. Ramp metering has the potential to minimize these effects and prevent freeway breakdown.

RAMP METERING STRATEGIES

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

Single-Lane One Car per Green

This strategy allows one car to enter the freeway during each signal cycle. Each signal cycle may have green, yellow, and red signal indications. The lengths of green plus yellow indications are set to ensure sufficient time for one vehicle to cross the stop line. The length of red interval should be sufficient to ensure that the following vehicle completely stops before proceeding. From a theoretical point of view, the smallest possible cycle is 4 seconds with 1 second green, 1

second yellow, and 2 seconds red. This produces a meter capacity of 900 vph. However, field observations have shown that a 4-second cycle is too short to achieve the requirement that each vehicle must stop before proceeding. Also, any hesitation on the part of a passenger-car driver may cause the consumption of two cycles per vehicle. A more reasonable minimum cycle is around 4.5 seconds, obtained by increasing the red time to 2.5 seconds. This increase results in a meter capacity of 800 vph (per lane).

Single-Lane Multiple Cars per Green

This strategy, also known as platoon or bulk metering, permits two or more vehicles to enter the freeway during each green indication. The most common form of this strategy is to allow two cars per green. Three or more cars can be allowed; however, this will sacrifice the third objective (breaking up platoons). In previously unpublished research, one of the authors developed an analytical model to study the behavior of the queue discharge for passenger cars. This research investigated the time required to encourage only the specified number of vehicles to cross the stop line. In addition, this research investigated how long the yellow change interval should be so that no "dilemma zone" routinely occurs for the next motorist in queue who is legally expected to stop at the stop bar. Table 1 provides the recommended signal timings. For comparison purposes, the table also provides the theoretical capacity of a one-car-per-green meter. The reader should note that contrary to what one might think, platoon metering does not produce a drastic increase in capacity over a single-lane one-car-per-green operation. The reason is that this strategy requires more green, yellow, and red times to ensure reliable operation as ramp speed increases, resulting in a longer cycle length. Consequently, there are fewer cycles in one hour.

Table 1. Recommended Controller Timings for Platoon Metering.

Interval Times (sec)						
Interval	**Vehicles Per Cycle**					
	1	**2**	**3**	**4**	**5**	**6**
Red	2.00	2.00	2.32	2.61	2.86	3.08
Yellow	1.00	1.70	2.00	2.22	2.41	2.58
Green	1.00	3.37	5.47	7.35	9.13	10.83
Cycle Length	4.00	7.08	9.78	12.19	14.40	16.49
Meter Capacity	900	1017	1104	1181	1250	1310

In cases where ramp demand includes a significant number of trucks or slow-moving vehicles, meter capacities may be lower than those provided in Table 1. Figure 2 provides a graphical representation of the results given in Table 1. The reader should also note that when implementing platoon metering, a specific regulatory sign message can also be displayed to denote the desired (maximum) number of vehicles entering per green (signal cycle per lane), such as TWO CARS PER GREEN. Displaying this message requires predetermination of the number of cars to allow per cycle. Furthermore, it should be noted that this sign can cause driver confusion when used with flush-on-green operation.

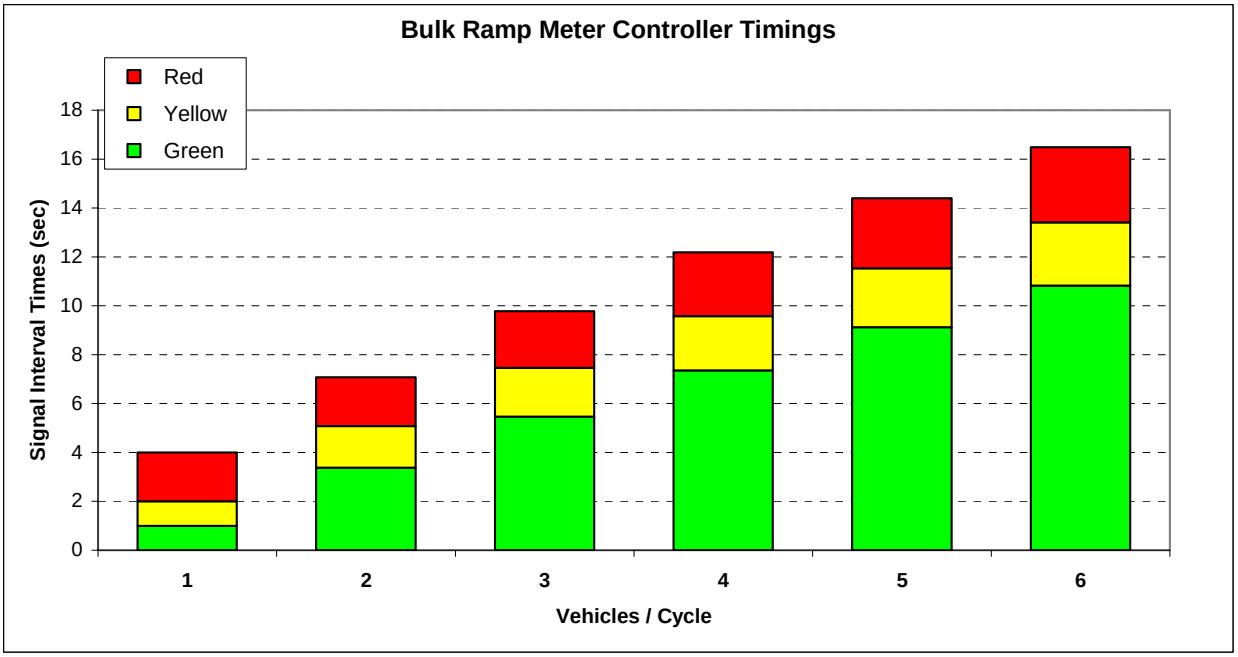


Figure 2. Controller Timings for Platoon Metering.

Dual-Lane Metering

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

TYPES OF RAMP METERING

Researchers classify ramp metering according to several categories. These classifications are described here and are based on a discussion provided in Chapter 7 of the Freeway Management and Operations Handbook [10].

Local and Systemwide

Local metering uses local traffic conditions to select metering rates. Systemwide metering establishes metering rates for several ramps based on traffic conditions for the entire freeway segment containing selected ramps.

Pretimed and Traffic Responsive

Pretimed systems use metering rates established using historical data. These systems cannot respond to fluctuations in traffic conditions. Traffic responsive strategies use data from freeway detectors to select or calculate metering rates.

Restrictive and Non-Restrictive Metering

A restrictive metering strategy sets metering rates below the non-metered demand level. This type of metering achieves the full benefits of ramp metering but often results in ramp queue reaching the upstream intersection and blocking it. A non-restrictive strategy sets the metering rate equal to the average non-metered ramp demand.

Metering with Queue Override

Queue override can be used with any type of metering. In the less restrictive operation, a queue condition on the on-ramp forces the implementation of maximum metering rate. In the more restrictive case, a queue condition on the on-ramp shuts the metering operation off until the queue has dissipated. Texas uses this type of operation. The latter case requires that sufficient storage space (distance from stop bar to queue detector) be provided to contain the cyclic arrival of a platoon of vehicles from the upstream signal.

Integrated Operation of Ramp and Upstream Traffic Signal

In certain situations, it may be possible to improve ramp metering operation by controlling or metering ramp demand at approaches to the upstream signal. In this approach, the objective is to distribute excess ramp demand before it actually reaches the on-ramp. However, this area needs further research [11, 12].

QUALITY OF METERING STRATEGIES

As a policy, Texas chose to implement ramp metering operation with the queue override feature. By design, this strategy services all ramp demand, regardless of ramp demand or the metering rate used. Furthermore, this type of operation can reliably satisfy only the third objective of ramp metering, and only when sufficient storage space exists to accommodate cyclic arrival of platoon from the upstream signal. Assuming an optimal design, Figure 3 shows metering availability of the three metering strategies for a range of ramp demand volumes [6]. Metering availability is defined as the percent of time the signal is displaying the green, yellow, and red sequence. For a ramp meter to produce the desired benefits, the engineer should select a metering strategy appropriate for the current or projected ramp demand. Figure 2 provides the following information about the quality of single- and dual-lane metering strategies:

- Single lane ramps can be used to provide good quality metering (metering availability of 80 percent or higher) when the ramp demand is less than 1200 vph.
- The quality of metering for single-lane ramps is fair for demand levels between 1200 and 1500 vph.

- Single-lane metering should not be used for demands higher than 1500 vph.
- Dual-lane metering provides good quality metering for demands up to 1650 vph.

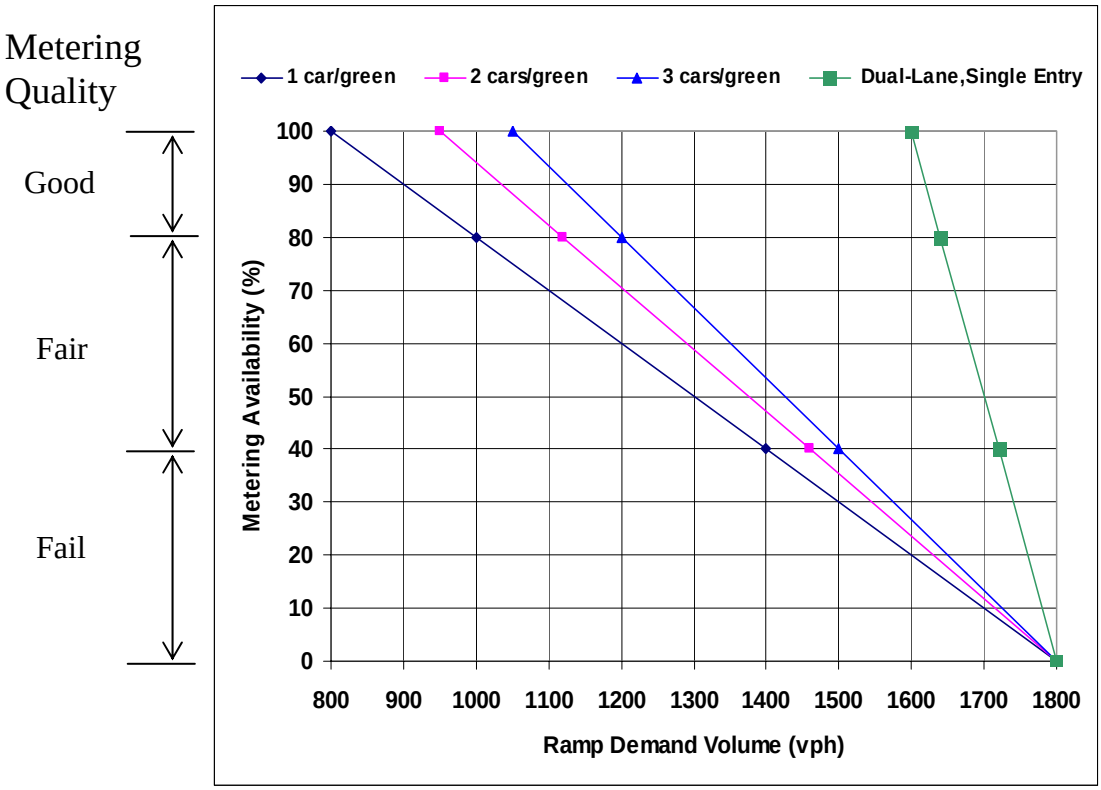


Figure 3. Quality of Metering Strategies for Various Levels of Ramp Demand.

In Houston, most on-ramps where ramp metering is desired are single-lane. Many of these on-ramps have demands upwards of 1200 vehicles per hour but are located in highly developed areas where it is not possible to acquire right-of-way needed for implementing dual-lane metering. Thus, engineers have to rely on platoon metering to minimize queue flushing.

An example of bulk metering is the southbound Kirby on-ramp at U.S. 59 in Houston. A recent field study of this ramp showed that during the evening peak period, the short-term demand fluctuated between 1484 vph to 1527 vph and the meter availability during that time was 39 percent. This number is close to that predicted by the graph in Figure 3. The minor difference is because of the fact that the signal cycle of 8.7 seconds (with 5-second green, 1.7-second yellow, and 2-second red) was servicing 2 or 3 cars per green with an average of 2.5 cars per green. In contrast, the northbound Abrams ramp on S.H. 360 in Arlington provides one-car-per-green operation to service estimate ramp demand of 1242 vph. Meter availability at this ramp was found to be only 9.3 percent, much less than that predicted by Figure 3. Low performance at this ramp is because the current design does not provide sufficient space to store cyclic queues from the upstream signal. The design issue is addressed in a later section of this chapter.

OVERVIEW OF CURRENT RAMP METERING OPERATION IN TEXAS

Texas uses an off-the-shelf controller, which meets the TxDOT specifications for ramp control [3, 6]. Two versions (1.01 and 2.0) of this controller are in current use. Figure 4 illustrates a single-lane meter with demand, queue, freeway, and merge detectors that may be installed at a site. Demand detector is mandatory. Its purpose is to ensure that the meter displays green only when a vehicle is present at the meter. In the absence of a vehicle, the meter dwells in red. Excessive queue detector is also mandatory. It establishes an upper limit on delay to ramp vehicles and prevents a ramp queue from spilling back into the upstream traffic signal. When an excessive queue condition is detected, the controller enables the flush mode until the queue of vehicles clears. In the flush mode, the signal may either turn off or display a continuous green indication. When the excessive queue condition clears, the meter goes through a start-up cycle before resuming normal metering operation. During this time, the signal is not metering and is considered to be unavailable. The excessive queue detector should be located to provide sufficient storage space on the ramp and safe stopping distance for vehicles joining the maximum queue.

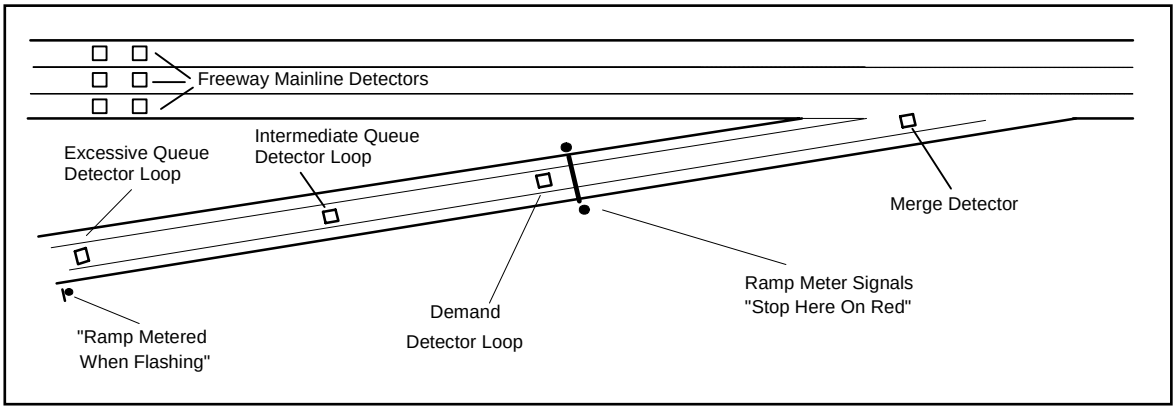


Figure 4. Key Components of Texas Ramp Metering Systems.

The controller provides for four (numbered 0 to 3) plans, each with eight levels (0 through 7). Level 0 corresponds to no metering, and levels 1 through 7 provide fastest to slowest metering, respectively. Each level has an associated user-programmed headway (inverse of metering rate). For each level, the user can also define occupancy, speed, or volume thresholds for providing traffic responsive operation using data from freeway detectors. These settings enable the controller to initiate, vary, and terminate ramp metering operation based on the selected variable.

In version 2.0 of the ramp controller, the intermediate queue detector can be activated to select metering rates to match changing ramp demand. In the older version of this controller, the excessive queue detector can be programmed to provide this functionality instead of queue flushing. This controller mode uses occupancy from the detector to increase or decrease the metering level. An intermediate queue detector cannot shut off metering. Lastly, when the excessive queue detector initiates queue flushing, normal metering operation cannot resume until the queue condition at the intermediate queue detector has been cleared.

DESIGN CONSIDERATIONS FOR OPTIMAL OPERATION

Installation of a ramp meter to achieve the desired objectives requires sufficient room at the entrance ramp. The determination of minimum ramp length to provide safe, efficient, and desirable operation requires careful consideration of several elements described below [5, 6]:

- distance for a stopped vehicle at the meter to accelerate and attain safe merge speeds,
- sufficient storage space to handle cyclic queue of vehicles, and
- stopping distance for vehicles discharged from the upstream signal to safely stop behind the maximum queue of vehicles being metered.

Distance from Meter to Merge

Figure 5 shows an example of acceleration length for passenger cars as they accelerate from a stop to design speed for various ramp grades [5, 6]. About 419 feet is presumed needed to accelerate from a stop at the meter to a 40 mph merging speed on level grade. Desired distance to merge increases with increasing freeway merge speed and ramp grade. For further information, the reader is referred to AASHTO guidelines [13].

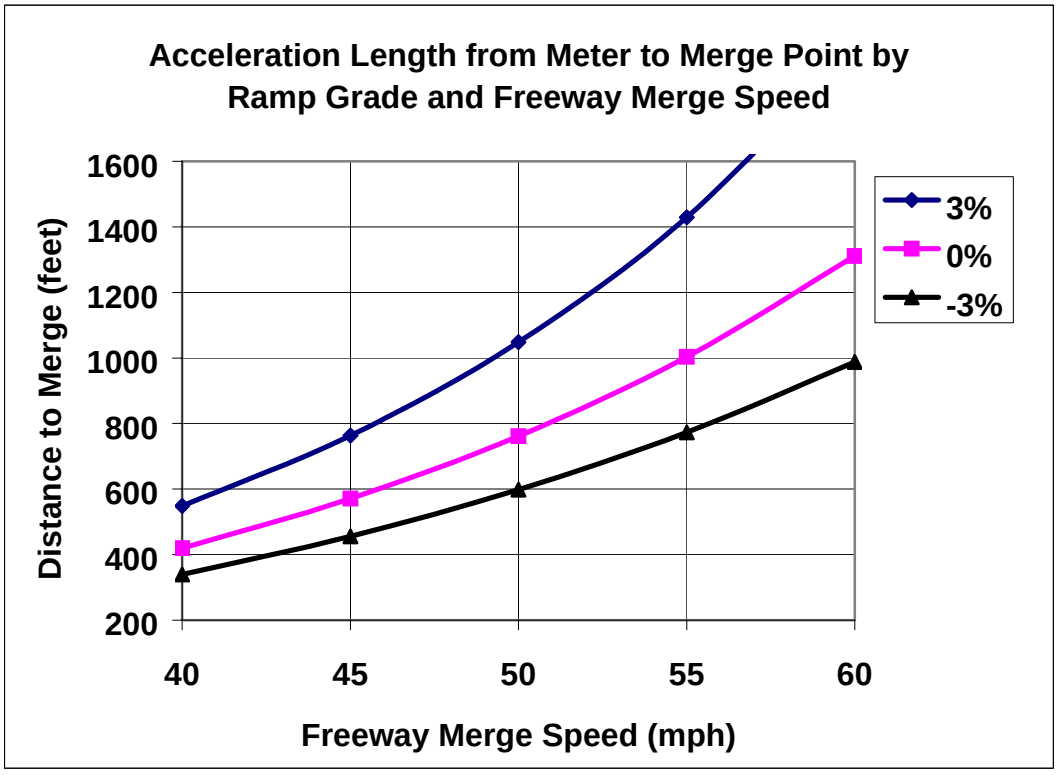


Figure 5. Distance from Ramp Meter to Freeway Merge for Three Ramp Grades Based on AASHTO Passenger Car Acceleration Criteria.

Safe Stopping Distance and Storage Space

These distances are constrained by ramp geometry, location of signal pole, and the placement of excessive queue detector. This research recommended that the queue detector be installed at least 250 feet downstream of the intersection to provide a safe stopping distance behind a standing queue at the meter. Furthermore, this research developed the following generalized model for determining storage requirements for ramp metering.

$$L = 0.820V - 0.0002435V^2 \qquad V \le 1600\,vph \qquad (1)$$

where L is the total distance needed from the queue detector to the meter (feet), and V is the expected peak-hour ramp volume (vph). As an example, this equation calculates a storage requirement of 541 feet for ramp demand of 900 vph.

Ramp Spacing Related to Service Time

Ramps should be sufficiently long to permit a reasonable service time charge for using the freeway during peak traffic conditions (to encourage diversion) while still metering at a relatively high flow rate [5, 6]. The time a vehicle spends in queue at the meter, S, depends on the length of queue on arrival and the mean time of service per vehicle, T_s, or the cycle time of the meter. Thus,

$$S = E(n) \times T_s = \frac{L(ft)}{25(ft/veh)} \times \frac{60(\min/hr)}{M(vphpl)} = 2.4\frac{L(ft)}{M(vphpl)} \qquad (2)$$

where:

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

Using this equation, one can also calculate the maximum length of queue to be stored (that is, storage space) to provide an acceptable service time. For instance, if a service time of 2 minutes or less is desired, the required storage space will be 750 feet (2×900/2.4). This sample calculation assumes a metering rate of 900 vph and storage space of 25 feet per vehicle. For the storage space of 541 feet calculated in the previous section, the maximum service times will be 1.62 and 1.44 minutes, respectively.

RAMP METERING SYSTEMS AND ALGORITHMS

Numerous ramp metering algorithms have been developed over the past several decades. This section provides an overview of such algorithms. Some of these algorithms have been implemented or evaluated in considerable detail.

ALINEA

ALINEA uses a local feedback ramp metering strategy [14, 15, 16]. ALINEA attempts to maximize freeway mainline throughput by maintaining desired freeway occupancy. Thus, it requires only one freeway detector per lane located downstream of the entrance ramp. Figure 6 illustrates ALINEA detector location. It also illustrates the detector location for traditional traffic responsive control. The user should note that ALINEA provides closed-loop traffic responsive control where metering rates are calculated to maintain desired occupancy. In contrast, the traditional traffic responsive control is an open system that uses preprogrammed occupancy threshold values to select an appropriate metering rate from a lookup table.

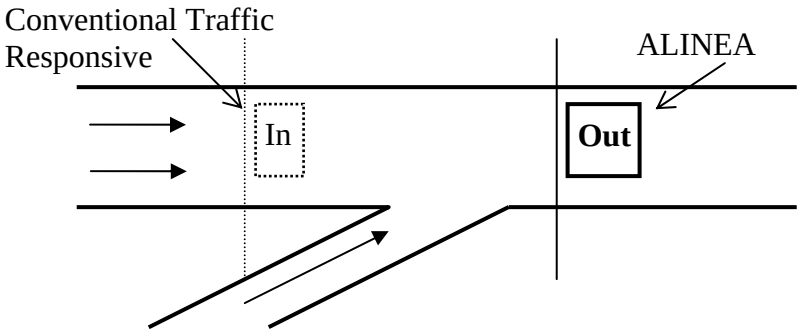


Figure 6. Detector Requirement for ALINEA.

ALINEA uses the following equation for deriving ramp metering rate for control period *t*:

$$r(t) = r(t-1) + K_r[O - O_{out}(t)] \qquad (3)$$

Where O is the desired occupancy threshold, O_{out} is the measured occupancy at time *t*, *r(t-1)* is the metering rate in the previous time period, and K_r is a regulatory parameter. Developers of ALINEA [14] suggest a value of 70 vehicles per hour for K_r. They also describe successful implementation for two cases where detection was 40 and 400 meters downstream of the entrance ramp. In these cases, occupancy was measured every 60 seconds. In European field implementations, desired occupancy values of 18 to 30 percent have been used. Because this value can be changed at any time, the strategy can be used in a coordinated system.

The ALINEA algorithm assumes that vehicles from the meter reach at the detector within the measurement time. When the detector is too far downstream or the sample time is too short for this assumption to be true, the following equation should be used [14]:

$$r(t) = r(t-1) + K_r[O - O_{out}(t)] + K_p[O_{out}(t) - O_{out}(t-1)] + \gamma[q_{in}(t) - q_{in}(t-1)] \qquad (4)$$

Authors suggest:

$$K_p = \delta/(T\alpha) - K_r > 0 \qquad (5)$$

where: $\alpha = \mu / 100\lambda$

T = sample time in seconds,
μ = number of lanes,
λ = vehicle length in kilometers, and
$\gamma \leq 1$ is a smoothing parameter.

BOTTLENECK

This centralized algorithm has been used in Seattle, Washington, for a number of years [15, 16, 17]. It provides local- and system-level control on a selected freeway section. The local-level metering rate is selected from a look-up table. This rate is based on the evaluation of upstream demand and downstream capacity. The system or bottleneck metering rate is based on system capacity constraints. The system-level control identifies the bottleneck, determines the volume reduction needed, and then distributes this reduction to upstream ramps according to predetermined weights.

ZONE

Minnesota's ZONE algorithm divides a freeway under consideration into several zones of 3 to 6 miles in length [15, 16]. The upstream end of a zone is a free-flow area, whereas downstream end of a zone is a critical bottleneck. ZONE calculates metering rates based on volume control in each zone. To accomplish this ZONE relies on proper division of zones, accurate estimates of bottleneck capacity, and accurate measurements of all in- and out-flows from a zone. The algorithm calculates metering rates for each zone using the following equation:

$$M + F = X + B + S - (A + U) \qquad (6)$$

where:

M = total metered on-ramp volume,
F = total metered freeway-to-freeway volume,
X = total measured off-ramp volume,
B = bottleneck capacity,
S = space available within the zone (calculated using measured freeway occupancy),
A = total upstream freeway volume, and
U = total measured non-metered ramp volume.

ZONE also provides for local control using the occupancy control philosophy.

RAMBO

RAMBO, developed by TTI for use by TxDOT, consists of two programs [7]. RAMBO I is a program for evaluating plans generated based on ramp metering specifications TxDOT-550-80-950-02 dated December 1991. RAMBO II is a system ramp metering package that evaluates ramp metering rates based on forecasted traffic conditions along an extended section of freeway containing up to 12 metered on-ramps and 12 exit ramps. RAMBO II is based on the formulation and optimization of a linear programming model [18, 19].

MILOS

Multi-Objective, Integrated, Large-Scale, and Optimized System (MILOS) has been designed to provide real-time adaptive control of an integrated system of freeways and arterial roads [20]. It has been tested in a laboratory setting using simulation but has not been implemented in the field due to lack of infrastructure needed for real-time control.

Other Algorithms and Proposed Systems

Several other ramp metering systems have been developed [16]. These include:

- SWARM operates on local and system levels. It identifies bottlenecks based on predicted traffic conditions rather than measured conditions. Thus, its performance depends on the quality of predictions.
- MALINEA (modified ALINEA) is a local algorithm.
- METLINE is an extension of ALINEA for system-level control of a group of ramps.
- Coordinated systems based on Artificial Neural Networks and Fuzzy theory.
- ARMS model is developed by researchers at TTI. This model contains algorithms for local- and system-level control [21].

SIMULATION FOR EVALUATING RAMP METERING ALGORITHMS

Stochastic computer simulation is practical methodology for evaluating control strategies in a controlled environment and for evaluating algorithms not supported by existing field hardware. This section describes several simulation models and provides an overview of their use in evaluating ramp metering algorithms.

TSIS/CORSIM

It was developed with Federal Highway Administration support [22]. It is the oldest and the most popular micro-simulation program in its class. CORSIM provides several ramp metering algorithms including, clock-time metering, demand-capacity metering, speed-control metering, multiple-occupancy threshold metering, and ALINEA. CORSIM does not support the excessive queue detector used at ramp meters in Texas. Furthermore, CORSIM does not allow placing a detector in the merge lane. The limitations of existing ramp metering algorithms, however, can be overcome by using an external (software or real) controller. TSIS API provides a mechanism to achieve this result. This feature has been extensively used by the proposed research team.

TexSim

TTI developed TexSim, a micro-simulation program, for evaluating advanced real-time traffic control strategies [23]. In TexSim, ramp metering can be implemented by using an external software controller developed by TTI, or by connecting a real controller through an interface device. TTI researchers have extensively used both types of controllers, especially hardware-in-the-loop simulation, in recent research projects [4, 5, 6]. When interfaced with a real controller, TexSim is also a useful tool for providing controller training.

VISSIM

VISSIM, developed in Germany, is a micro-simulation program for simulating a variety of control conditions [24]. It contains features above and beyond those provided by CORSIM and TexSim. These include: pedestrian flow, trains, busses, and 3-D graphics. VISSIM does not contain a ramp metering controller; however, it is very easy to create any control logic using the built-in vehicle actuated programming (VAP) capability. Furthermore, several researchers in this project have extensive experience with VISSIM and have developed interfaces for conducting hardware-in-the-loop simulation with it.

PARAMICS

PARAMICS is a micro-simulation model developed in Scotland [25]. PARAMICS does not provide a controller for simulating ramp metering operation. However, it does provide an API and a plan language that can be used for implementing any desired traffic control logic. In recent years, California-based PATH program has funded the development of code for using its API to simulate several ramp metering algorithms. These algorithms include ALINEA, BOTTLENECK, and ZONE [15]. However, the queue override feature, a must in any Texas implementation, was not considered. In another study [16], researchers used plan language in PARAMICS to study no metering versus four local metering strategies, all using freeway and presence (stop bar) detectors. These four strategies resulted from the "Yes" and "No" cases for queue and merge detectors. In this research, the purpose of the queue detector was to implement maximum metering (not flushing) in the presence of long queues. The researchers found that similar to CORSIM, PARAMICS does not allow a detector to be placed in the merge lane. Thus, the merge detector had to be placed in the mainline. Furthermore, they found that the use of plan language does not allow aggregation of detector information over time.

ASSESSMENT OF PRACTICE AND EXISTING TECHNOLOGY

Texas is the only state that uses an off-the-shelf ramp controller. This controller provides a wide range of features including the capability to operate under systemwide control from a central location. The Arlington system has the basic ability to directly communicate to the controllers from a central location. In Houston, however, no infrastructure currently exists to provide this type of communication. Thus, any changes needed in the controller have to be done in the field. Without a communications infrastructure, systemwide ramp metering cannot be installed in Houston even if this strategy had the potential to improve traffic conditions. In the near-term, the only solution is to provide improvements by optimally using the current local ramp metering strategy.

One method of achieving this objective would be to optimally program the controller for satisfying the needs of specific ramp metering locations. During project meetings with the TxDOT advisory panel for this project, it was determined that TxDOT Houston staff needs controller training. Based on this assessment, researchers organized a one-day training workshop in College Station, Texas. This training used an actual controller (RMC 300) connected to the TexSim simulation program. This type of system (Figure 7) is referred to as hardware-in-the-loop (HITL) simulation. During this hands-on training session, researchers demonstrated the

effects of ramp metering for various controller settings and demand patterns. In addition, researchers provided training on how to set up pretimed and traffic responsive operations. Chapter 3 provides details of the RMC 300 controller.

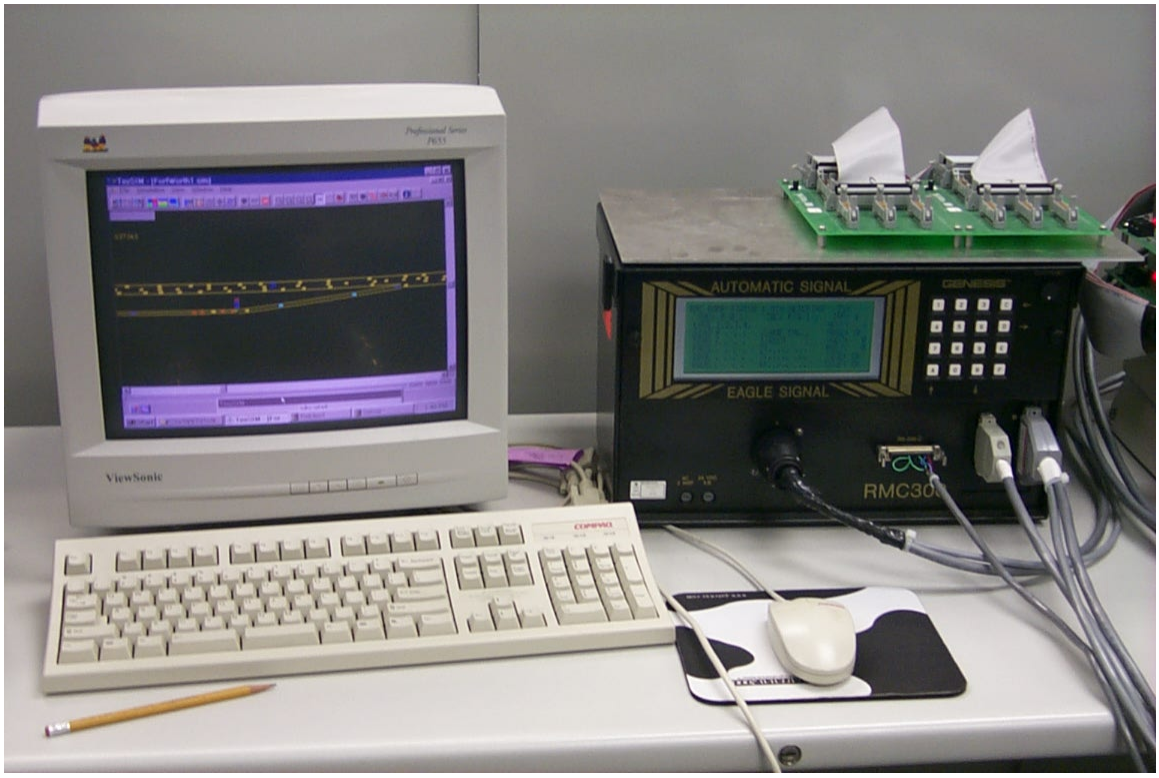


Figure 7. Hardware-in-the-loop Simulation Using TexSim.

Another method of achieving the best operation in Houston would be to determine systemwide metering rates using historical data and implement these rates within the local controller. RAMBO II can be used to achieve this objective. However, the existing version of this DOS software does not work very well under a modern operating system. To facilitate the use of RAMBO II, researchers developed a Windows version of this program. Enhancements required developing a new user interface and adjustments to the RAMBO optimization module. In addition, several enhancements were made to the software. Furthermore, researchers used data collected in this project for a section of U.S. Highway 290 to demonstrate how to use this software. Chapter 4 describes the new RAMBO II software.

Several advanced ramp metering algorithms have been developed and implemented in states other than Texas. Previous research using restrictive metering has shown ALINEA and BOTTLENECK to be the most promising of these algorithms. However, the performance of these algorithms has not been verified for the type of non-restrictive metering used in Texas. Furthermore, from an implementation point of view, ALINEA is easier to implement in the near-term if it is found to work well under non-restrictive metering. In this project, researchers used computer simulation to compare ALINEA with the current metering operation in Texas. Researchers used the VISSIM simulation program to perform these comparisons. Chapter 5 provides details of this work.

CHAPTER 3:
TEXAS RAMP-METER SYSTEM

In this chapter, we present key features of ramp metering systems in Texas. Figures 8 and 9 illustrate various components of single-lane and dual-lane ramp meters, respectively, currently used in Texas. These include detectors, signs, and signals. The following subsections provide descriptions of these components.

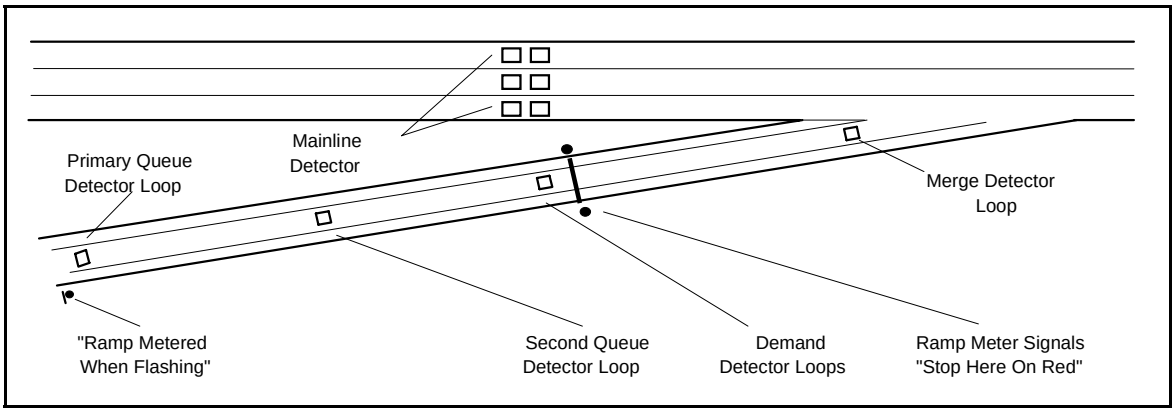


Figure 8. Single-Lane Ramp-Meter System.

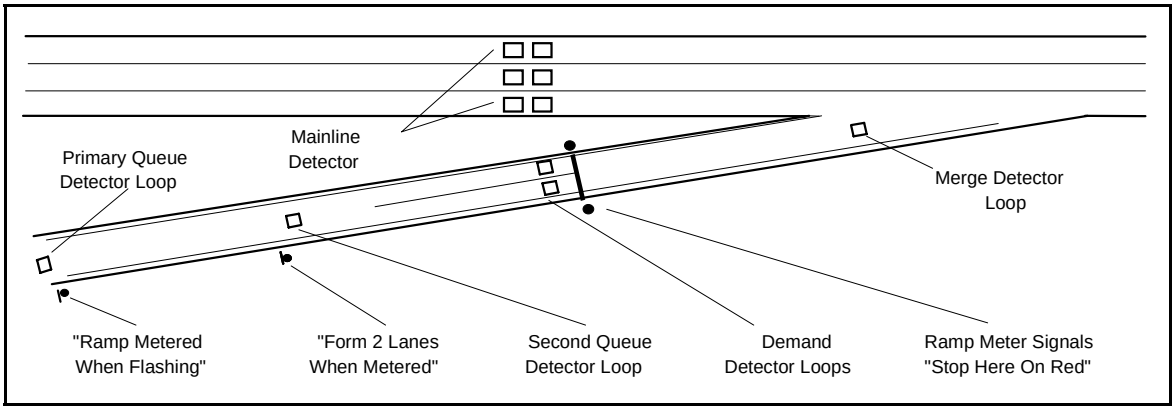


Figure 9. Dual-Lane Ramp-Meter System.

LOOP DETECTORS

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

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

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

Demand Detector

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

Primary Queue Detector

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

Second Queue Detector

A second queue detector, installed between the demand detector and the primary queue detector, is optional and provides for adapting to traffic demand at the ramp. Houston does not use this type of detector, but the Arlington system does.

Mainline Detectors

Optional mainline detectors consist of a pair of detectors in each freeway lane. These detectors, placed upstream of the entrance ramp gore, are used to obtain volume and occupancy data for implementing traffic-responsive metering. Houston has these types of detectors at several locations. Houston uses traffic responsive operation to automatically initiate or terminate ramp metering operation based on freeway conditions. Arlington also has these types of detectors, but the current operation there does not provide traffic responsive control.

Merge Detector

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

WARNING AND REGULATORY SIGNS

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

Control Devices

The final element of the single-lane or multiple-lane traffic control devices is the traffic signal display. As the motorist nears the ramp-meter stop-bar, one of two standard signing and traffic signal display conventions is used to inform the driver of the regulatory requirements of the ramp meter and to indicate when the motorist is allowed to enter the freeway. Figures 10 and 11 illustrate the typical post-mounted signal used for single- and dual-lane metering. Note that signal heads are installed on both sides of the entrance ramp. However, in some single-lane locations two signal heads are located on a single pole. Also, these three-section signal heads are installed on breakaway posts because they are within the 30-foot clear zone. Furthermore, the signal- and dual-lane meters utilize a different number of signal heads on each pole.

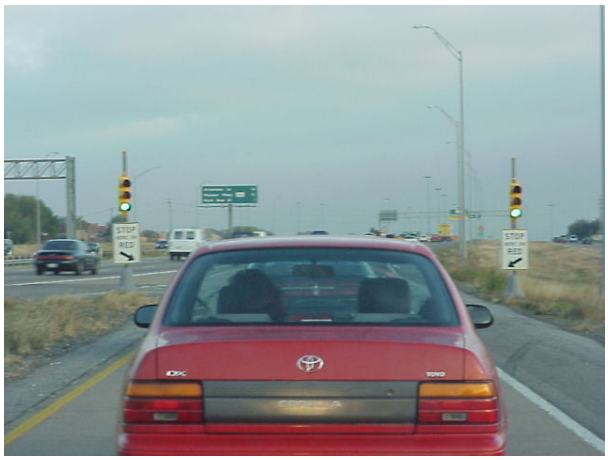
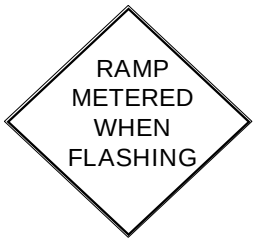
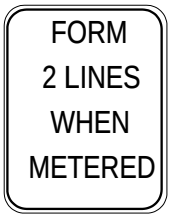


Figure 10. Single-Lane Meter.

Figure 11. Dual-Lane Meter.

Table 3. Ramp Metering Signing Locations and Applications.

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

As illustrated in Figure 10, single-lane meters use one signal head on each side of the ramp. One of these signals is installed at an angle where vehicles stopped at the meter can clearly see the lights. The other is installed at an angle that allows lights to be seen from the ramp entrance. Additionally, a "Stop Here On Red" sign is posted below each signal head.

For dual-lane meters (Figure 11), two three-section heads are installed on each pole. The top signal head points to vehicles entering the ramp, while the bottom signal head points to vehicles stopped at the meter. Signals on the left side pole are for the left lane and signals on the right side pole are for the right lane. A "Stop Here On Red" sign is mounted on each pole between the

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

TEXAS RAMP CONTROLLERS

As stated earlier, Texas uses controllers specifically manufactured for ramp metering operation by Eagle TCS of Austin, Texas. Two versions of Eagle RMC 300 controllers are currently being used in Texas. The older controller runs software version 1.01, dated July 1992. The newer version (dated February 1998 or later) of this controller provides several enhancements over its predecessor [26]. This version of the controller is being used on all five ramps in Arlington and several ramps in Houston. Both versions of this controller operate in the following basic manner:

1. When the metering operation begins, the controller activates the flashing beacon accompanying the “Ramp Metered When Flashing” sign. The beacon flashes throughout the metering duration.

2. The controller activates the metering operation consisting of a start-up cycle followed by regular metering cycles. Each metering cycle begins only when the demand detector detects a vehicle. These cycles continue until the metering operation terminates or gets suspended.

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

1. The old controller simultaneously activates the flashing beacon and the start-up cycle at the signal. In contrast, the new controller provides the user the capability to enter the duration for which the beacon will flash before activating the start-up cycle. In selecting this duration, the engineer should take into consideration the time it takes for a vehicle just crossing the beacon to go past the meter before it is activated.

2. In the old controller, the green time for the start-up cycle is 15 seconds long and cannot be changed by the user. In many cases, this fixed value results in an unproductive period. In addition, the start-up cycle uses the same values for yellow and red times programmed by the user for the metering cycle. Therefore, the user must carefully select these common values, especially the yellow time, to suit the driver expectancy at the end of both these cycles. In contrast, the new controller provides the user flexibility to enter different durations for green, yellow, and red signal indications for each of the start-up and regular cycles, thereby giving a better control to fine-tune the operation.

3. The old controller can meter only one lane, whereas the new controller is capable of metering up to four lanes, including one lane for high-priority vehicles.

4. The new controller provides a capability to automatically adjust metering rates using data from an intermediate queue detector.

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

As mentioned previously, Texas adopted a policy of preventing a ramp queue from blocking an upstream traffic signal. Additionally, this policy also prevents operations of a ramp meter if it would result in more than 2 minutes of delay to any ramp vehicle. The primary queue detector is used as a means of implementing this policy, and therefore, is a required component of ramp-meter installations in Texas. During the metering operation, if the occupancy of this detector exceeds a user-specified threshold (i.e., 50 percent) value for a specified length of time (i.e., 20 seconds), the controller suspends the ramp metering operation and provides time for the queue to flush. The controller resumes metering operation when the occupancy decreases to a value below the specified threshold value. When in the flush mode, the new controller is capable of turning off all signal lights (flush-in-dark mode) or displaying a green signal (flush-in-green mode). Texas ramp metering controller permits both types of operation [26]. Comparative field studies of the flush-on-dark and the flush-on-green operations indicate that both modes result in some start-up delay at the beginning of the flush period, but the onset of delayed response occurs at different times [3, 6]. In the case of flush-on-dark operation, the delay is generally due to hesitation of the first vehicle; whereas, in flush-on-green operation, the delay results from the second and third vehicles in the queue. The following paragraphs provide further detail about the current version of ramp metering controller.

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

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

Setting proper thresholds are important for achieving the desired ramp metering operation. In addition, user-specified minimum durations for metering and non-metering periods ensure unnecessary cycling between these periods and ensure the elimination of unproductive flush cycles. Therefore, it is essential to set up these parameters carefully to produce optimal operation.

CHAPTER 4:
RAMBO II UPGRADE FOR WINDOWS

Data from several sites in Houston show that many congested freeway segments also have high-demand on-ramps. To better manage these facilities, a systemwide approach is necessary. However, since Houston currently does not have communication and detection infrastructure to implement an online systemwide ramp metering system, the best approach is to develop system-based metering rates and implement these rates locally. Ramp Adaptive Metering Bottleneck Optimization II (RAMBO II) program developed by TTI researchers is a tool to facilitate this objective. In this project, researchers developed an upgrade to the existing DOS version of RAMBO II to allow its use on computers with a Windows operating system. As part of this upgrade, researchers developed a new user interface and enhanced the software to allow analysis and optimization of facilities much larger than those permitted by the older version. This chapter describes the theory and features of RAMBO II. The "Help" facility distributed with the program provides a step-by-step exercise on how to use RAMBO II.

MODELS IN RAMBO II

RAMBO II, a type of macroscopic model, formulates and optimizes a given instance of a ramp metering problem as a linear program (LP). The objective is to maximize the sum of metering rates for all input ramps across all time slices. A time slice is defined as a period of time for which data are being supplied by the user. For instance, if the user wishes to enter 15-minute counts for a 2-hour period, the RAMBO data will have eight 15-minute time slices. The LP formulation is presented as follows.

LP Formulation

Maximize: $P = \sum_{k=1}^{W} \sum_{i=1}^{N} X_i(k)$ vehicles per time slices, vpt (7)

for all freeway system inputs, $i = 1, \ldots, N$, and time slices,
$k = 1, \ldots, W$, at H time slices per time.

Subject to the following constraints:

$\sum_{i=1}^{j} A_{ij}(k)X_i(k) \leq B_j(k)$ for all freeway sections $j = 1, \ldots, L$ (8)

$P_m \sum_{i=1}^{j-1} A_{im}(k)X_i(k) + E_m X_m(k) \leq C_m$ for all m,k (9)

$R_m(k) = T_m(k) - X_m(k)$ for all m,k (10)

$Q_m(k) = (1/H)(1 - d_m)R_m(k)$ for all m,k (11)

$T_m(k+1) = D_m(k+1) + HQ_m(k)$ for all m,k (12)

$Q_m(k) \leq U_{m,max}$ for some m (13)

$X_{m,min} \leq X_m(k) \leq T_m(k)$ and $X_{m,max}$ for all m,k (14)

Where:

i,m = input i; metered ramps (m) start at $i = 2$ ($i = 1, 2, \ldots, N$)
j = freeway section ($j = 1, 2, \ldots, L$)
k = time slice ($k = 1, 2, \ldots, W$)

$X_i(k)$ = input flow at input i in time slice k
$A_{ij}(k)$ = proportion of vehicles entering at input i which pass through freeway section j in time slice k
$B_j(k)$ = capacity of freeway section j in time slice k
$D_i(k)$ = base demand at input i in time slice k
$T_m(k)$ = total ramp demand $D_m(k) + Q_m(k\text{-}1)$ at ramp m in time slice k
$X_{m,min}$ = minimum metering rate for metered ramp m
$X_{m,max}$ = maximum metering rate for metered ramp m
U_m = queue storage capacity at ramp m
E_m, C_m = equivalency, capacity, based on the type of on-ramp m
P_m = proportion of mainline vehicles in merge lane at ramp m
$Rm(k)$ = demand not serviced at on-ramp m during time slice k
$Q_m(k)$ = queue length at on-ramp m at the end of time slice k, the number of vehicles transferred to time slice k+1
d_m = fraction of potentially delayed vehicles diverting from metered ramp m
H = number of time slices per unit time t, H = 1, 2, …

Constraint (8) states that total traffic on each freeway section cannot exceed the corresponding freeway capacity. Freeway capacity is supplied by the user. Constraint (9) denotes that the total traffic at the ramp merge point must be below the corresponding ramp merge point capacity. Equation (10) models the demand that is not serviced at an on-ramp. Equation (11) expresses queue lengths at on-ramps at the end of each time slice, i.e., the number of vehicles transfers to next time slice. Finally, equation (12) states that the total ramp demand of the current time slice is composed of the new ramp demand for the current time slice and the ramp vehicles, which were not serviced during the last time slice. It should be noted that RAMBO II does not model queue flushing.

The above LP model requires trip distribution from all inputs of the freeway system to all possible outputs. To estimate the trip distribution, RAMBO II uses a gravity-based model which is based on relative travel times and distances. Readers interested in further detail about this aspect should refer to Messer [19].

Merge Constraint

In the above LP formulation, the selections of optimal ramp metering rates are constrained by the merge capacity of each section. Merge capacity of a freeway section is a function of the number or percent (P_m) of vehicles in the merge lane just upstream of the merge point. RAMBO II automatically calculates this value. Figure 12 describes this calculation.

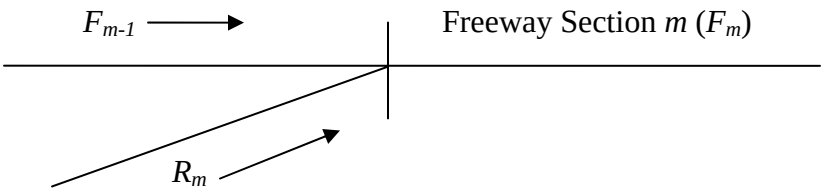


Figure 12. Freeway Merging Area of Entrance Ramp *m*.

Specifically, P_m is defined as the fraction of freeway traffic in the merge lane at entrance ramp *m*. Consider the freeway merging area of entrance ramp *m* as in Figure 12. Assuming that equilibrium exists among the freeway approach lanes, P_m is determined by the following equation:

$$P_m = \max\left(0.02, \frac{1}{n_m} - \alpha \frac{(n_m - 1)(n_m + 7)}{n_m}\left(\frac{R_m}{F_{m-1}}\right)\right) \qquad (15)$$

where:

n	=	Number of lanes on freeway link *m*;
R_m	=	Ramp demand at entrance ramp *m*;
F_{m-1}	=	Freeway demand at upstream freeway link; and
α	=	Freeway merge lane use calibration factor.

As per the above formula, P_m is a function of several factors, however, its lower limit has been set equal to 0.02. Furthermore, in cases where an auxiliary lane exists to facilitate merging, RAMBO II sets P_m equal to 0.02 regardless of the upstream freeway demand and ramp demand. In RAMBO II, the default value of α is 0.14. Figures 13 and 14 illustrate the behavior of P_m for varying ramp demand, freeway demand, and calibration factor. As shown in Figure 13, P_m reduces as ramp demand increases. This behavior of the model is consistent with driver behavior. In contrast, P_m reduces as α increases. Also, as α approaches zero, the model starts to equally distribute freeway traffic across all lanes.

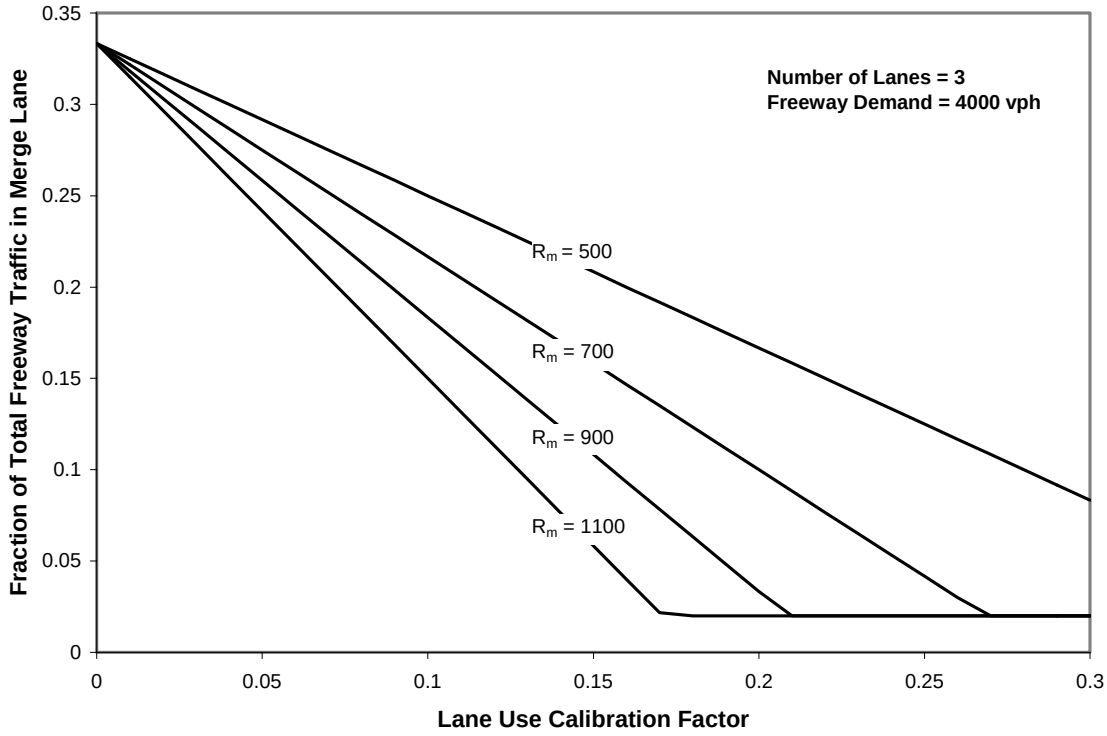


Figure 13. Behavior of P_m for Varying Ramp Demands and Calibration Factors.

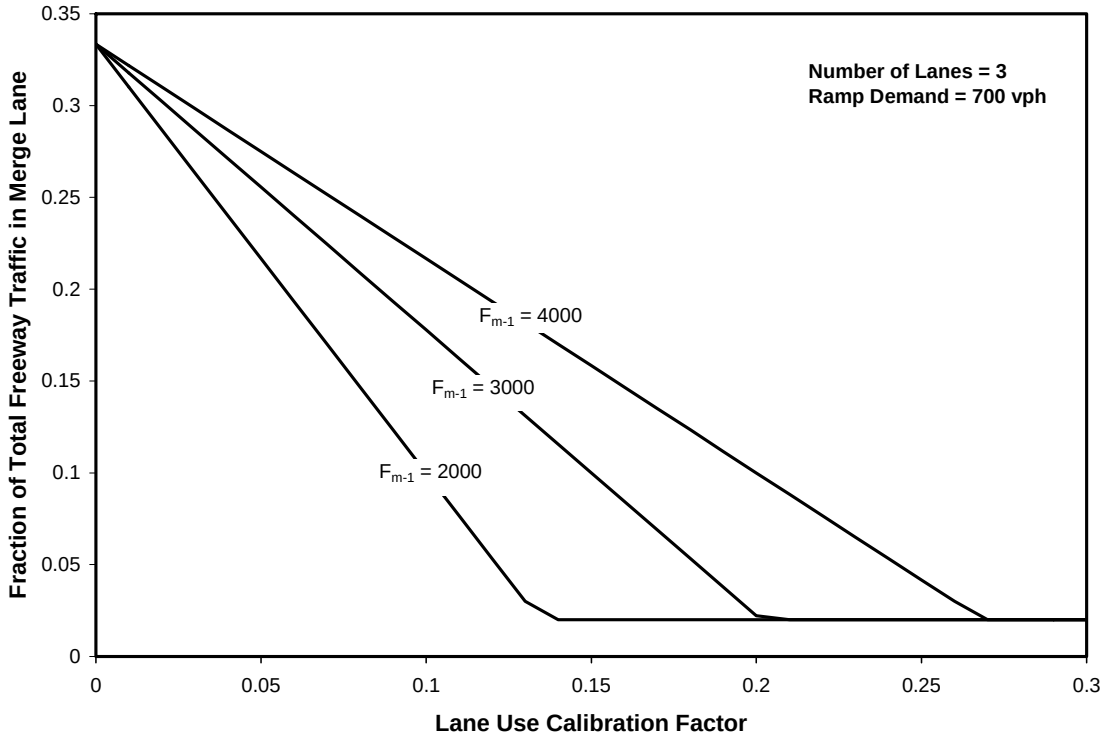


Figure 14. Behavior of P_m for Varying Freeway Demands and Calibration Factors.

Figure 14 illustrates the behavior of P_m for changes in total freeway traffic. Here, the ramp-demand of 700 vph from Figure 13 is compared to two cases of lower freeway demand. The user will observe that an increase in freeway demand results in an increase in P_m.

RAMBO II USER INTERFACE

RAMBO II has been developed using a multiple-document architecture that allows the user to open, and work with, up to five data files at any given time. In addition to a standard menu in Windows-based programs, the user interface is composed of four pages (Tabs), namely, System page, Freeway Parameters page, Operations Analysis page, and Plot page. The Plot page activates (becomes visible) only after an optimization run has been made.

System Page

Figure 15 shows the System page screen. This page contains two sections regarding the freeway system. The "System Information" section contains general information including; a system name, number of entrance and exit ramps, number of time slices per hour, and total number of time slices. The user should notice that "Number of Entrance Ramps" and "Number of Exit Ramps" are not input fields. It is because these fields are updated automatically after the freeway system has been defined on the "Freeway Parameters" page.

The “Calibration Factors” section allows users to specify factors and data that are used in the optimization. “Ideal capacity” is the ideal freeway capacity and is set to 2400 vehicles per hour per lane by default. “Timeplan capacity (%)” denotes the service capacity as a percentage of the ideal capacity. It is calculated using the number provided by the user. For instance, in Figure 15, the service capacity for timeplan 1 is 2304 which is 96 percent of 2400. “Equity Factor” is used to achieve metering rate equity for adjacent ramps and is equal to 0.8 by default. “Lane Use Alpha Factor” is the freeway merge lane use calibration factor described previously.

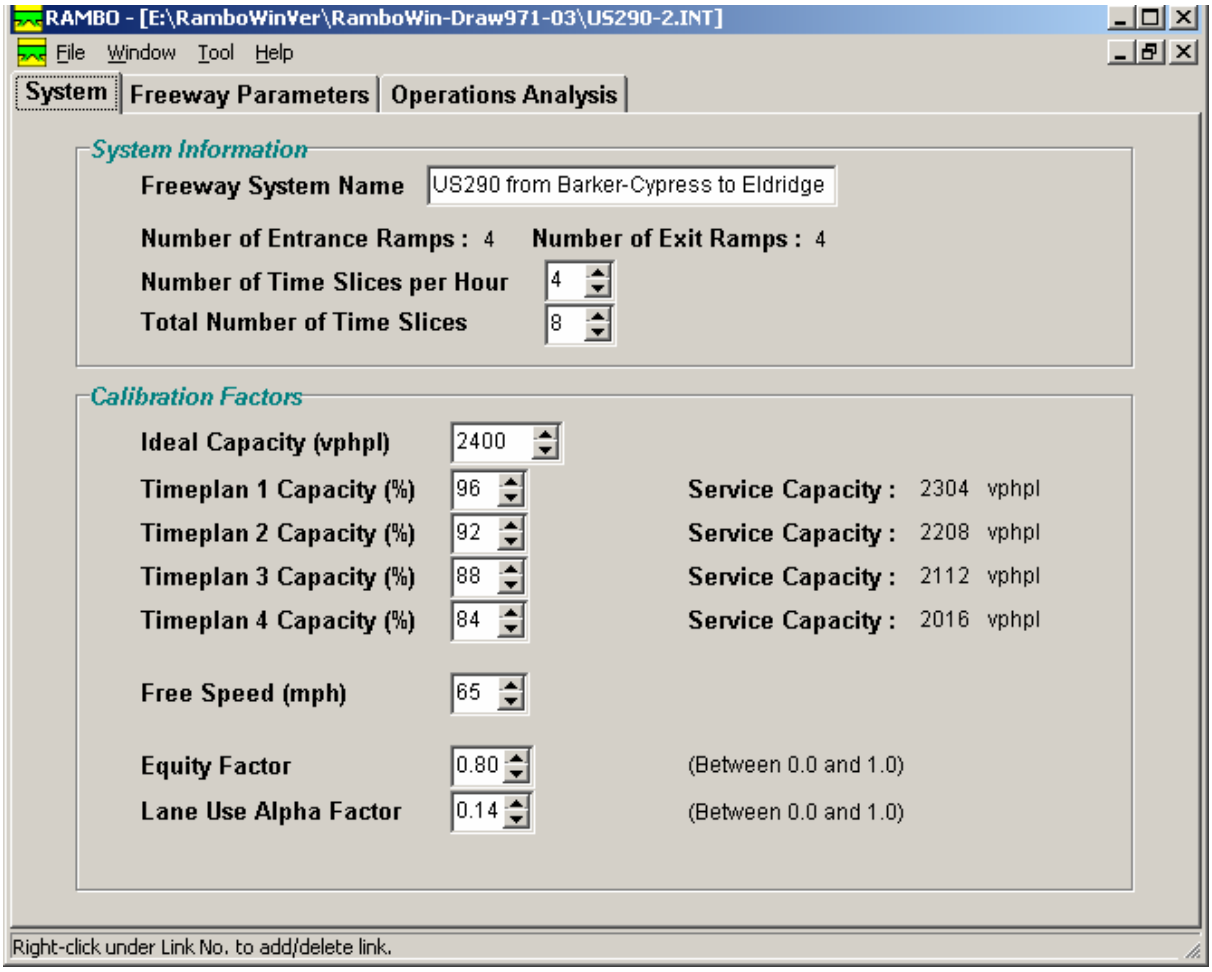


Figure 15. System Page.

Freeway Parameters Page

Freeway Parameters page allows users to define the layout of the freeway system. There are two sections on this page, namely, Freeway Links section and Freeway Ramps section. An example of the Freeway Parameters page is shown in Figure 16.

A freeway section with an entrance or an exit ramp can be added by using the “Add On-Ramp” or the “Add Off-Ramp” button. The program adds each new freeway section at the end of the currently defined freeway. Alternatively, the user can add a new section by placing the mouse

pointer in the column labeled “Link No.,” followed by a right-click. This action activates a menu which allows the user to select the type of section. In this case, the program inserts a new freeway section below the link pointed by the mouse. Similarly, the user can remove a freeway section by activating the same menu. In the latter case, the program deletes the link pointed by the mouse. The program assumes that a ramp (entrance or exit) is at the upstream end of the corresponding link.

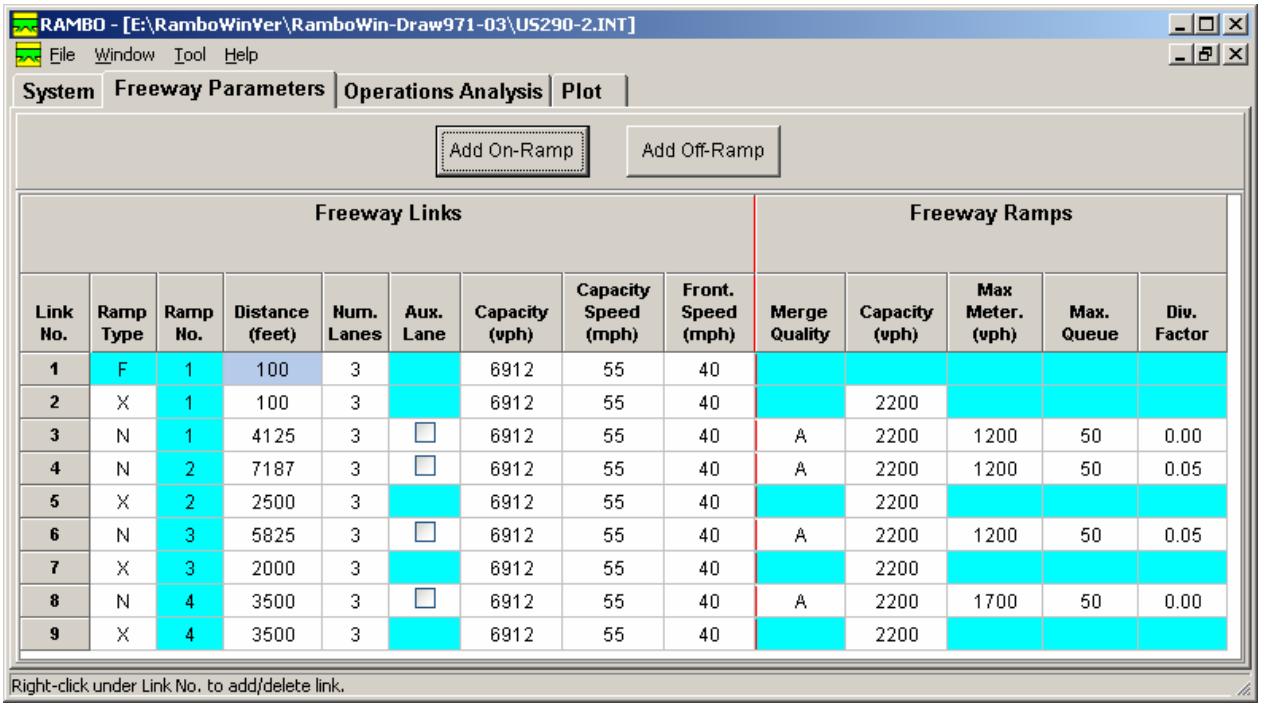


Figure 16. Freeway Parameters Page.

Freeway Links Section

Freeway Links section contains information regarding the section on the freeway. “Ramp Type” specifies the type of ramp associated with the freeway section, where “F” denotes the first freeway section, and “N” and “X” represent the freeway section with entrance and exit ramp, correspondingly. “Num Lanes” defines the total number of lanes on the freeway excluding an auxiliary lane. “Capacity” indicates the total service capacity of the freeway section. By default, the program sets service capacity of a new section equal to timeplan 1 service capacity. “Front. Speed” represents frontage road overall travel speed.

Figure 17 provides a graphical representation of the first five links from data shown in Figure 16. As illustrated, link 1 corresponds to the first freeway section, link 2 corresponds to the second freeway section beginning with an exit ramp, followed by two sections with entrance ramps, and another section with an exit ramp. Distance (d_i) of each freeway section should be measured as shown in Figure 17.

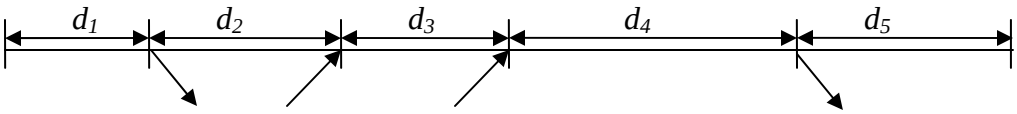


Figure 17. Distance of Freeway Links in a Freeway System.

Freeway Ramps Section

This section contains information regarding the ramps. "Max. Meter." is the maximum metering rate; "Max. Queue" is the maximum queue allowed on the entrance ramp; and "Div. Factor" is the diversion factor for entrance ramp queue. Also, "Capacity" denotes ramp merge point capacity. It is a function of ramp geometrics. "Merge Quality" is an indicator corresponding to ramp merge point capacity as follows: A-2200 vph, B-2000 vph, and C-1800 vph. Selecting "U" for Merge Quality allows the user to enter capacity values other than these three predefined values.

Note that "Max. Queue" is not used in the LP formulation. However, the user can compare it with corresponding ramp queue resulting from metering to assess the consequences. A queue exceeding the storage space may: 1) spillback into the upstream signal, or 2) result in queue flushing. In the latter case, incremental queue in each time slice should be used for comparison.

Operations Analysis Page

Figure 18 shows a screen shot of the Operations Analysis page. There are three sections under this page, namely, Traffic Input Data section, Demand Analysis section, and Optimization Results section.

RAMBO - [E:\RamboWinVer\RamboWin-Draw971-03\US290-2.INT]

File Window Tool Help

System | Freeway Parameters | Operations Analysis

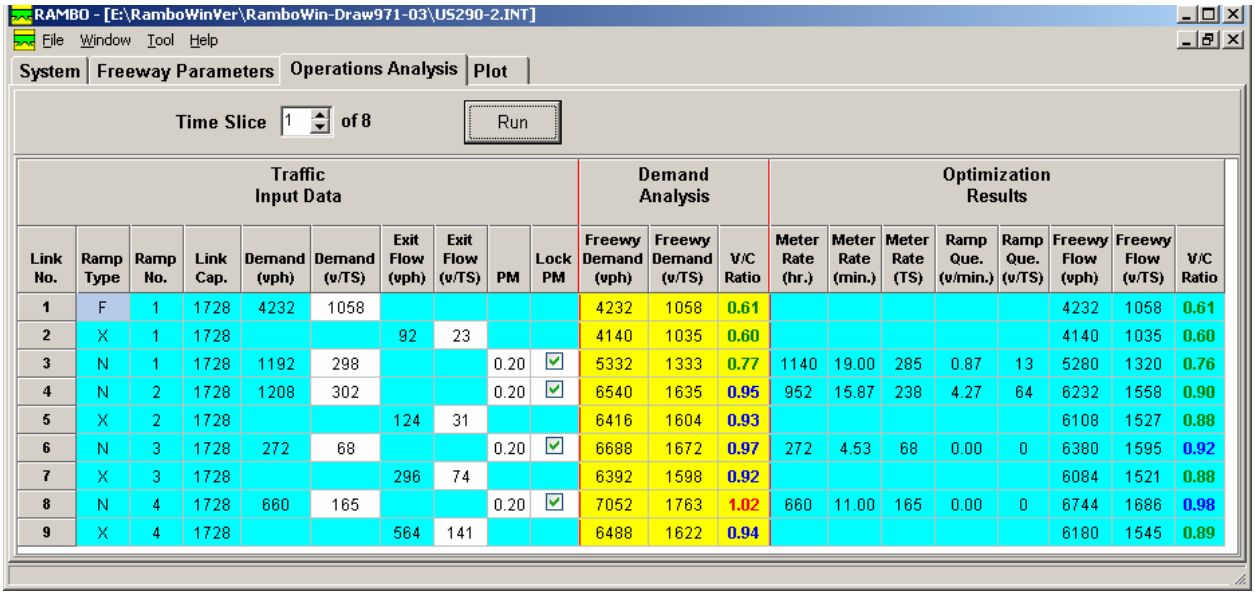
Time Slice 1 of 8 Run

	Traffic Input Data									Demand Analysis			Optimization Results							
Link No.	Ramp Type	Ramp No.	Link Cap.	Demand (vph)	Demand (v/TS)	Exit Flow (vph)	Exit Flow (v/TS)	PM	Lock PM	Freewy Demand (vph)	Freewy Demand (v/TS)	V/C Ratio	Meter Rate (hr.)	Meter Rate (min.)	Meter Rate (TS)	Ramp Que. (v/min.)	Ramp Que. (v/TS)	Freewy Flow (vph)	Freewy Flow (v/TS)	V/C Ratio
1	F	1	1728	4232	1058					4232	1058	0.61								
2	X	1	1728			92	23			4140	1035	0.60								
3	N	1	1728	1192	298			0.20	☑	5332	1333	0.77								
4	N	2	1728	1208	302			0.20	☑	6540	1635	0.95								
5	X	2	1728			124	31			6416	1604	0.93								
6	N	3	1728	272	68			0.20	☑	6688	1672	0.97								
7	X	3	1728			296	74			6392	1598	0.92								
8	N	4	1728	660	165			0.20	☑	7052	1763	1.02								
9	X	4	1728			564	141			6488	1622	0.94								

Figure 18. Operations Analysis Page (before optimization).

Traffic Input Data section contains the flow and capacity information of each freeway link. In this section, all inputs are with respect to a time slice. In other words, "Demand" and "Exit Flow" of each freeway section are input as number of vehicles per time slice. "PM" is defined as the fraction of freeway traffic in the merge lane at entrance ramp *M*. If there is an auxiliary lane on the freeway section, "PM" is set to 0.02. By default, the program calculates this value automatically for each entrance ramp in each time slice. The details of these calculations were presented earlier. If a user-specified "PM" value for a particular freeway section is entered, the same value will be used for all time slices for this freeway section.

Demand Analysis section presents the freeway demand and volume by capacity ratio for each freeway section provided that there is no metering. These calculations assume an unlimited merge capacity and are similar to HCM 2000 procedures [27]. After entering the necessary information, the user can click on the "Run" button and the program will model and solve the corresponding LP. The results of LP optimization are summarized under the Optimization Results section (Figure 19).



Traffic Input Data										Demand Analysis			Optimization Results							
Link No.	Ramp Type	Ramp No.	Link Cap.	Demand (vph)	Demand (v/TS)	Exit Flow (vph)	Exit Flow (v/TS)	PM	Lock PM	Freewy Demand (vph)	Freewy Demand (v/TS)	V/C Ratio	Meter Rate (hr.)	Meter Rate (min.)	Meter Rate (TS)	Ramp Que. (v/min.)	Ramp Que. (v/TS)	Freewy Flow (vph)	Freewy Flow (v/TS)	V/C Ratio
1	F	1	1728	4232	1058					4232	1058	0.61						4232	1058	0.61
2	X	1	1728			92	23			4140	1035	0.60						4140	1035	0.60
3	N	1	1728	1192	298			0.20	☑	5332	1333	0.77	1140	19.00	285	0.87	13	5280	1320	0.76
4	N	2	1728	1208	302			0.20	☑	6540	1635	0.95	952	15.87	238	4.27	64	6232	1558	0.90
5	X	2	1728			124	31			6416	1604	0.93						6108	1527	0.88
6	N	3	1728	272	68			0.20	☑	6688	1672	0.97	272	4.53	68	0.00	0	6380	1595	0.92
7	X	3	1728			296	74			6392	1598	0.92						6084	1521	0.88
8	N	4	1728	660	165			0.20	☑	7052	1763	1.02	660	11.00	165	0.00	0	6744	1686	0.98
9	X	4	1728			564	141			6488	1622	0.94						6180	1545	0.89

Figure 19. Operations Analysis Page (after optimization).

Plot Page

This page offers visual tools for analyzing the system and is activated only after optimization results are reported. V/C Ratio Plot (Figure 20) shows the volume by capacity ratio of freeway section, both with and without metering, for a particular time slice. Plot of Residual and Incremental Queue at Entrance Ramps (Figures 21 and 22) presents the queue information on each entrance ramp with metering. Finally, Plot of Incremental Queue at Entrance Ramps presents information on incremental queue in vehicles per minute with metering. As described below, this latter information can be used to estimate queue-flush frequency.

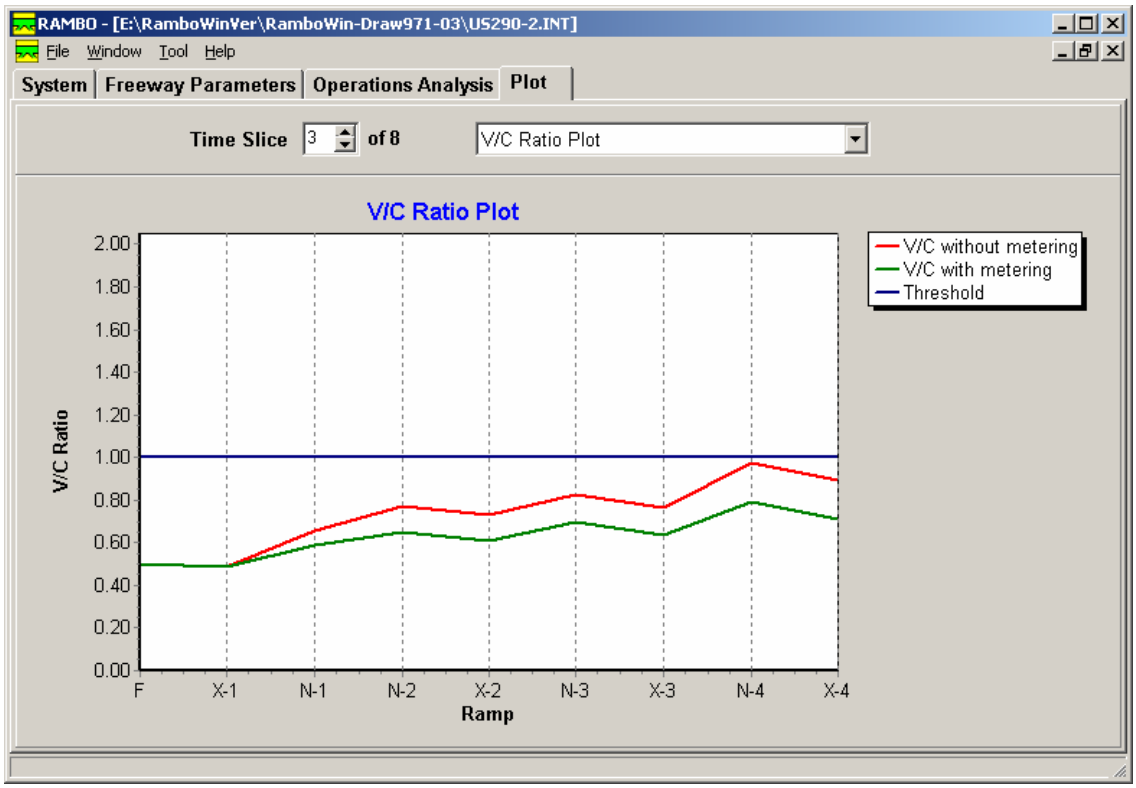


Figure 20. Volume by Capacity Plot.

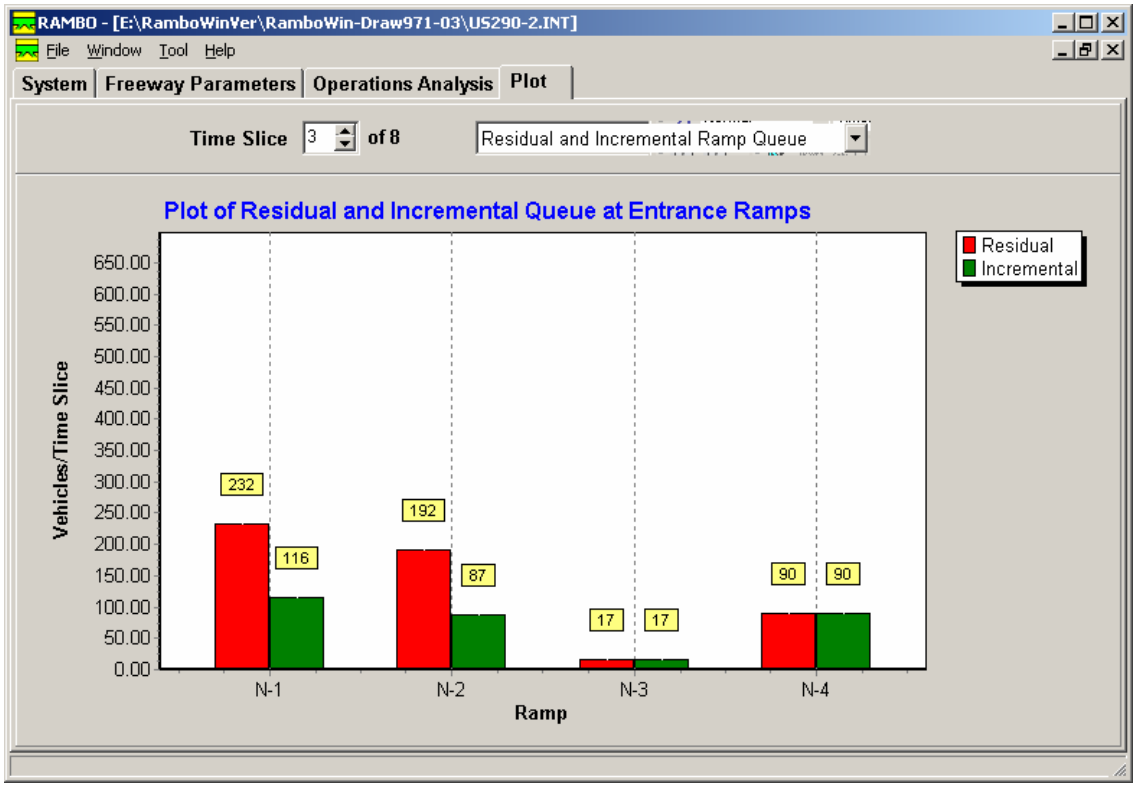


Figure 21. Plot of Residual and Incremental Queue at Entrance Ramps.

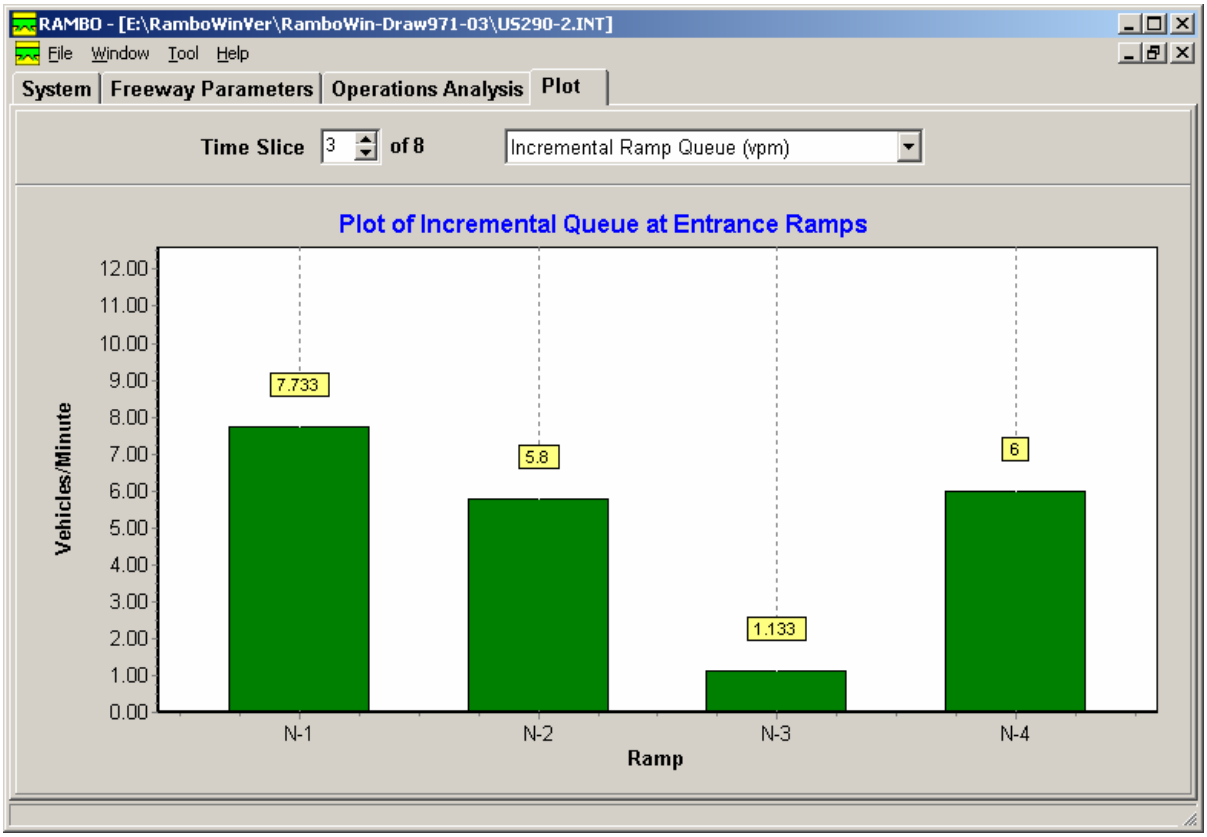


Figure 22. Plot of Incremental Queue at Entrance Ramps.

Figure 22 displays a plot of incremental queues during the third time slice for a section of Highway 290 in Houston, Texas, analyzed using RAMBO II for a 2-hour period consisting of eight 15-minute time slices. In this figure, N-4 identifies the entrance ramp located at FM 1960. This ramp has a dual-lane meter with queue flushing. The plot shows that the queue at this ramp will grow at a rate of 6 vehicles per minute if the optimized metering rate from RAMBO II is used. Because this is a dual-lane meter, the queue will grow at a rate of 3 vehicles per minute per lane. Assuming that the ramp provides storage space for 15 vehicles per lane and no queue at the beginning of this time slice, the estimated time to fill the storage-space (distance from the excessive queue detector to the stop-bar) will be 5 minutes. At that point the meter will flush existing queue and possibly new arrivals during flushing. It should be noted that the user-selected settings for the queue detector control the maximum size of the queue, whether the back of the queue is stopped or moving at the time of queue-flush, and whether the queue completely clears at the end of the flush-cycle. Furthermore, the traffic discharge patterns from the upstream signal also affect the actual value of incremental queue during any given minute. The user can get a better feel of that effect by converting this queue estimate from vehicles per minute to vehicles per signal cycle at the upstream signal (UC). For instance, if UC is 120 seconds, the queue in each lane will grow at a rate of 6 vehicles per UC, and flushing will occur during every third signal cycle after metering resumes. This average behavior also may vary depending on the density of platoons discharged and number of platoons released from the upstream signal during each UC.

CHAPTER 5:
COMPARISON OF RAMP METERING ALGORITHMS

As stated in Chapter 2, ALINEA is the only algorithm that can provide near-term potential benefits for the current Texas ramp metering operation. However, implementation of ALINEA can only be achieved if either the manufacturer of the RMC controller enhances it to include this algorithm, or TxDOT switches to using advanced traffic controllers and special software is developed (either in-house or under a sub-contract) to achieve this purpose. However, before such recommendations can be developed, there is a need to determine if ALINEA provides any significant benefits over the operation provided by the RMC 300 controller used in Texas. This chapter provides a detailed discussion of research conducted in this project to determine if ALINEA should be considered for the type of non-restrictive ramp metering operation, with excessive queue detector, used in Texas. The research approach was to use computer simulation. Because of the advantages provided by it, the research team selected VISSIM.

DEVELOPMENT OF SIMULATION TESTBED

Researchers developed a number of steps that are needed when using computer simulation for comparing the performance of ALINEA with the current RMC 300 operation used in Texas. The research team took the following steps, not necessarily in this chronological order:

1. Develop a Vehicle Actuated Program (VAP) code to implement the two controller logics to be evaluated. VAP is a VISSIM-supported programming logic similar to the Basic programming language. Because the developers of VISSIM do not supply any built-in signal-control logic other than the standard eight-phase traffic signal controller used at arterial intersections, such development is a basic requirement if VISSIM is to be used to evaluate any other control logic.
2. Verify that the VAP code is working as intended. Verification of basic RMC 300 operation was conducted by comparing its performance with the operation of HITL using an actual controller.
3. Develop various simulation scenarios. These simulation scenarios included a range of traffic and control conditions.
4. Create actual simulation cases and perform simulations.
5. Compare results of simulation runs.

The following subsections provide details of some of the key steps.

Development and Calibration of VAP Logic

Researchers first developed the VAP logic for providing several types of control with and without queue flushing. The types of control included: ALINEA with user-specified parameters, fixed metering using the specified maximum metering rate, no metering, and ramp closed. Appendix A provides a listing of this code. In the appendix, key parameters and begin points of various subroutines have been highlighted. All a user needs to do is to specify or change any values and re-compile the code before starting a simulation. VISSIM provides features for editing and compiling the code. For instance, a value of 1, 2, 3, or 4 can be specified for

"Algorithm" to simulate ALINEA, fixed metering, no metering, and ramp closure, respectively. In this research, we only used the first three scenarios. Similarly, the user can select if queue flushing is allowed or not by setting the value of "QueOverRide" to 1 or 2, respectively. We selected queue flushing for all metering cases.

Researchers first conducted numerous simulation studies to verify the performance of various options. This step involved visual verification of the animation provided in VISSIM. For most options, the next level of verification could not be conducted because there was no base available for verification. However, for the fixed metering logic this next step of verification was possible. In this step, researchers compared the operation of VAP logic for fixed metering with that of the real controller connected to VISSIM through HITL. This step is described below.

The major performance measures for the calibration included the number of queue flushes and the total duration of flush time from VISSIM simulations of VAP-based logic and RMC 300 ramp metering controller for the same traffic conditions. The parameters to be calibrated in VAP include the queue sampling interval and the transition time. The transition time in VAP is equivalent to the start-up transition in the RMC 300 controller.

The traffic data used in the calibration were based on a ramp metering location in Arlington, Texas. A fixed ramp metering headway of 4 seconds was used in the simulation runs. The 4-second headway is the highest metering rate (900 vph) that could be achieved for a single-lane one-car-per-green ramp meter, which is consistent with the metering rate currently used in Houston. To account for the random effects of simulation, five simulation runs were conducted using different random seed numbers, and the results from each simulation run were reported.

Figure 23 shows paired comparisons of the number of flushes from each simulation run with the VAP control and the RMC 300 controller. As can be seen, with RMC 300, an average of 11.4 flushes resulted compared to 11.8 flushes with VAP. The t-test showed a P-value of 0.82, which suggests that there is no statistically significant difference between the two results.

Similarly, Figure 24 shows paired comparisons of the total flush time from each simulation run with the VAP control and RMC 300 controller. As can be seen, with RMC 300, an average of 363 seconds resulted compared to 384 seconds with VAP. The t-test showed a P-value of 0.74, which again suggests that there is no statistically significant difference between the two results.

There are some discrepancies in the above results between the VAP-based fixed metering logic and the RMC 300 controller. These discrepancies may be because of time differences between the arrival of a vehicle at a detector and the registering of this call by the metering and the queue flush routines in VAP and RMC 300. In this regard, the reader should note that the RMC 300 controller uses a one-tenth-second resolution, while VISSIM (including the VAP logic) uses a one-second resolution.

In the VAP code, ALINEA uses the same queue override and transition routines as the RMC 300 emulation for fixed metering strategy. Thus the calibration results for VAP-based fixed metering given above also indirectly apply to ALINEA.

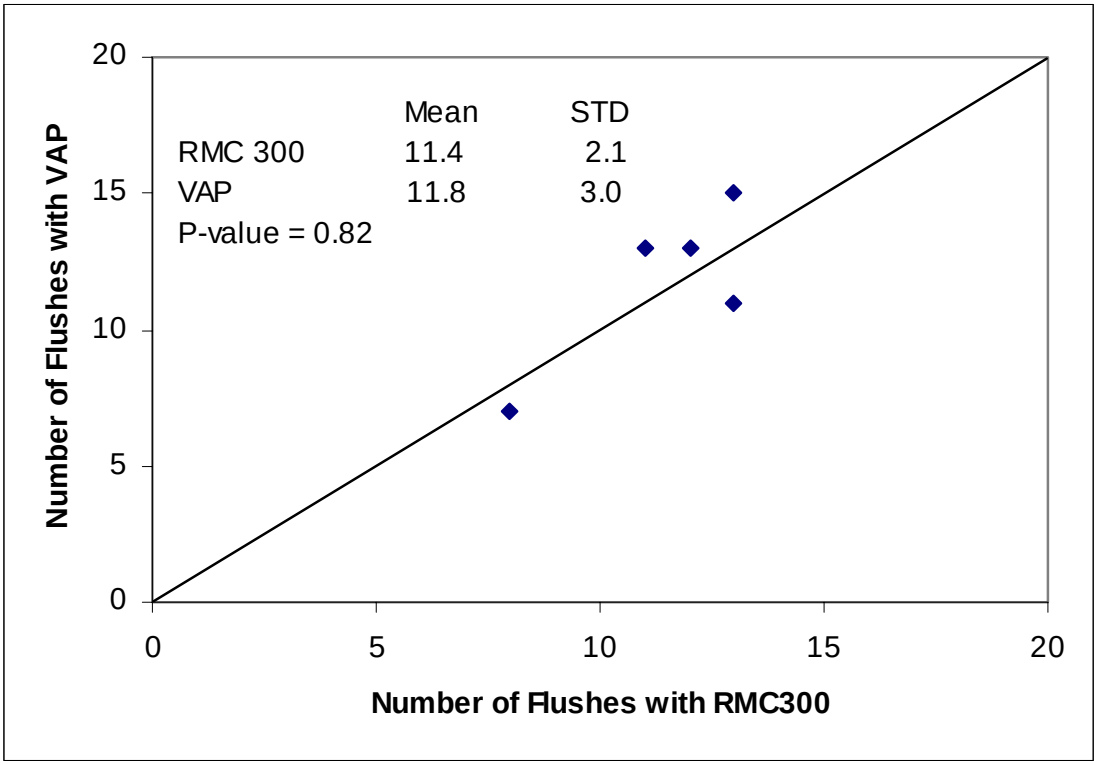


Figure 23. Results for Number of Flushes.

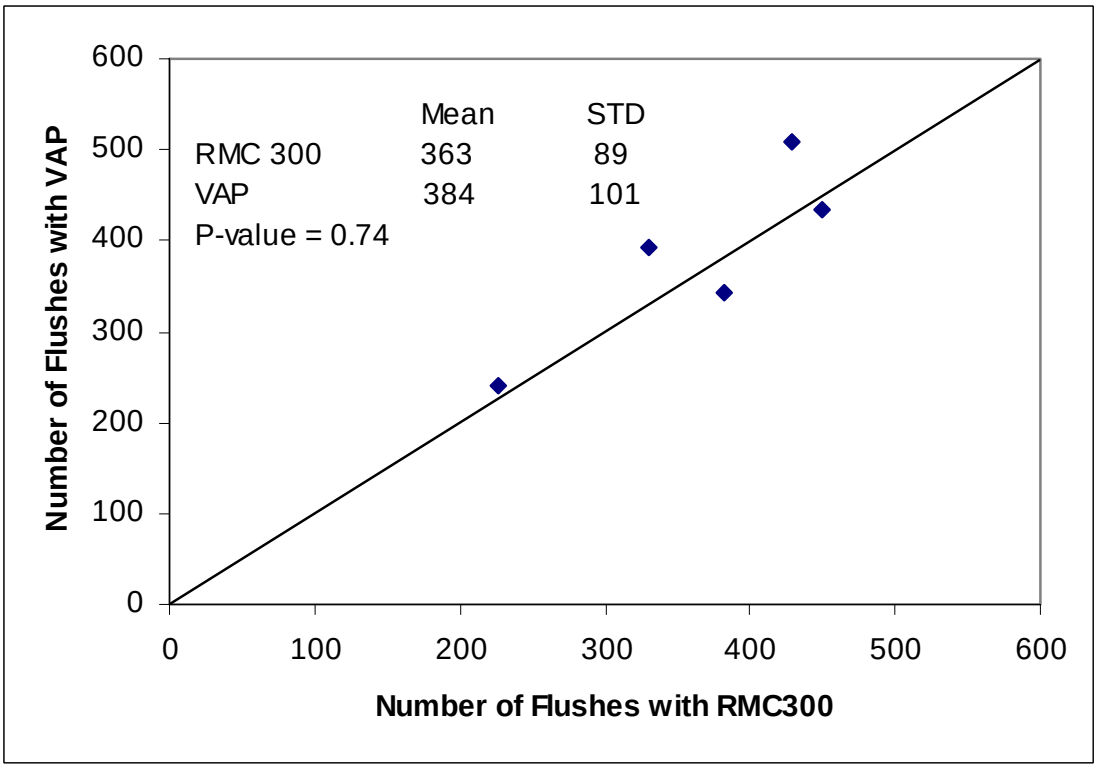


Figure 24. Results for Total Flush Times.

Development of Simulation Cases

For simulation purposes, researchers selected a freeway section from SH 360 in Arlington, Texas. At this location, the freeway has three lanes in each direction. The first step at this stage was to create a geometric representation and to link VAP code to this simulation. Figure 25 shows a screen capture from VISSIM showing the coded geometry. This system consists of the freeway section with one diamond interchange, two on-ramps, freeway lanes in both directions, and frontage roads. Researchers used previously developed VAP code to simulate four-phase control at the diamond interchange. This allowed the simulation to account for typical platoons arriving at the freeway ramps. Furthermore, researchers simulated control strategies at only the northbound on-ramp. As shown, this simulation file has more detectors than the detectors actually used in this research. Furthermore, a copy of the VAP code can be used to provide control at the southbound ramp as well. After the basic simulation file had been created, trial runs were made to identify any coding or other problems. These runs identified that under some heavy demand scenarios, shockwaves propagated far upstream of the ramp causing less than the specified number of vehicles to enter the freeway. This would cause discrepancies during comparisons. To eliminate this problem, researchers made the northbound freeway link leading to the ramp of interest several miles long.

Furthermore, researchers used features provided in VISSIM to collect several types of data. These data included:

- travel time and delay for the entire section of northbound freeway (approximately 4 miles);
- travel time, delay and average 10-minute queue length for ramp traffic. The travel time was collected for 1600 ft section ending just downstream of the meter.
- freeway throughput downstream of ramp merge;
- throughput at the meter (these data were collected only to verify the demand levels desired); and
- signal status (metering or flushing) from the ramp meter VAP. A program was also developed to process these data to produce meter availability.

In the next step, researchers developed several demand scenarios to account for medium to heavy traffic flow conditions common in Texas. VISSIM requires the input of entering volumes and origin-destination information. Researchers used synthetic data to create nine volume-to-capacity (V/C) ratios and corresponding demand (vph) scenarios shown in Table 4. For the purpose of this analysis, researchers assumed capacities of 900 and 2400 vph for the single-lane meter and each freeway lane, respectively. A metering capacity of 900 vph results if the meter cycle is 4 seconds long. The per-lane capacity of freeway used here is in line with that identified by the shaded box in Figure 1. This capacity value is in the range desired for preventing freeway breakdown.

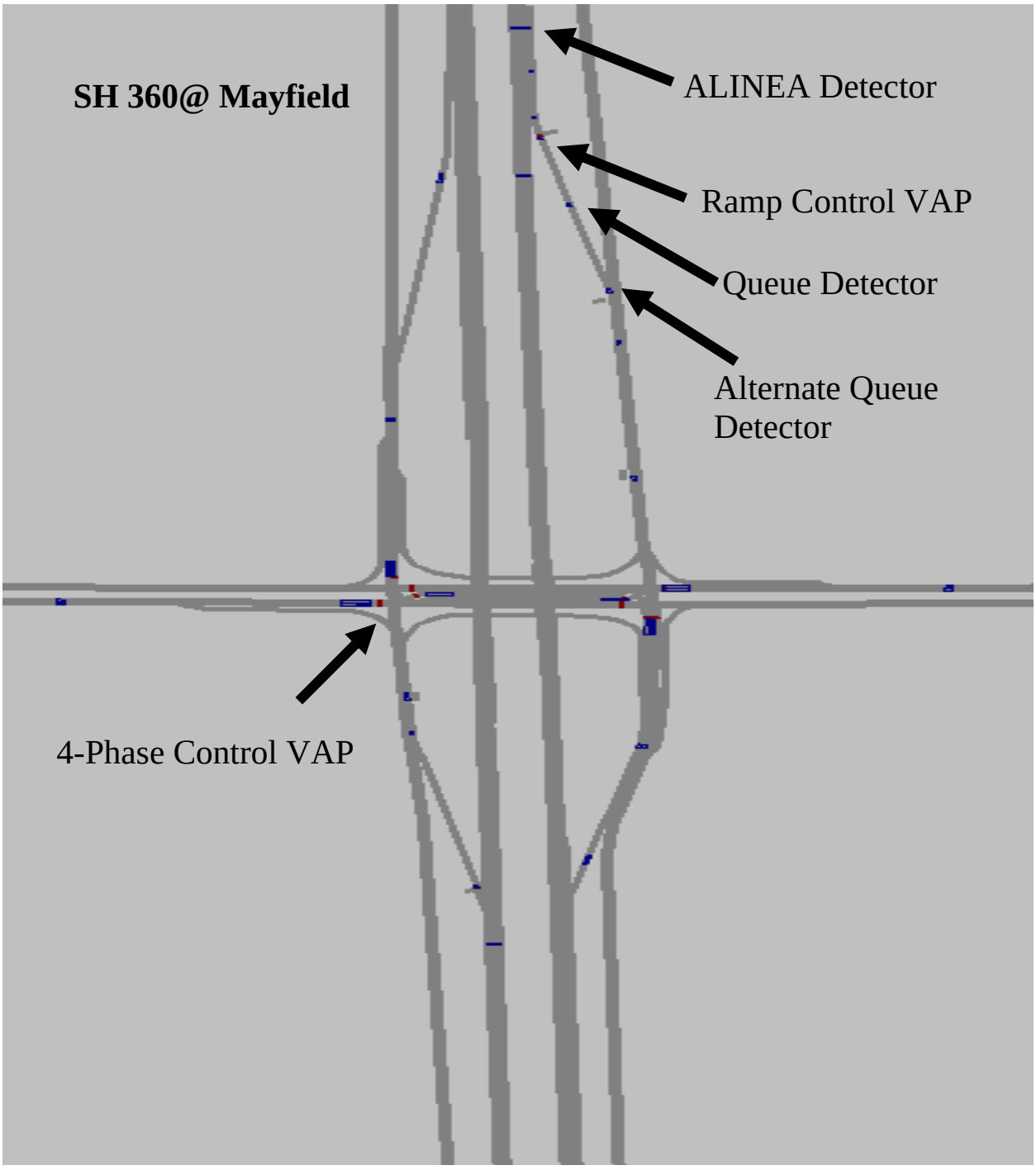


Figure 25. Geometry of Simulation Testbed.

Table 4. Nine Demand Scenarios for Simulation Runs.

Scenario Description		Desired Freeway V/C Ratio (Demand) Upstream of the On-Ramp	Desired V/C Ration (Demand) On the Ramp	Resulting Freeway V/C Ratio (Demand) Downstream of On-Ramp
Freeway Demand	**Ramp Demand**			
High	**High**	0.83 (5,976)	1.00 (900)	0.955 (6,876)
High Medium	**High**	0.75 (5,400)	1.00 (900)	0.875 (6,300)
Medium	**High**	0.69 (4,968)	1.00 (900)	0.815 (5,868)
High	**High Medium**	0.83 (5,976)	0.90 (810)	0.943 (6,786)
High Medium	**High Medium**	0.75 (5,400)	0.90 (810)	0.863 (6,210)
Medium	**High Medium**	0.69 (4,968)	0.90 (810)	0.803 (5,778)
High	**Medium**	0.83 (5,976)	0.80 (720)	0.930 (6,696)
High Medium	**Medium**	0.75 (5,400)	0.80 (720)	0.850 (6,120)
Medium	**Medium**	0.69 (4,968)	0.80 (720)	0.790 (5,688)

As shown in Table 4, high (H), high medium (HM), and medium (M) demands for freeway correspond to V/C ratios of 0.83, 0.75, and 0.69, respectively. The H, HM, and M demands for the on-ramp correspond to V/C ratios of 1.00, 0.90, and 0.80, respectively. As shown in the table, there are nine possible combinations of these demand levels. These are H-H, HM-H, M-H, H-HM, HM-HM, M-HM, H-M, HM-M, and M-M. The last column in the table results when all ramp vehicles are able to enter the freeway. This situation is always true for ramp meters with queue flush. For each of the demand scenarios described in Table 4, researchers performed five replications of simulation runs for the following control conditions:

- no metering,
- fixed metering of 900 vph, and
- ALINEA (three scenarios with desired occupancies of 18 percent, 20 percent, and 22 percent). In the following discussion, these three cases are referred to as ALINEA-18, ALINEA-20, and ALINEA-22.

Thus, there are four control scenarios with metering and one without metering. In addition, researchers used two design cases for each of the four metering scenarios. The two design features used by researchers included 400 ft and 600 ft storage spaces for ramp queue.

Simulation Runs and Summary Generation

All the cases identified in the previous section resulted in a total of 405 simulation runs. To increase productivity, researchers first created simulation files for all 405 different cases. Then they used a batch process to execute groups of simulation runs. Once the simulation runs were complete, they processed output files from VISSIM to summarize the results. Appendix B provides graphs of these results. The next section provides a summary of key findings.

SIMULATION RESULTS

Ramp Performance

Section B1 in Appendix B provides the results for meter availability. The following is a summary of findings:

- Fixed metering resulted in the highest metering availability for all cases. According to the "Metering Quality" defined in Figure 3, the quality of this strategy is classified as "Good."
- For two high volume (H-H and H-M) scenarios, ALINEA provided "Fair" metering. The performance of ALINEA-22 is slightly better than ALINEA with lower occupancy thresholds.
- For high medium (HM) and medium (M) combination scenarios, all strategies provided metering availability of 90 percent or higher.
- In all but one case, 600 ft storage space resulted in higher metering quality than the 400 ft storage. The only exception was ALINEA-18 for the H-M case. In this case, the quality for 400 ft spacing was slightly higher than the 600 ft spacing. This difference of 1.39 percent may be due to randomness in simulation.

Section B2 in Appendix B provides average travel time for ramp vehicles. The following is a summary of findings:

- The travel time without metering was approximately 30 seconds in all cases.
- As expected, the travel time with metering was higher than no metering for all cases.
- The travel time for fixed metering was the lowest among metering strategies. It ranged from 50-60 seconds for the six high-medium and high demand scenarios for the ramp traffic. For the three medium-demand ramp traffic scenarios, travel time ranged between 40-50 seconds. Thus, in the worst case, fixed metering caused about 30 seconds of average delay per vehicle as compared to no metering.
- For the high-freeway-demand cases, ALINEA-18 was worse than ALINEA-20 and ALINEA 22, especially for the 600 ft case. For other scenarios, there was no significant difference.
- For all strategies, the travel time for 600 ft storage space was more than the 400 ft storage space. Furthermore, the travel times became more and more similar as the total downstream demand reduced.

Section B3 in Appendix B presents the results of delay analysis for ramp traffic. These results are similar to travel-time results. The reason is that delay is equal to actual travel time minus the ideal travel time. The following is a summary of results:

- In all cases, the average delay for fixed metering is less than 35 seconds.
- For 600 ft storage space, the average delay for all strategies is less than 60 seconds.
- For 400 ft storage space, the average delay is less than 41 seconds.

Section B4 in Appendix B presents the analysis of average 10-minute queues for ramp traffic. The results for queue length are similar to travel time and delay. The following is a summary of these results:

- Among all cases, fixed metering produced the shortest average queue length. In the worst scenario, the average queue length was less than 210 ft.
- Among ALINEA strategies, ALINEA-22 produced the shortest queues, except one case (H-M) where the 600 ft case of ALINEA-22 had a slightly larger queue (about two vehicles) than the ALINEA-20 strategy.

Freeway Performance

Section B5 in Appendix B shows the freeway throughput results for the two highest demand scenarios for which differences were observed among strategies. In these cases, the throughput for fixed metering is slightly better than other strategies, however, these differences are not significant. The maximum difference among these cases was approximately 40 vehicles per hour.

Section B6 in Appendix B provides the results of average travel time analysis on freeway. The following is a summary of results:

- Except three high-demand scenarios (H-H, H-HM, and H-M) for the freeway, travel times for all metering strategies are basically the same as no metering.
- For the H-H case, metering has some effectiveness depending on the strategy and the storage space. Fixed metering with 600 ft storage provides the best results with a 37-second reduction in average travel time as compared to no metering. For the 600 ft storage, ALINEA-22 is second-best with average travel-time savings of 28 seconds. For the 400 ft case, ALINEA-18 proves to be the best with 18-second reduction in average travel time. For reference, the total travel time with no metering was 322 seconds. Thus, fixed metering produces an improvement of 11.5 percent.
- For the H-HM case, only fixed metering with 600 ft storage is better than no metering. It produced a 5-second savings in average travel time compared to no metering. In this case, travel time with no metering was 266 seconds. Thus, the 5-second savings translates to less than a 2 percent improvement. The travel times for all other strategies are higher than no metering. ALINEA-20 with 400 ft storage space is the worst with an increase of 30 seconds in average travel time.
- For the H-M case, all metering strategies produce longer average travel times on the freeway. The worst case is ALINEA-18 with 600 ft storage. In this case, there is an 18-second (7 percent) increase in the average freeway travel time.

Summary and Further Explanation

Simulation results presented in the previous section show that ramp metering with queue flush operation provides benefits only when freeway demand is high. In addition, the only strategy that works well is the fastest metering with a queue storage space of 600 ft. The reader should recall earlier comments that the type of metering used in Texas has the potential to achieve only one of three objectives of ramp metering; namely, breaking up the platoon of traffic from the upstream

signal to improve the merge operation. Figure 26 illustrates the effects of an unbroken platoon of ramp traffic (black vehicles) on freeway traffic in the merge area. In this figure, arrows represent the direction of ramp and freeway traffic flow. Figure 27 illustrates a situation if another un-metered platoon arrives before the effects of previous platoon-merge have dissipated. In this case, the situation becomes even worse. Ramp metering can prevent, or in the worst case, delay, the onset of such conditions.

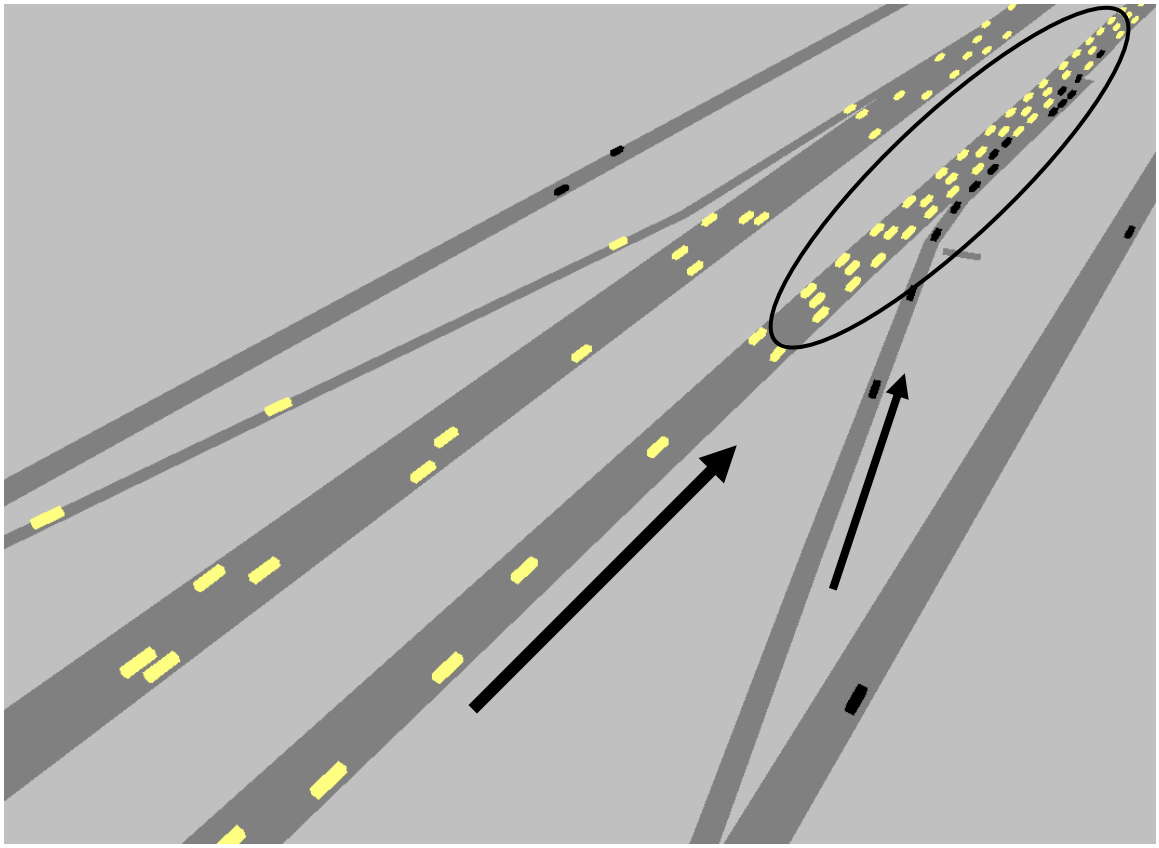


Figure 26. Effects of Platoon with No Metering.

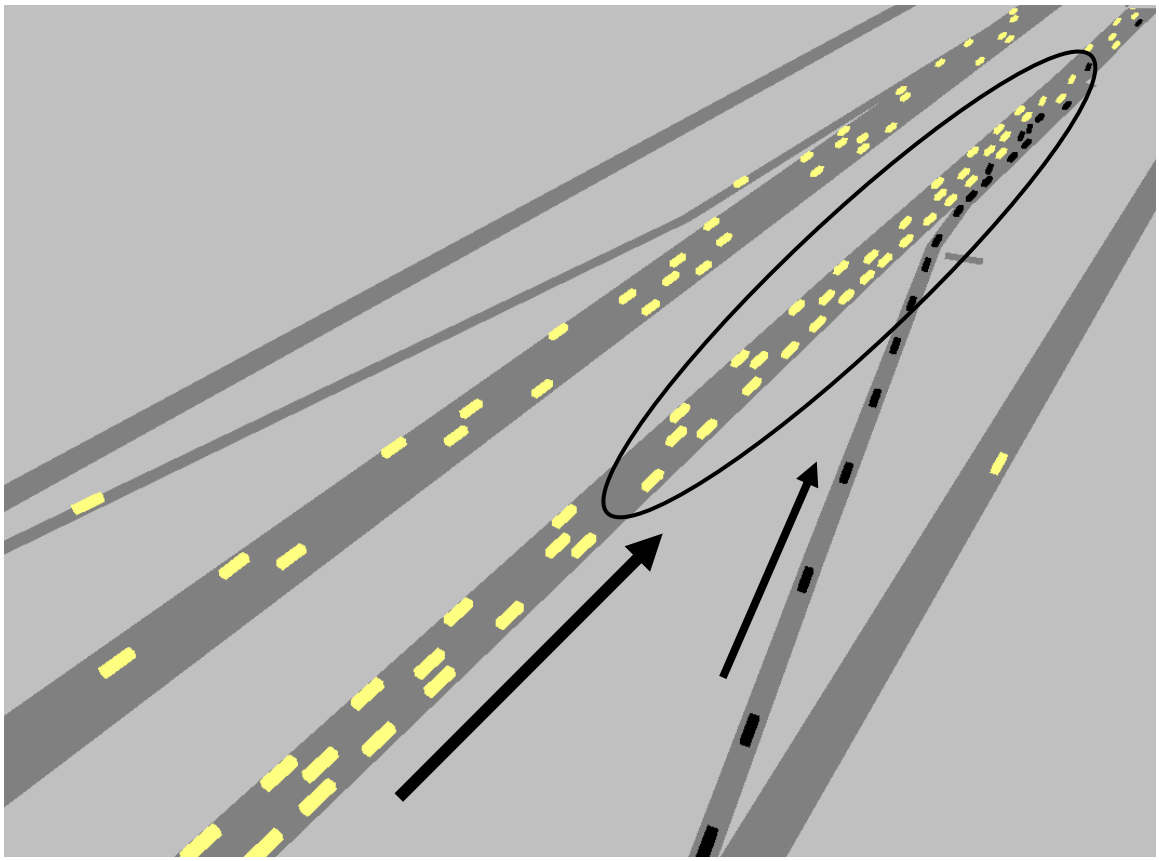


Figure 27. Effects of the Arrival of Back-to-Back Un-Metered Platoon.

Figure 28 shows the same demand scenario with metering at the on-ramp. As illustrated in this figure, ramp metering significantly improves the merge operation. However, a queue flush can quickly degrade traffic conditions on the freeway. Figures 29 and 30 illustrate potential queue flush scenarios and their effects. Figure 29 shows the state where metering operation has just resumed after a queue flush. As can be seen from this figure, another queue is already building at the on-ramp while the freeway has not yet recovered from the adverse effects of the previous queue flush. In this simulation scenario, the ramp queue quickly fills the storage space and another queue-flush occurs. Figure 30 shows the state of freeway traffic conditions just after the end of the second queue-flush. As can be seen from this figure, the freeway condition has reached a point where a quick recovery is not possible. The primary cause of this situation is insufficient storage space.

The storage space is considered insufficient when it cannot reliably contain cyclic or short-term ramp demand, which can be higher than the meter capacity. For ramp metering with queue flush to be effective, the meter availability needs to be very high. Simulation studies conducted in this project have shown that in many situations with frequent flushing, ramp metering can actually harm freeway traffic operation as compared to no metering. This happens when the flushed queues (platoons of vehicles) have higher densities than platoons released from an upstream signal, which may disperse slightly by the time the vehicles reach the merge point.

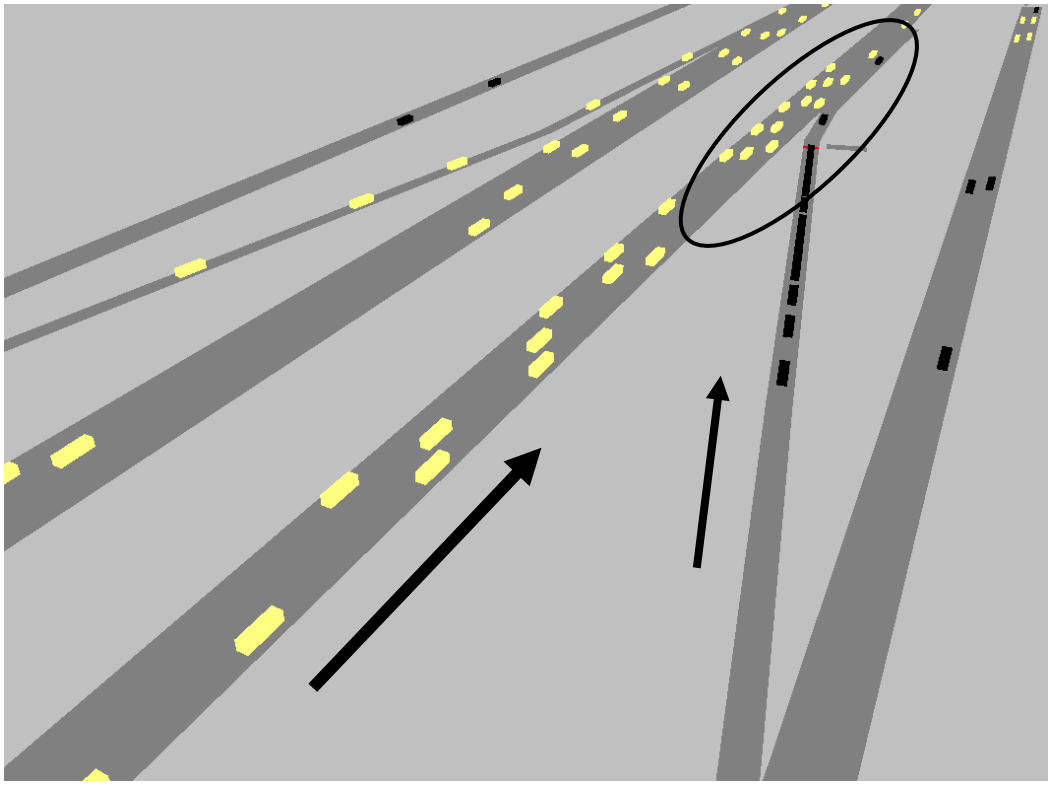


Figure 28. Operation with Ramp Metering.

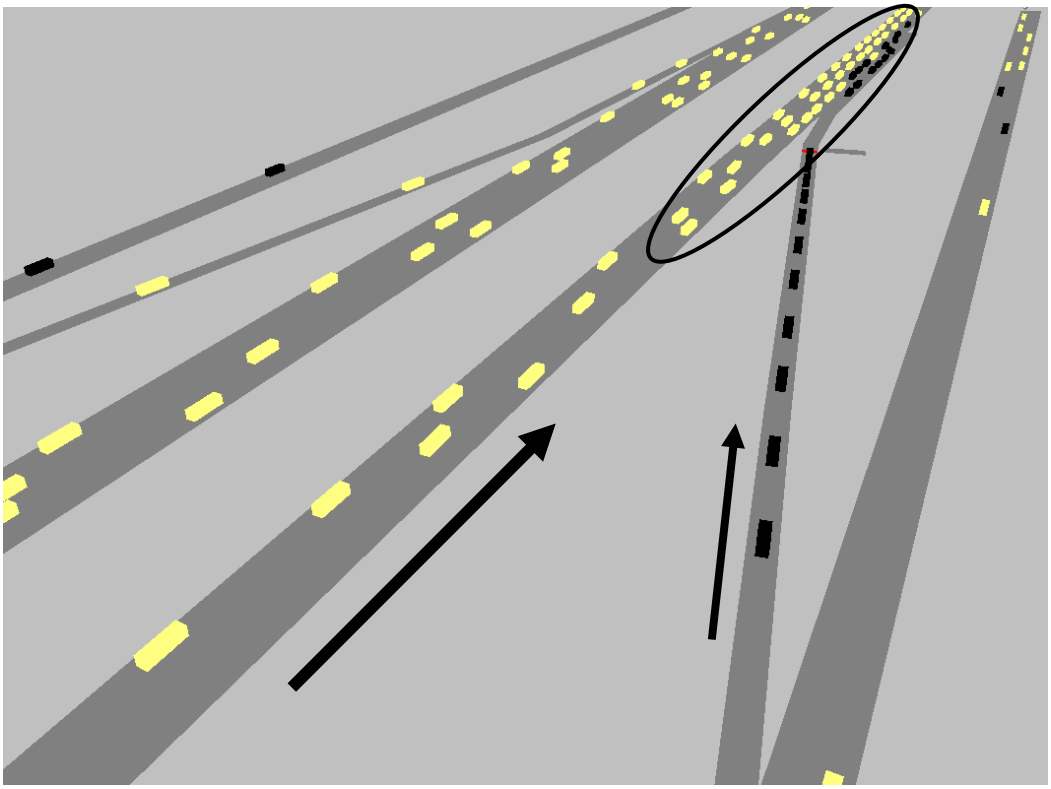


Figure 29. Queue Buildup Immediately Following a Flush.

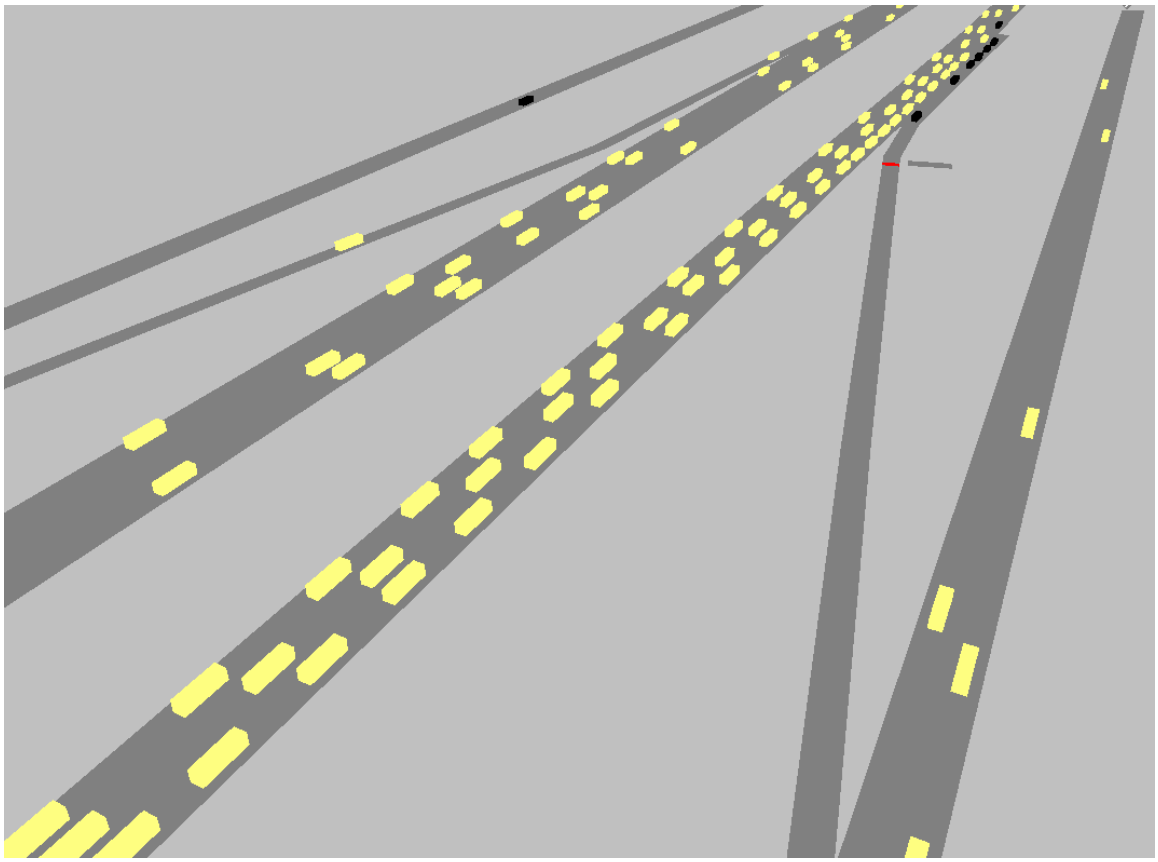


Figure 30. End of the Second Queue Flush.

CHAPTER 6:
RAMP METERING GUIDELINES FOR TEXAS

Many freeways in large metropolitan areas of Texas are now facing heavy freeway and ramp demands, and TxDOT has many questions regarding ramp metering operation at such sites. Simulation studies of such facilities have demonstrated that the current ramp metering approach in Texas provides marginal benefits under certain scenarios. The following conclusions can be drawn from the simulation studies conducted by researchers to investigate the benefits of ramp metering with queue flush:

- Queue flushing causes significant adverse effects on freeway operations.
- Metering with frequent queue flushing may cause more harm than good. This is especially true if a queue-flush occurs before the effects of a previous queue-flush have been dissipated.
- Except high-demand cases for freeway traffic, ramp metering with queue flush does not produce any significant improvement in local freeway traffic conditions. Thus, causing extra delay to ramp traffic cannot be justified unless metering can produce improvements to freeway flow at downstream sections.
- Traffic responsive ramp metering operation (i.e., ALINEA) based on freeway conditions does not provide any benefits when queue flush is permitted. The reason is that such operation often results in meter capacity to be lower than ramp demand, resulting in frequent flushing.
- Metering at the fastest rate provides local benefits only when queue flush is eliminated or significantly minimized. Research shows that the metering availability needs to be high (90 percent or higher) for producing this result. These objectives can be met only when the meter capacity is at least as high as average ramp demand and sufficient storage space is available to accommodate cyclic demand at the ramp.

RAMP METER INSTALLATION AND OPERATIONS GUIDELINE

Immediate-Use Guidelines

Ramp metering with queue-flush operation should not be used at high-demand isolated ramps if any of the following conditions is true:

1. if the meter capacity is less than ramp demand for any significant time during the desired control period;
2. upstream freeway demand is less than 80 percent of the downstream freeway capacity. Furthermore, metering operation responsive to freeway traffic conditions (i.e., traditional traffic responsive operation) should not be used under these conditions;
3. if the total freeway-plus-ramp demand is more than 95 percent of freeway capacity downstream of the merge point;
4. if ramp demand is more than the merge capacity; or
5. if sufficient storage cannot be provided to accommodate higher cyclic demand.

Additional guidelines are provided in the following subsections.

Metering Strategies

In cases where the first condition cannot be satisfied with the use of single-lane one-car-per-green strategy, dual-lane metering is recommended. However, when space restrictions make it infeasible to provide two lanes, platoon or bulk metering to provide two or three cars per green can be used with caution. For this purpose, researchers recommend use of green, yellow, and red times provided in Table 5.

Table 5. Suggested Controller Timings.

Interval Times (sec)			
Interval	**Vehicles Per Cycle**		
	1	**2**	**3**
Red	2.00	2.00	2.32
Yellow	1.00	1.70	2.00
Green	1.00	3.37	5.47
Cycle Length	4.00	7.08	9.78
Meter Capacity	900	1017	1104

Acceleration Distance

Ability of metered vehicles to smoothly merge with freeway traffic requires the presence of sufficient acceleration distance. AASHTO guidelines should be used to determine this distance [13]. Figure 31 shows an example of acceleration length for passenger cars as they accelerate from a stop at a meter to design speed for three ramp grades [5, 6].

Placement of Excessive Queue Detector

It is recommended that the queue detector be installed at least 250 feet downstream of the intersection to provide safe stopping distance behind a standing queue at the meter. Furthermore, the following generalized model can be used to calculate the storage requirement. Here, storage is defined as the distance from excessive queue detector to the stop bar at the meter.

$$L = 0.820V - 0.0002435V^2 \qquad V \le 1600\,vph \qquad (16)$$

where L is the total distance needed from the queue detector to the meter (feet), and V is the expected peak-hour ramp volume (vph). Table 6 provides recommended storage space in feet for various ramp demands. As an example, ramp demand of 900 vph results in a storage distance of 541 feet. The reader should note the fact that these storage distances assume single-lane operation. For dual-lane operation, a transition zone (of at least 75 feet) from one lane to two lanes should be provided. Thus, the location of queue detector for (L_D) should be determined by the following equation which accounts for transition distance (T) from single lane to two lanes at ramp entrance and length of two side-by-side lanes in the vicinity of the meter:

$$L_D = (T) + (L - T)/2 \qquad (17)$$

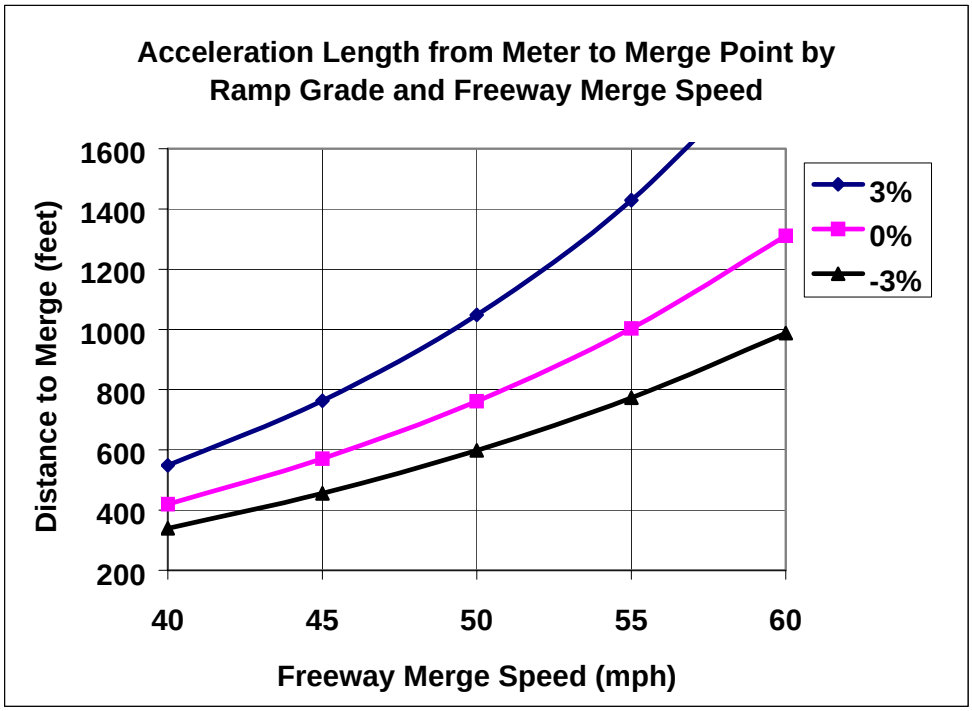


Figure 31. Determination of Acceleration Distance for Metered Vehicles.

Table 6. Storage Space Requirement for Various Ramp Demands.

Ramp Demand (vph)	Storage Distance (ft)
500	350
600	405
700	455
800	500
900	541
1000	576
1100	608
1200	635
1300	654
1400	671
1500	682

Delay to Ramp Vehicles

One objective of ramp metering is to impose delay to ramp vehicles in an attempt to discourage short freeway trips. The following equation can be used to calculate queue detector location to achieve maximum desired delay (or service) times:

$$L = \frac{M \times S_D \times L_V}{60} \qquad (18)$$

where:

S_D	=	desired service time (delay) at the meter per lane, minutes;
M	=	ramp metering rate, vphpl;
L_V	=	effective length of a vehicle in queue; and
L	=	length of storage space, feet.

For an effective vehicle length of 25 feet, a metering rate of 900 vph, and a desired service time of 2 minutes, the storage space is calculated to be 750 feet.

Longer Term Perspective

It should be emphasized that the use of ramp meters with queue flushing does not offer significant local benefits over no metering. However, metering a system consisting of several consecutive on-ramps can improve downstream freeway conditions and keep motorists happy. As traffic conditions worsen, and as Houston and other TxDOT districts move forward with the use of ramp meters as a systemwide traffic management strategy, we strongly recommend the use of more restrictive metering that is responsive to ramp demand. The ideal approach is to use systems-level metering with real-time determination of ramp metering rates to keep freeway operations at the desirable levels. However, real-time systemwide operation requires installation of detection and communication infrastructure which is non-existent in Texas. In this regard, the following intermediate steps can be taken:

- Where possible, eliminate the use of queue flushing with more restrictive metering. In the existing controller, the excessive queue detector can be programmed to implement a specified maximum metering rate without flushing the queue.
- Use queue detectors to provide traffic-responsive metering based on ramp demand. In this strategy, which is a standard feature of the existing ramp controllers in Texas, the controller can be programmed to vary ramp metering rates based on ramp demand.
- In the near term, use RAMBO II for off-line calculation of system-based ramp metering rates. RAMBO II develops these rates using capacity and merge constraints for the entire freeway segment specified by the user.

REFERENCES

1. Lancaster, S., B. Fette, L. Busler, K. Miller, C. Messer, and S. Wohlschlaeger. *Evaluation and Enhancement of Texas Ramp Metering Strategies, Compliance, and Alternative Enforcement Techniques: Go With the Flow Houston Public Outreach Plan*. TTI Report FHWA/TX-98/1295-1, College Station, Texas, August 1997.
2. Messer, C.J., and M.A. Butoric. *A Dual-Lane Flow Signal Plan for Texas*. TTI Report FHWA/TX-98/1295-2, College Station, Texas, August 1997.
3. Chaudhary, N.A., and C.J. Messer. *Ramp Metering Technology and Practice: Tasks 1 and 2 Summary*. TTI Report FHWA/TX-00/2121-1, College Station, Texas, May 2000.
4. Chaudhary, N.A. *Implementation of Arlington Ramp Metering System*. Project Summary Report 3982-S, College Station, Texas, January 2001.
5. Chaudhary, N.A., and C.J. Messer. *Freeway On-Ramp Design Criteria for Ramp Meters with Excessive Queue Detectors*. Transportation Research Record 1796, 2003.
6. Chaudhary, N.A., and C.J. Messer. *Ramp-Metering Design and Operations Guidelines for Texas*, Research Report FHWA/TX-01/2121-2, TTI, College Station, Texas, October 2000.
7. Messer C.J., M. Thomadakis, H. Charara, and T. Urbanik II. *Ramp Adaptive Metering Bottleneck, Optimization (RAMBO) User's Manual*. TTI Report FHWA/TX-94/1232-31, College Station, Texas, November 1994.
8. Piotrowics, G., and J. Robinson. *Ramp Metering Status in North America – 1995 Update*, Virginia Department of Transportation, June 1995.
9. Persaud, B., S. Yagar, D. Tsui, and H. Look. *Breakdown-Related Capacity for Freeway with Ramp Metering*. Transportation Research Record 1748, TRB, Washington, D.C., 2001.
10. *Chapter 7 – Ramp Management and Control.* Freeway Management and Operations Handbook, Federal Highway Administration, Washington, D.C., U.S. Department of Transportation, September 2003.
11. Tian, Zongzhong. *Development and Evaluation of Operational Strategies for Providing an Integrated Diamond Interchange Ramp-Metering Control System*. Ph.D. Dissertation, Department of Civil Engineering, Texas A&M University, College Station, Texas, May 2004.
12. Pooran, F., and R. Summer. *Coordinated Operation of Ramp Metering and Adjacent Traffic Signal Control Systems*. Report FHWA-RD-95-130. Federal Highway Administration, Washington, D.C., 1996.
13. *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials, Washington, D.C., 2001.
14. Papageorgiou, M., H. Hadj-Salem, and F. Middelham. *ALINEA Local Ramp Metering*. Transportation Research Record 1603, National Research Council, Washington, D.C., 1991.
15. Chu, L., H.X. Liu, W. Recker, and H.M. Zhang. *Development of a Simulation Laboratory for Evaluating Ramp Metering Algorithms*. Paper 02-3427 presented at the TRB Annual Meeting, Washington, D.C., January 2002.
16. Zhang, M., T. Kim, X. Nie, and W. Jin. *Evaluation of On-ramp Control Algorithms*. California PATH Research Report UCB-ITS-PRR-2001-36, December 2001.
17. Jacobson, L., K. Henry, and O. Mahyar. *Real-Time Metering Algorithm for Centralized Control*. Transportation Research Record 1232, National Research Council, Washington, D.C., 1989.

18. Messer, C.J. *Advanced Freeway System Ramp Metering Strategies for Texas*. Report FHWA/TX-94/1232-23, College Station, Texas, October 1993.
19. Messer, C.J. *A Design and Synthesis of a Multilevel Freeway Control System and a Study of Its Associated Operational Control Plan*, Ph.D. Dissertation, Texas A&M University, College Station, 1969.
20. Ciarallo, F., and P. Mirchandani. *RHODES-ITMS-MILOS: Ramp Metering System Test*. Report FHWA-AZ02-481, University of Arizona, Tucson, Arizona, April 2002.
21. Liu, J.S., J.L. Kim, Y. Chen, Y. Hao, S. Lee, T. Kim, and M. Thomadakis. *An Advanced Real-Time Ramp Metering System (ARMS): The System Concept*. Report FHWA/TX-94/1232-24, College Station, Texas, November 1994.
22. *CORSIM, Version 1.03, User's Manual*. Kaman Science Corporation, Colorado Springs, Colorado, April 1997.
23. Koothrappally, J. *Object-Based Advanced Traffic Simulation Modeling*. Paper presented at the 68th Annual ITE Meeting, Institute of Transportation Engineers, Toronto, Ontario, Canada, August 1998.
24. Parker, M. *Zooming in on Traffic Microsimulation*. Traffic Technology International, 2002.
25. Smith, M., S. Druitt, G. Cameron, and D. McArthur. *PARAMICS Final Report*, Report No. EPCC-PARAMICS-FINAL, University of Edinburgh, Parallel Computing Center, Scotland, July 1994.
26. *RMC 300 Ramp Controller Unit*. Product Manual, PIM-189, Rev. B.00, Eagle Traffic Control Systems, Austin, Texas, November 1997.
27. *Highway Capacity Manual - HCM 2000*. Transportation Research Board, Washington, D.C., 2000.

APPENDIX A: VAP CODE

```
PROGRAM RampMeter;
/** Ramp meter for Peak direction **/

CONST
/** select ALGORITHM to run **/

Algorithm = 1,   /** 1 - ALINEA; 2 - Fixed; 3 - No Meter; 4 - Ramp closure
**/
QueueOverRide = 1,  /** 1 - queue override; 0 - no queue override  **/

QueueCountInterval = 5,
OccupancyInterval = 20,
GreenInterval = 2.0,
KR = 70,  /** ALINEA constant **/
MaxRate = 900,
MinRate = 240,

FixedRate = 900, /* used for fixed metering, Can only model rates 400, 450,
515, 600, 720, 900, 1200 */

RedInterval = 2.0,

TransitionPeriod = 20,

NumberofDetectors = 4,          /** total num. of downstream  detectors **/
dd1 = 100,  dd2 = 101, dd3 = 102, dd4 = 103,   /**downstream detector numbers
**/

NumberMeterLane = 1,
d_Presence1 = 5, /** presence detector-Lane 1 **/
/*d_Presence2 = 12,*/ /** presence detector-Lane 2 **/

QueueDetector_Advance = 4,

/*QueueDetector_Inter = 2,*/

Occupancy_Opt = 0.20,  /** optimal or target occupancy **/
Occupancy_Threshold = 0.010,  /** threshold to metering **/
Queue_Threshold = 0.90,  /** for ramp queue detection **/

/* Data Collection Parameters  */
StartTime = 600,
EndTime = 12000;

/*********************************************************************/
SUBROUTINE ALINEA;

IF CountTimer = OccupancyInterval THEN

      TRACE (variable (MeterPrevious));

      IF OccupancyInterval = 1 THEN   /** set interval to 1-sec, for report
purposes **/
```

```
            AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate
(dd3) + Occup_rate (dd4))/NumberofDetectors;
            AvgOccup_DownStreamDet := AverageOcc;
      ELSE
            AvgOccup_DownStreamDet := Occup_DetDownStream /
(OccupancyInterval);  /**  **/
      END;

      IF AvgOccup_DownStreamDet < Occupancy_Threshold THEN
            MeterRate := 80000;
      ELSE
            MeterRate := MeterPrevious + KR*(Occupancy_Opt -
AvgOccup_DownStreamDet)*100;
      END;


      IF MeterRate >= MaxRate THEN
            MeterRate := MaxRate;  /**  **/
            RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
            MeterPrevious := MeterRate;
      ELSE
            IF MeterRate <= MinRate THEN
                  MeterRate := MinRate;
                  RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
                  MeterPrevious := MeterRate;
            ELSE
                  RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval;
                  MeterPrevious := MeterRate;
            END;
      END;

      /**SumVeh := front_ends(dd1) + front_ends(dd2) + front_ends(dd3)
+front_ends(dd4);**/
      SumVeh := rear_ends(dd1) + rear_ends(dd2) + rear_ends(dd3)
+rear_ends(dd4);
      FlowRate := (SumVeh/OccupancyInterval) * 3600;

      /** TRACE (variable); **/
      TRACE (variable (AvgOccup_DownStreamDet, FlowRate));
      TRACE (variable (MeterRate, RedInt));
      /** TRACE (variable (AvgOccup_DownStreamDet)); **/

      RESET(CountTimer);
      Occup_DetDownStream := 0;
      clear_rear_ends(dd1);
      clear_rear_ends(dd2);
      clear_rear_ends(dd3);
      clear_rear_ends(dd4);

ELSE
      AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate (dd3) +
Occup_rate (dd4))/NumberofDetectors;
      Occup_DetDownStream := Occup_DetDownStream + AverageOcc;

END.
```

```
/*************************************************************************/
SUBROUTINE FixedMeter;

      MeterRate := FixedRate;

/*    RedInt := (3600/MeterRate)*NumberMeterLane - GreenInterval. */
      RedInt := RedInterval.

/*************************************************************************/
SUBROUTINE NoMeter;

IF CountTimer = OccupancyInterval THEN

      IF OccupancyInterval = 1 THEN   /** set interval to 1-sec, for report
purposes **/
            AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate
(dd3) + Occup_rate (dd4))/NumberofDetectors;
            AvgOccup_DownStreamDet := AverageOcc;
      ELSE
            AvgOccup_DownStreamDet := Occup_DetDownStream /
(OccupancyInterval);  /**  **/
      END;


      SumVeh := rear_ends(dd1) + rear_ends(dd2) + rear_ends(dd3)
+rear_ends(dd4);
      FlowRate := (SumVeh/OccupancyInterval) * 3600;

      /** TRACE (variable); **/
      TRACE (variable (AvgOccup_DownStreamDet, FlowRate));
      /**TRACE (variable (MeterRate, RedInt)); **/
      /** TRACE (variable (AvgOccup_DownStreamDet)); **/

      RESET(CountTimer);
      Occup_DetDownStream := 0;

      clear_rear_ends(dd1);
      clear_rear_ends(dd2);
      clear_rear_ends(dd3);
      clear_rear_ends(dd4);

ELSE
      AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate (dd3) +
Occup_rate (dd4))/NumberofDetectors;
      Occup_DetDownStream := Occup_DetDownStream + AverageOcc
END.

SUBROUTINE RampClose;

      RedInt := 1000000;
      sg_red(1);
      sg_red(2);

IF CountTimer = OccupancyInterval THEN

      IF OccupancyInterval = 1 THEN   /** set interval to 1-sec, for report
purposes **/
```

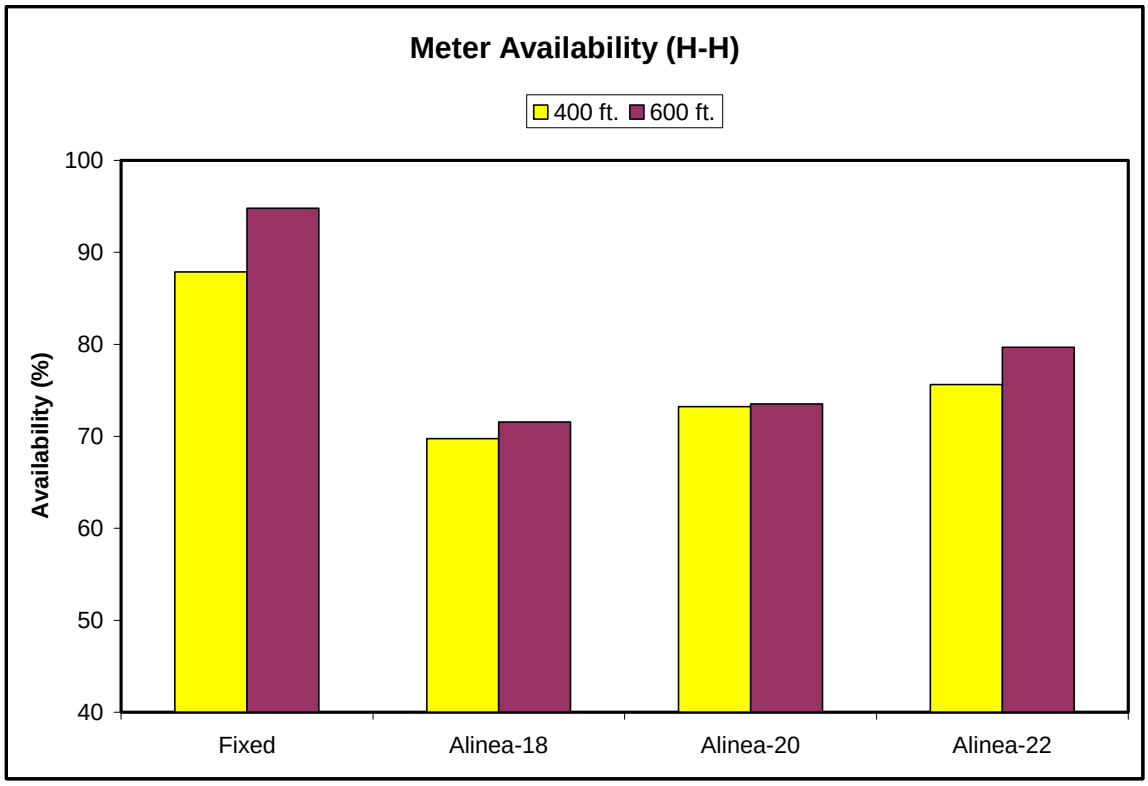
```
            AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate
(dd3) + Occup_rate (dd4))/NumberofDetectors;
            AvgOccup_DownStreamDet := AverageOcc;
      ELSE
            AvgOccup_DownStreamDet := Occup_DetDownStream /
(OccupancyInterval);  /**  **/
      END;


      SumVeh := rear_ends(dd1) + rear_ends(dd2) + rear_ends(dd3)
+rear_ends(dd4);
      FlowRate := (SumVeh/OccupancyInterval) * 3600;

      /** TRACE (variable); **/
      TRACE (variable (AvgOccup_DownStreamDet, FlowRate));
      TRACE (variable (MeterRate, RedInt));
      /** TRACE (variable (AvgOccup_DownStreamDet)); **/

      RESET(CountTimer);
      Occup_DetDownStream := 0;

      clear_rear_ends(dd1);
      clear_rear_ends(dd2);
      clear_rear_ends(dd3);
      clear_rear_ends(dd4);

ELSE
      AverageOcc := (Occup_rate (dd1) + Occup_rate (dd2) + Occup_rate (dd3) +
Occup_rate (dd4))/NumberofDetectors;
      Occup_DetDownStream := Occup_DetDownStream + AverageOcc
END.

/*************************************************************************/
SUBROUTINE MeterOperation;

/***********************************/
/**** METERING OPERATIONS        ****/
/***********************************/
/*Single-lane meter */

TRACE (variable (QueueSpill,FlushFlagCurrent));
TRACE (variable (FlushFlagPrevious,TransitionTimer));

IF (t_green(1) >= GreenInterval) OR (Occupancy(d_Presence1) <=0) THEN
      IF (QueueOverRide AND QueueSpill) THEN


            MeterPrevious := MaxRate; /** Do not start red if queuespill and
with override policy **/
            IF (SimuTime >= StartTime) AND (SimuTime < EndTime) THEN
                  TotalMeterFlushTime := TotalMeterFlushTime + 1;
                  TRACE (variable (SimuTime,TotalMeterFlushTime));
            END;
      ELSE
            /* No queue spill. Meter flush stops after transition */

            IF TransitionFlag = 0 THEN /* Not in transition */
```

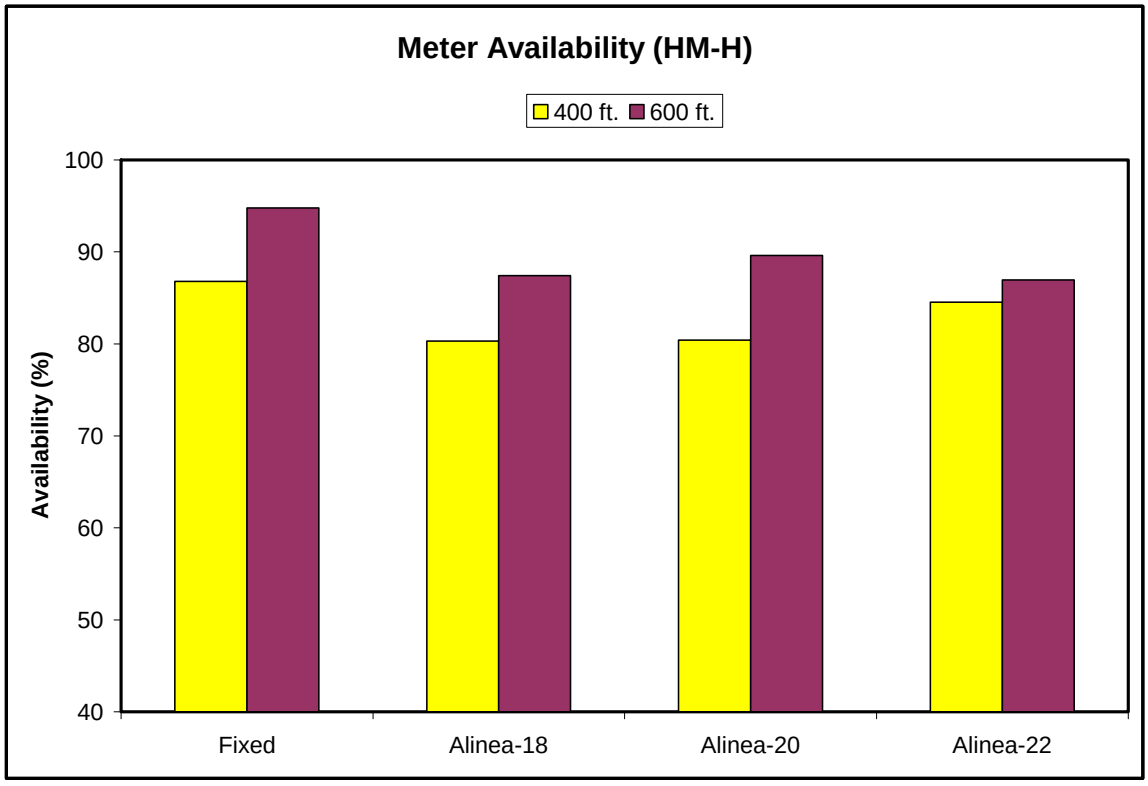
```
                  sg_red(1);
            ELSE
                  IF TransitionTimer >= TransitionPeriod THEN
                        sg_red(1);
                        Stop(TransitionTimer);
                        Reset(TransitionTimer);
                        TransitionFlag := 0;
                  END;
            END;

      END;
END;

IF (t_red(1) >= RedInt) THEN   /*Red has the desired metering rate */
      IF Occupancy(d_Presence1) > 0 THEN
            sg_green(1);

      END;
END.

/*****************************/
/**** This is the main routine ****/
/*****************************/

START(QueueTimer);
START(CountTimer);
SimuTime := SimuTime + 1;

IF QueueTimer = (QueueCountInterval + 1) THEN
      AvgOccup_AdvanceQueueDet := Occup_AdvanceQueueDet / QueueCountInterval;

      QueueSpill := AvgOccup_AdvanceQueueDet >= Queue_Threshold;

      FlushFlagPrevious := FlushFlagCurrent;

      IF QueueSpill THEN
            FlushFlagCurrent := 1;
      ELSE
            FlushFlagCurrent := 0;
      END;

      IF (FlushFlagPrevious = 1) AND (FlushFlagCurrent = 0) THEN
            Start(TransitionTimer);
            TransitionFlag := 1;

      END;

      RESET (QueueTimer);
      Occup_AdvanceQueueDet := 0;


ELSE
      Occup_AdvanceQueueDet := Occup_AdvanceQueueDet + Occup_rate
(QueueDetector_Advance);
END;
```

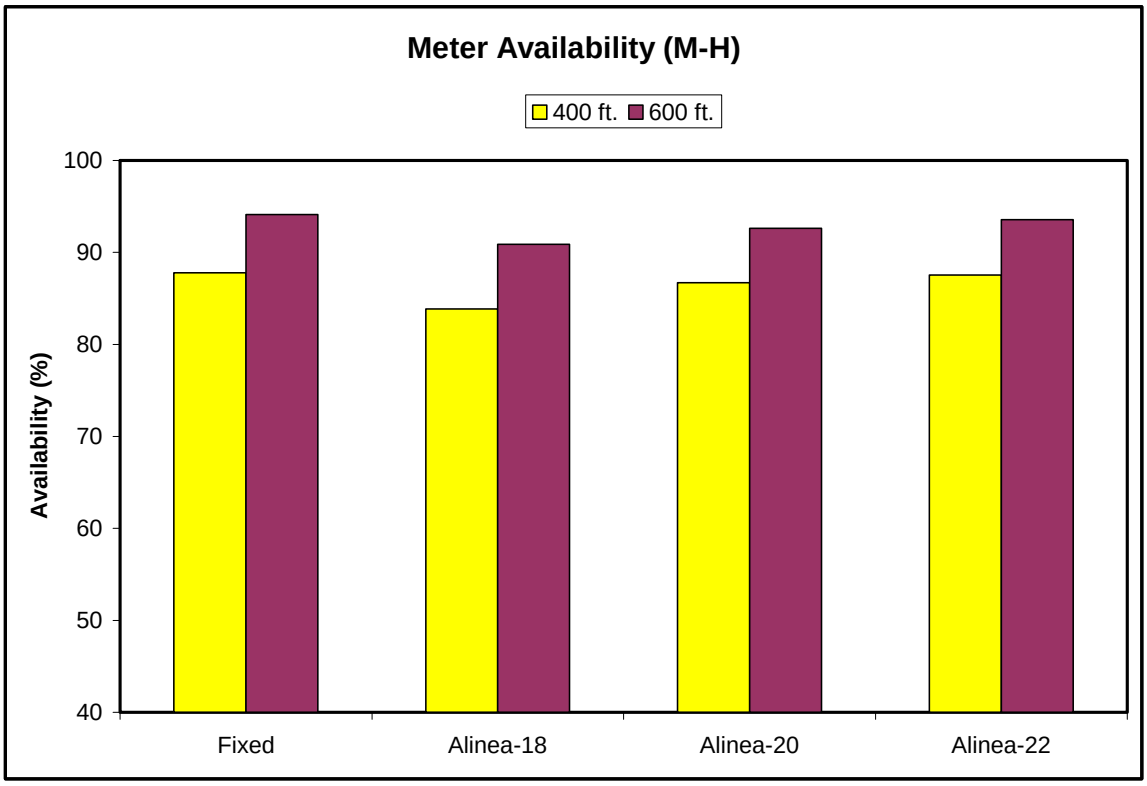
```
IF Algorithm = 1 THEN
      GOSUB ALINEA;
      GOSUB MeterOperation;
ELSE
      IF Algorithm = 2 THEN
            GOSUB FixedMeter;
            GOSUB MeterOperation;
      ELSE
            IF Algorithm = 3 THEN
                  GOSUB NoMeter;
            ELSE
                  IF Algorithm = 4 THEN
                        GOSUB RampClose;
                  END;
            END;
      END;
END.
```

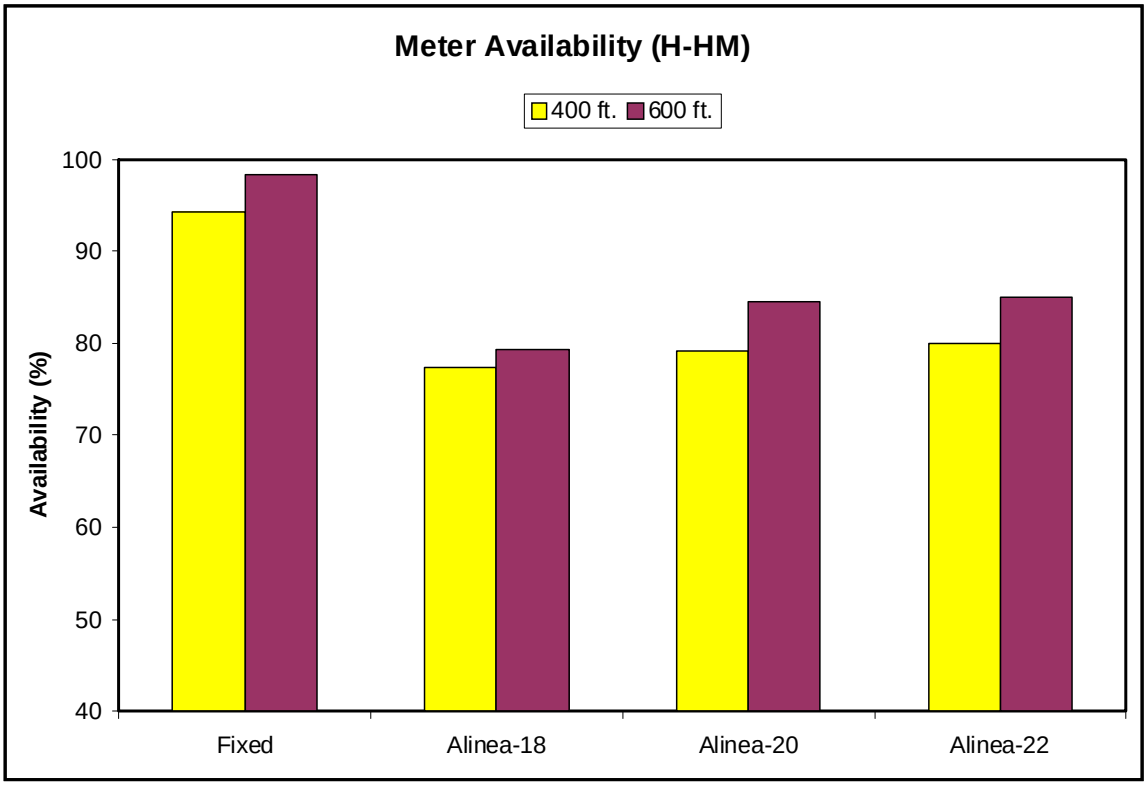
APPENDIX B: SIMULATION RESULTS

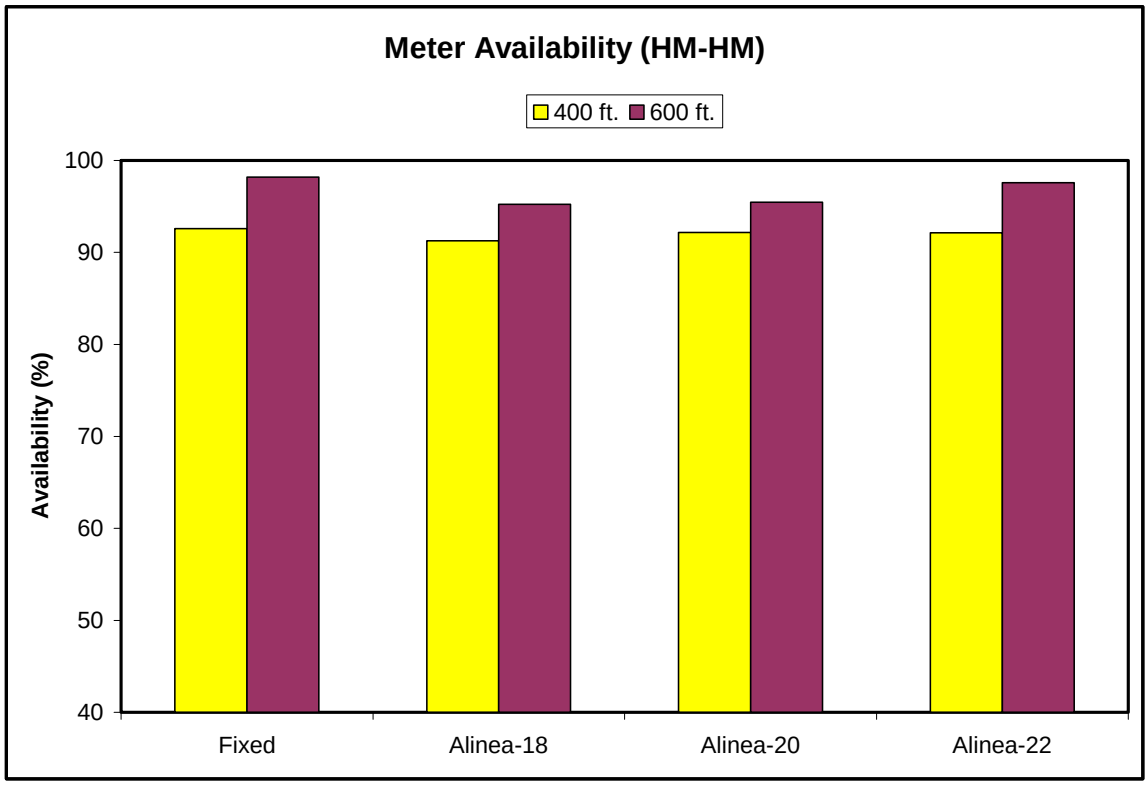
B1. METER AVAILABILITY

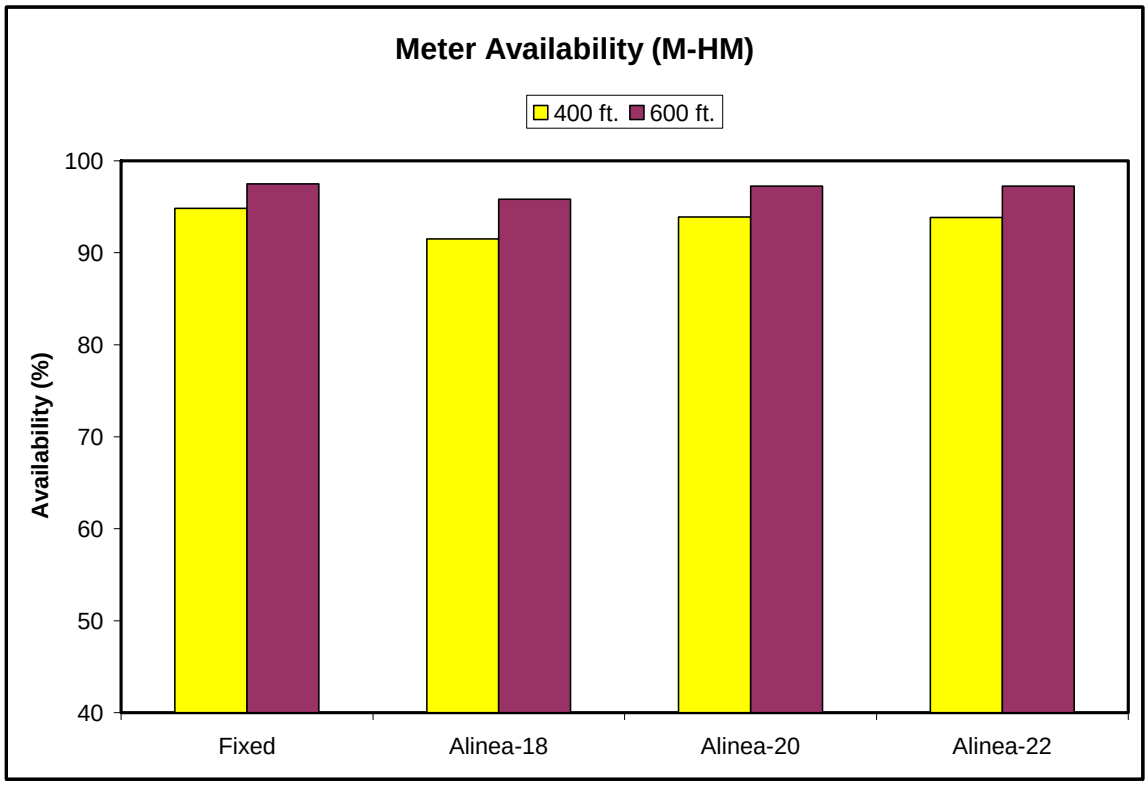


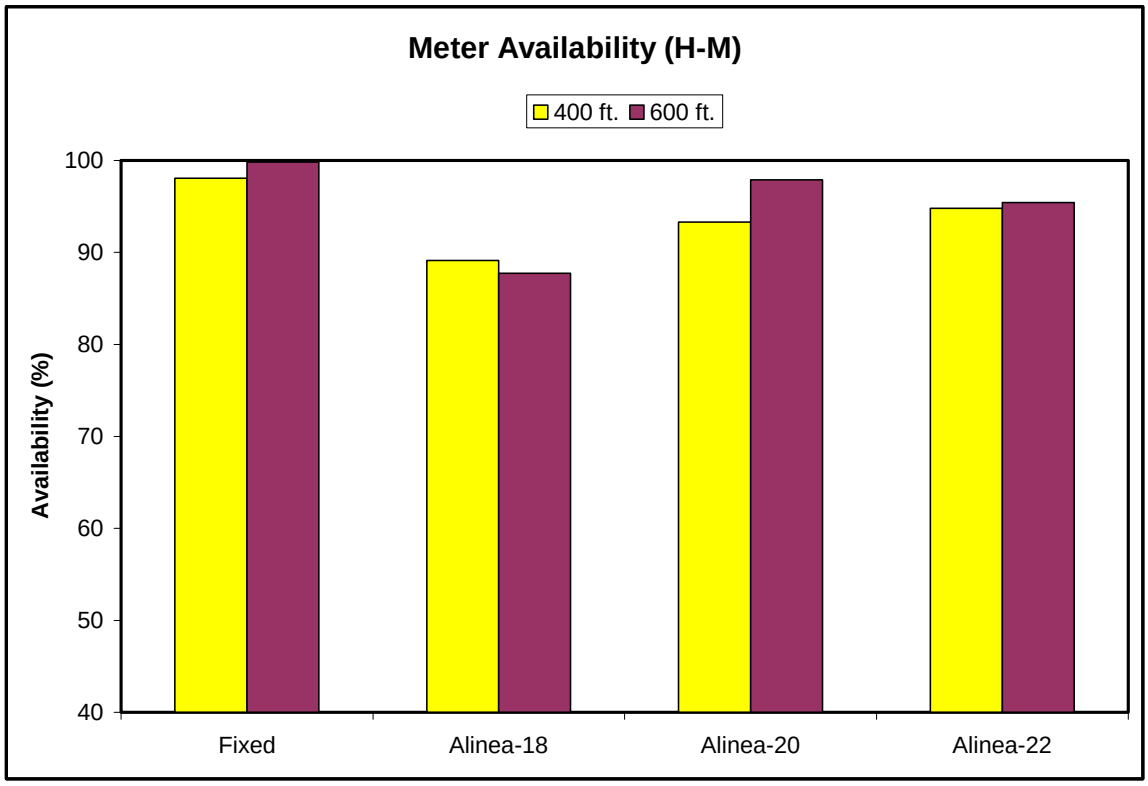


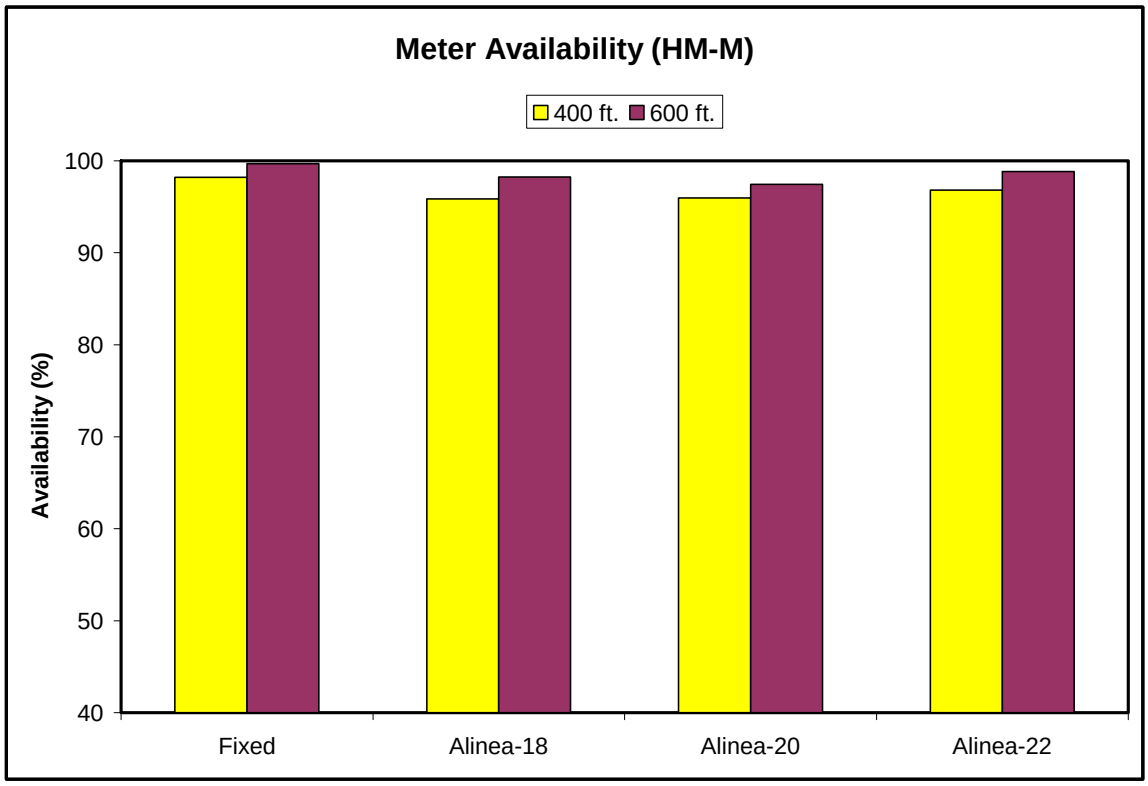

Meter Availability (M-H)
400 ft.
600 ft.
100
90
80
70
60
50
40
Availability (%)
Fixed
Alinea-18
Alinea-20
Alinea-22

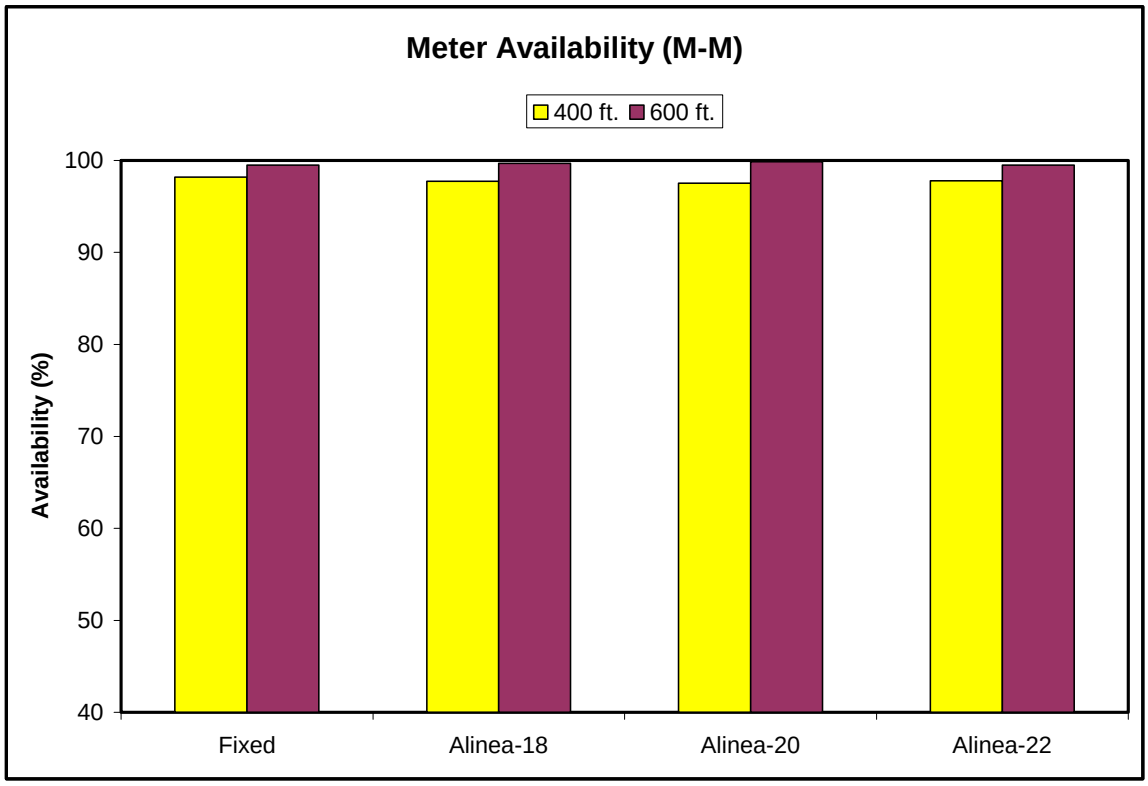

Meter Availability (H-HM)
400 ft.
600 ft.
100
90
80
70
60
50
40
Availability (%)
Fixed
Alinea-18
Alinea-20
Alinea-22


Meter Availability (HM-HM)
400 ft.
600 ft.
Availability (%)
100
90
80
70
60
50
40
Fixed
Alinea-18
Alinea-20
Alinea-22

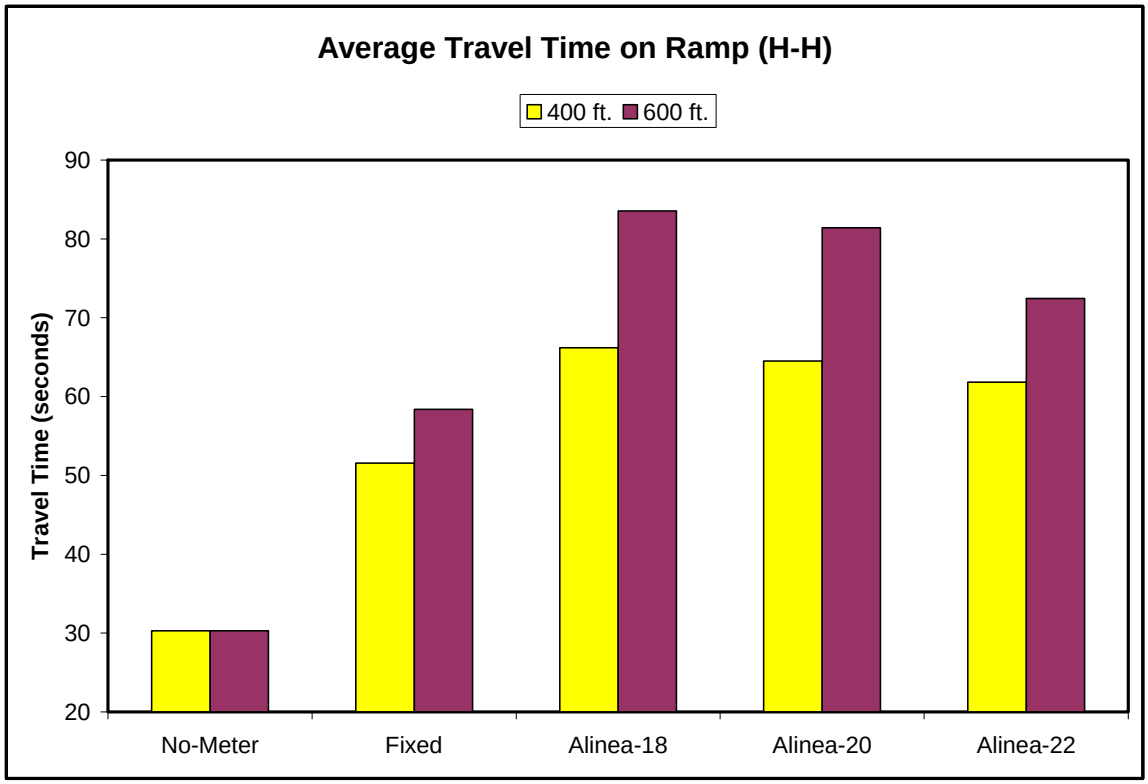

Meter Availability (M-HM)
400 ft.
600 ft.
Availability (%)
100
90
80
70
60
50
40
Fixed
Alinea-18
Alinea-20
Alinea-22

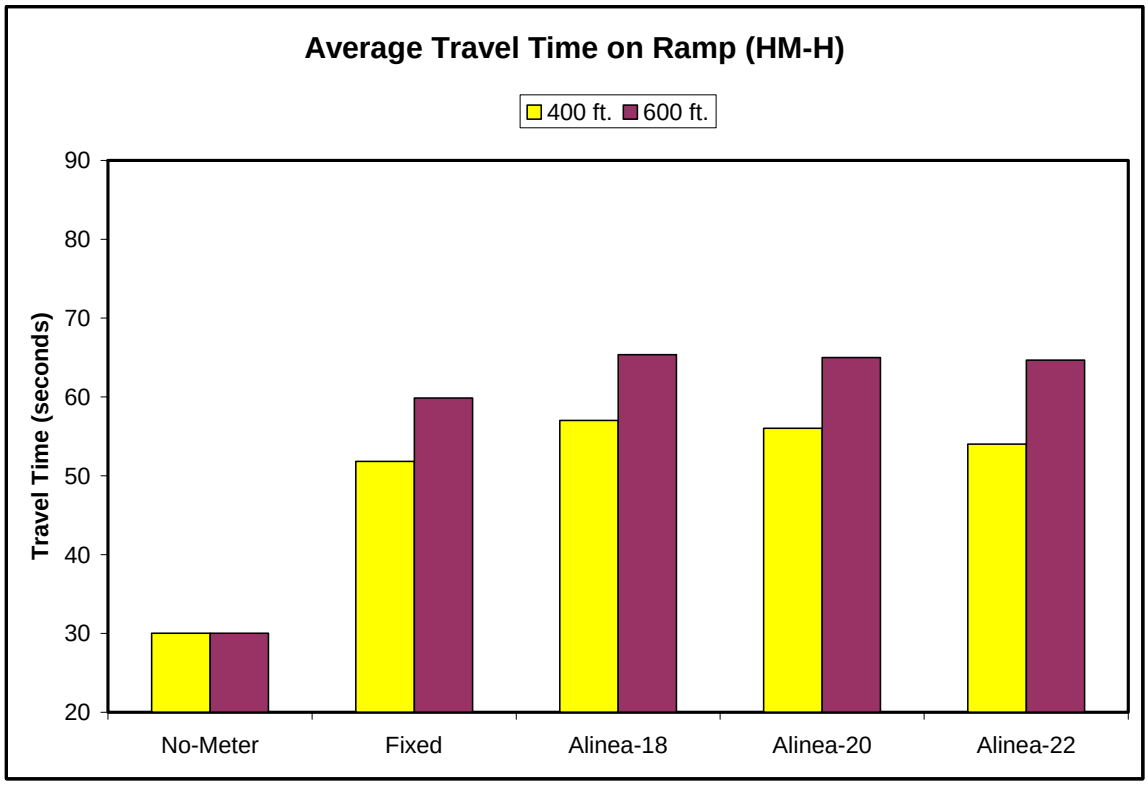

Meter Availability (H-M)
400 ft.
600 ft.
Availability (%)
100
90
80
70
60
50
40
Fixed
Alinea-18
Alinea-20
Alinea-22

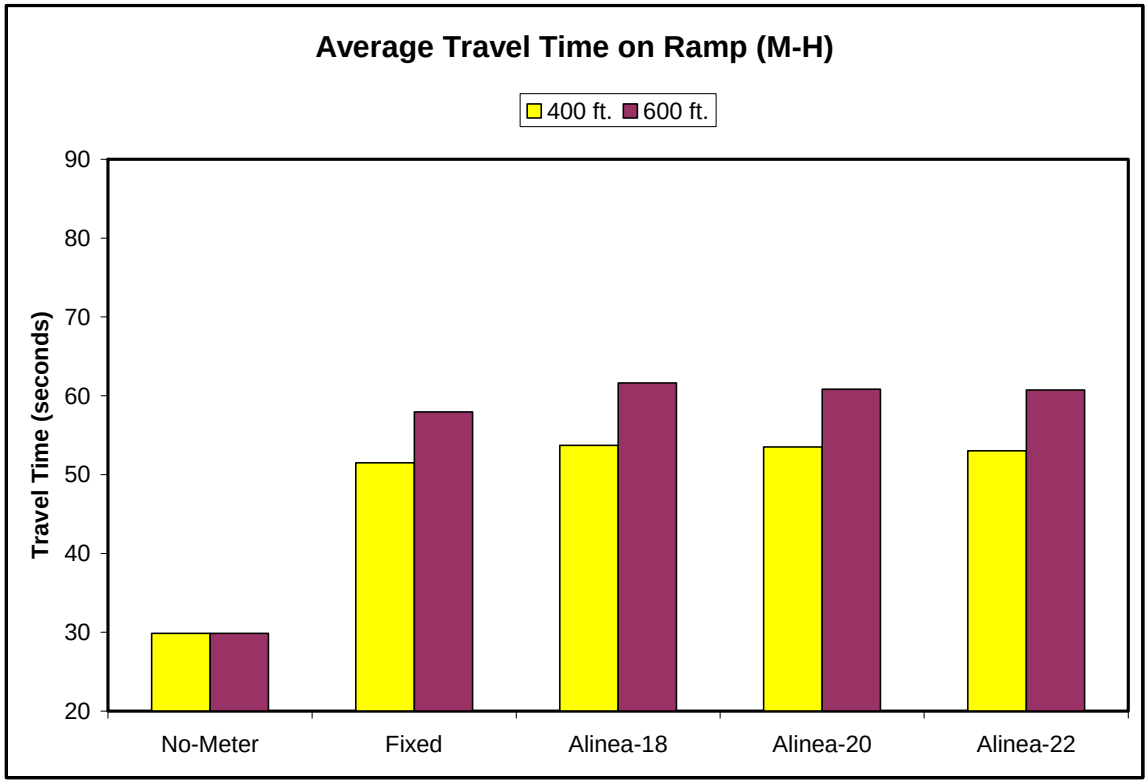

Meter Availability (HM-M)
400 ft.
600 ft.
Availability (%)
100
90
80
70
60
50
40
Fixed
Alinea-18
Alinea-20
Alinea-22

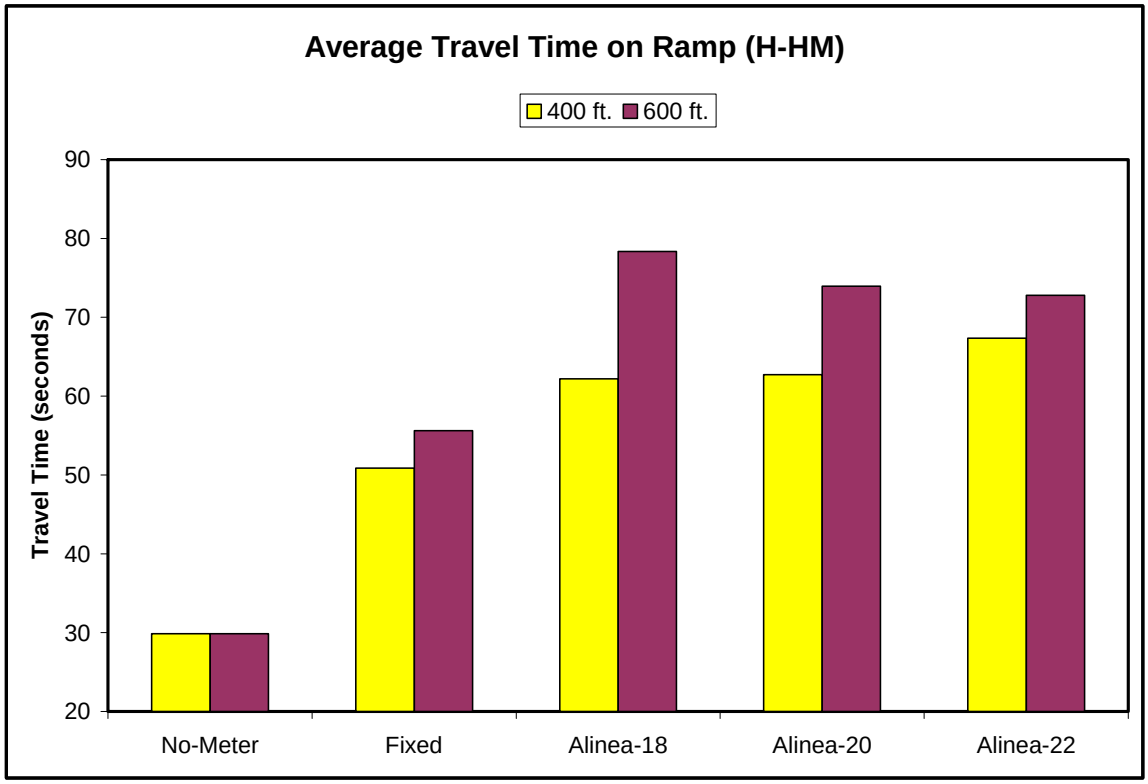

Meter Availability (M-M)
400 ft.
600 ft.
Availability (%)
100
90
80
70
60
50
40
Fixed
Alinea-18
Alinea-20
Alinea-22

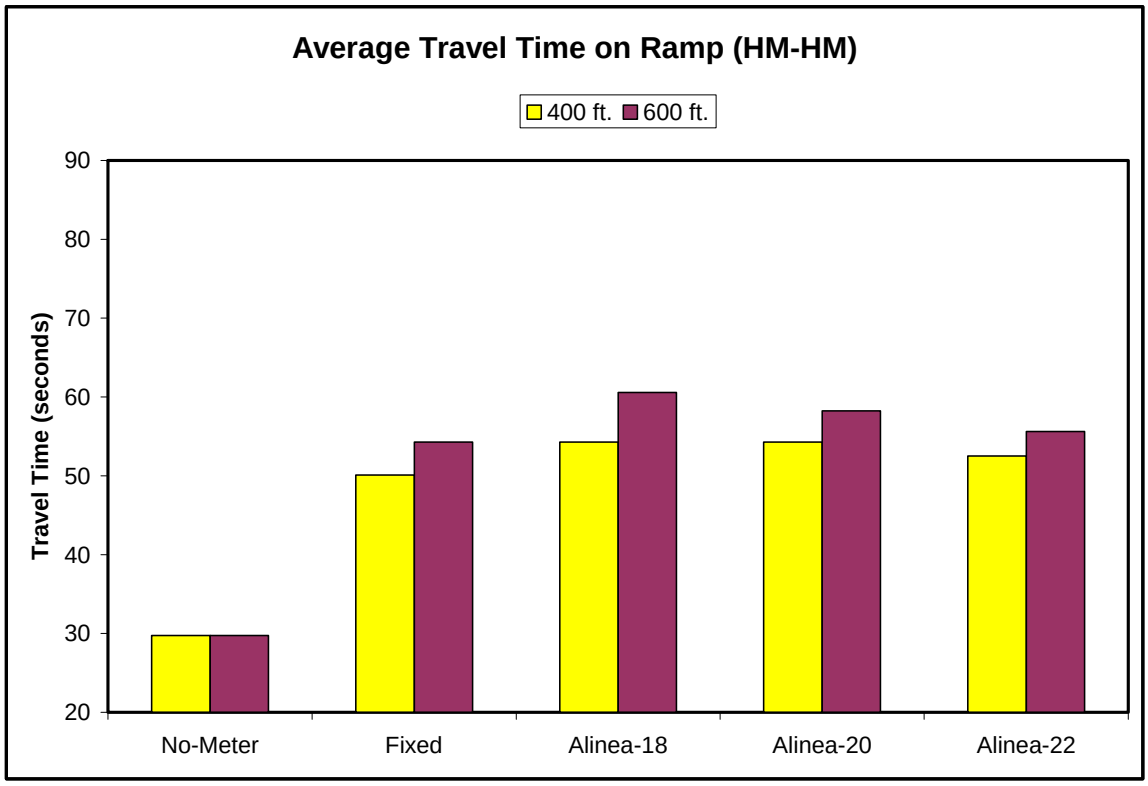
B2. AVERAGE TRAVEL TIME FOR RAMP TRAFFIC

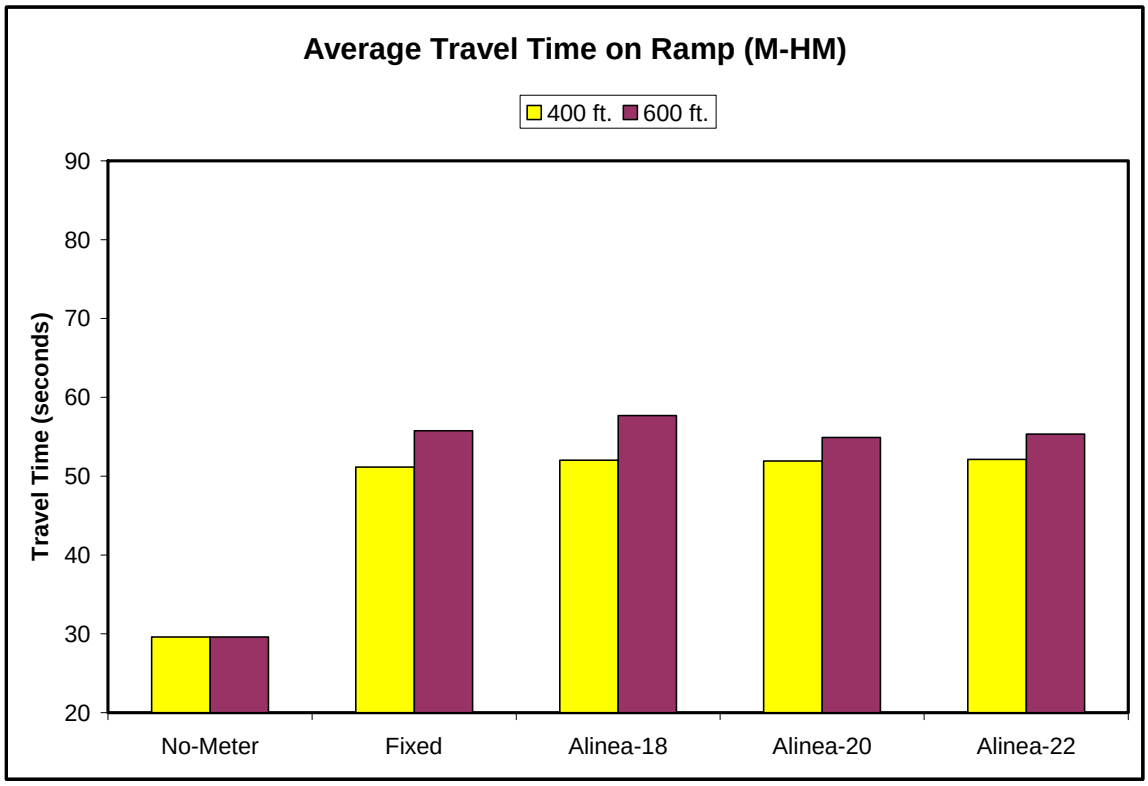


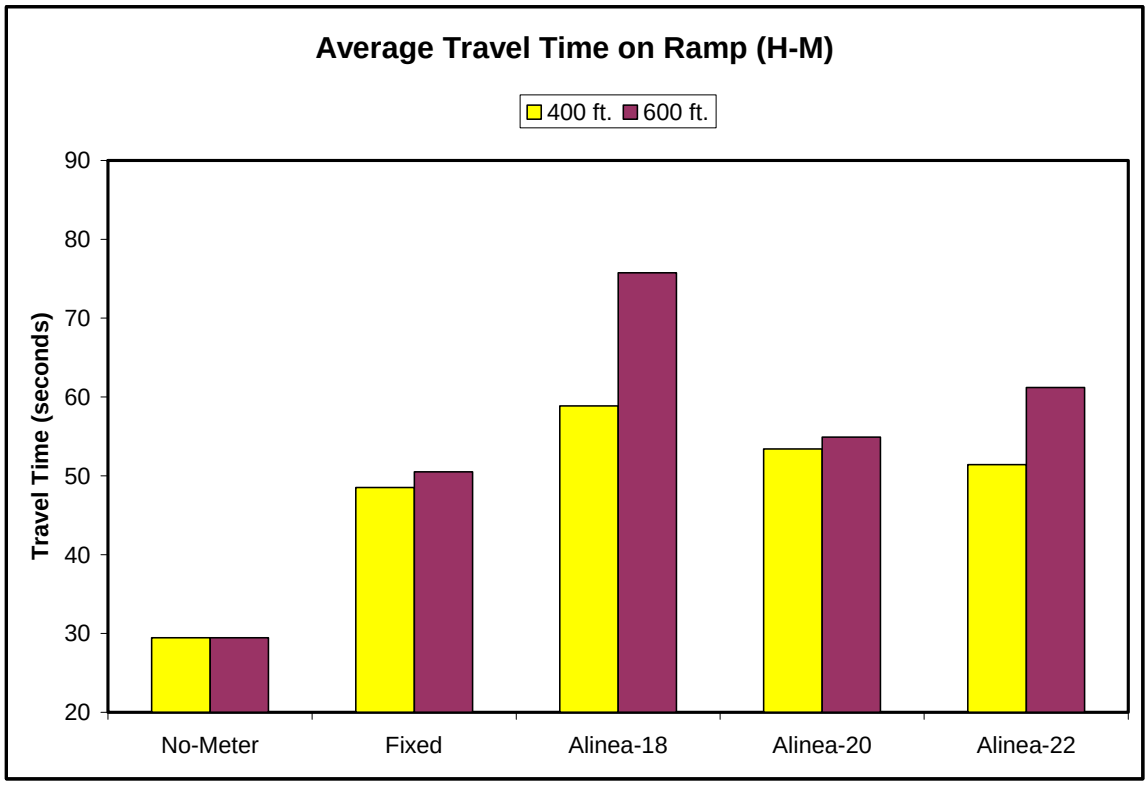


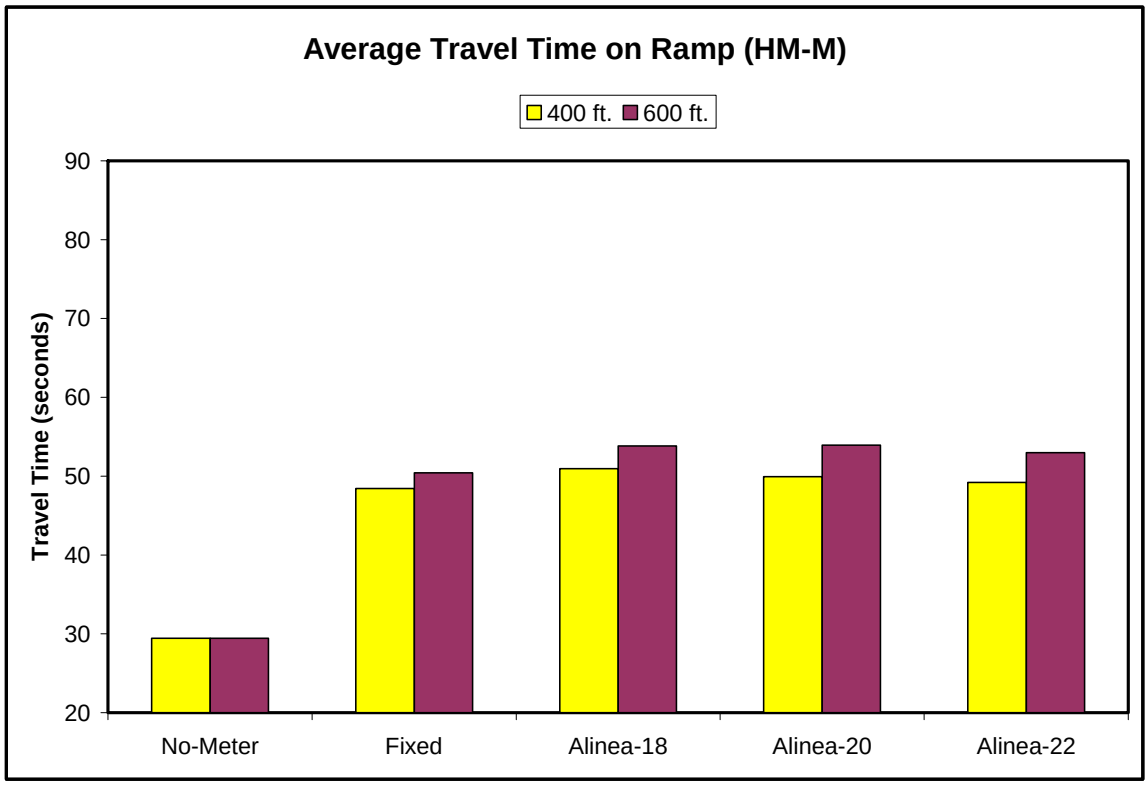

Average Travel Time on Ramp (M-H)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

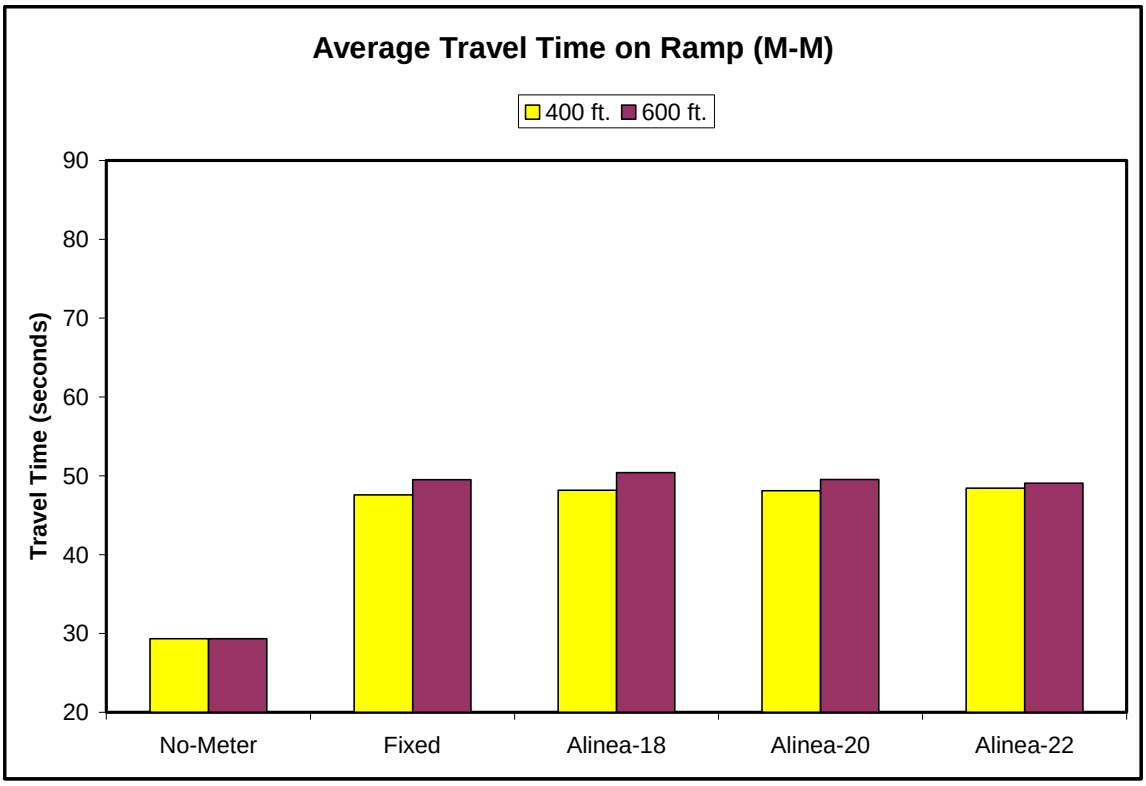

Average Travel Time on Ramp (H-HM)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22


Average Travel Time on Ramp (HM-HM)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

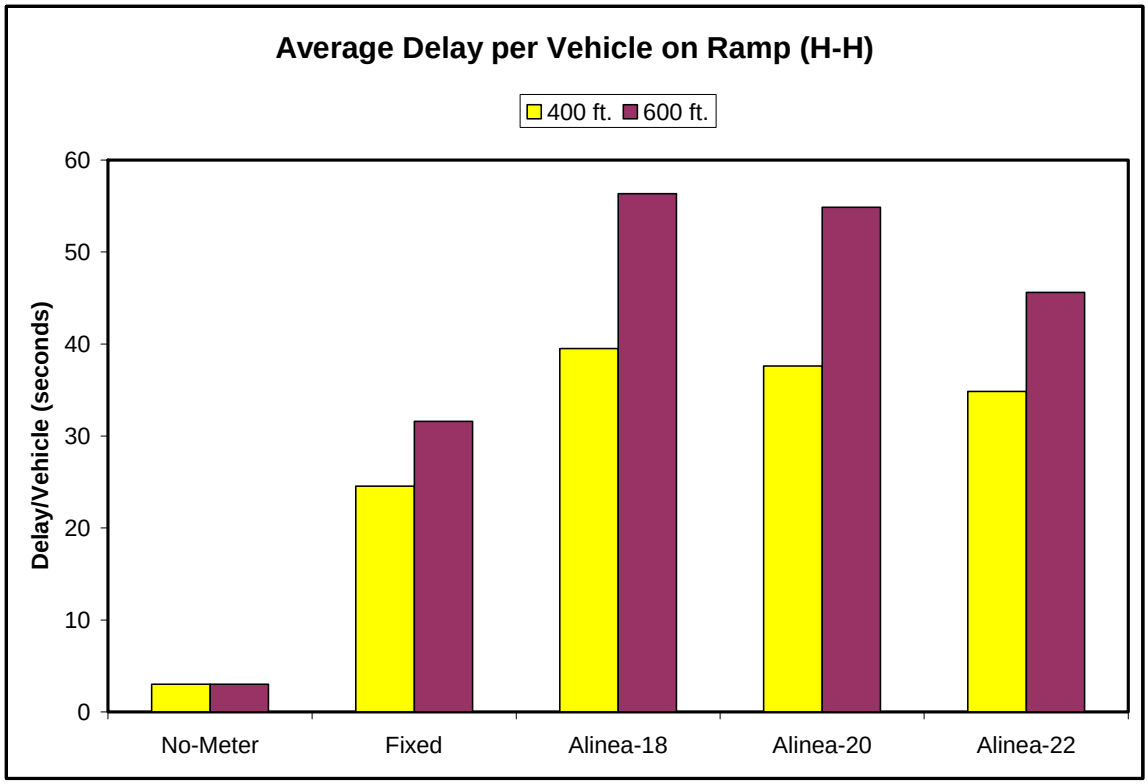

Average Travel Time on Ramp (M-HM)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

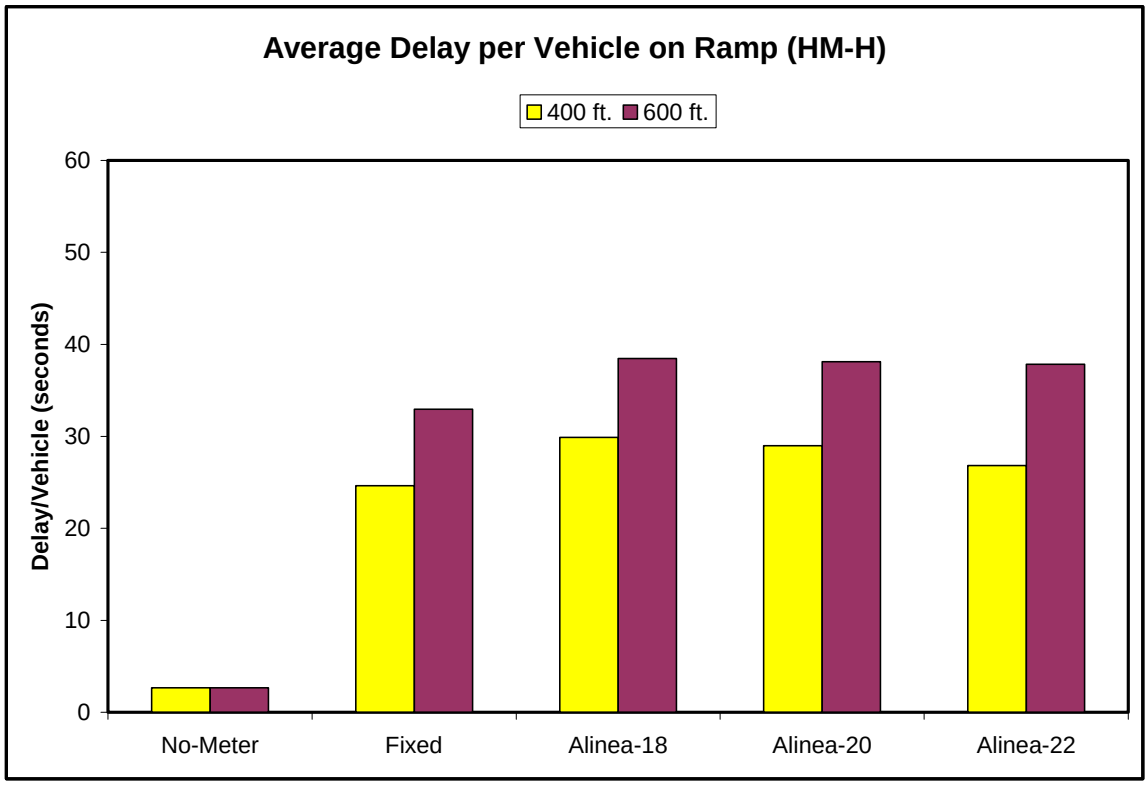

Average Travel Time on Ramp (H-M)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

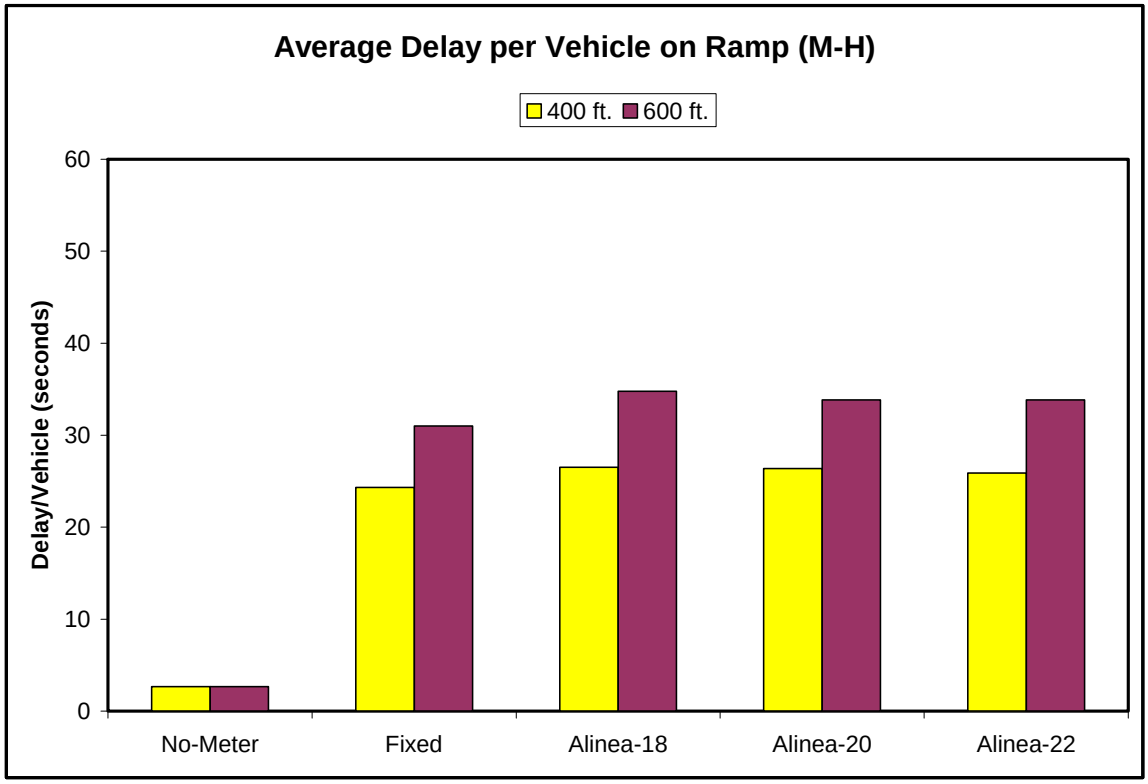

Average Travel Time on Ramp (HM-M)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

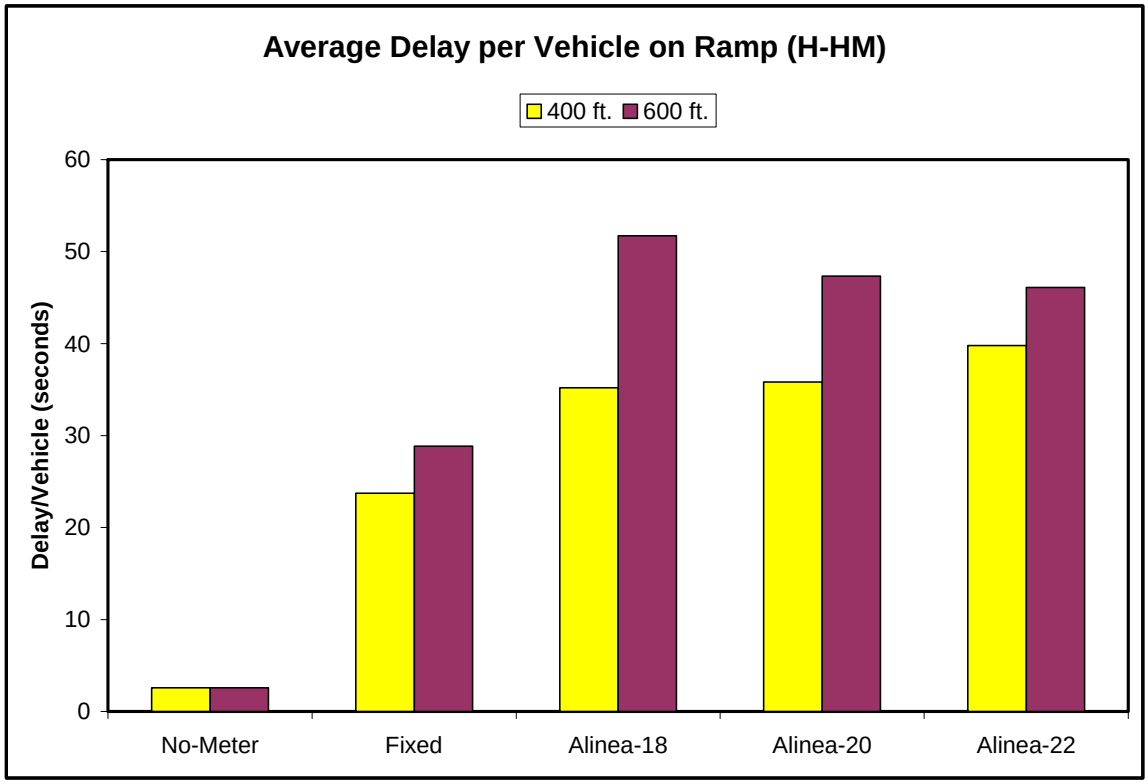

Average Travel Time on Ramp (M-M)
400 ft.
600 ft.
Travel Time (seconds)
90
80
70
60
50
40
30
20
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

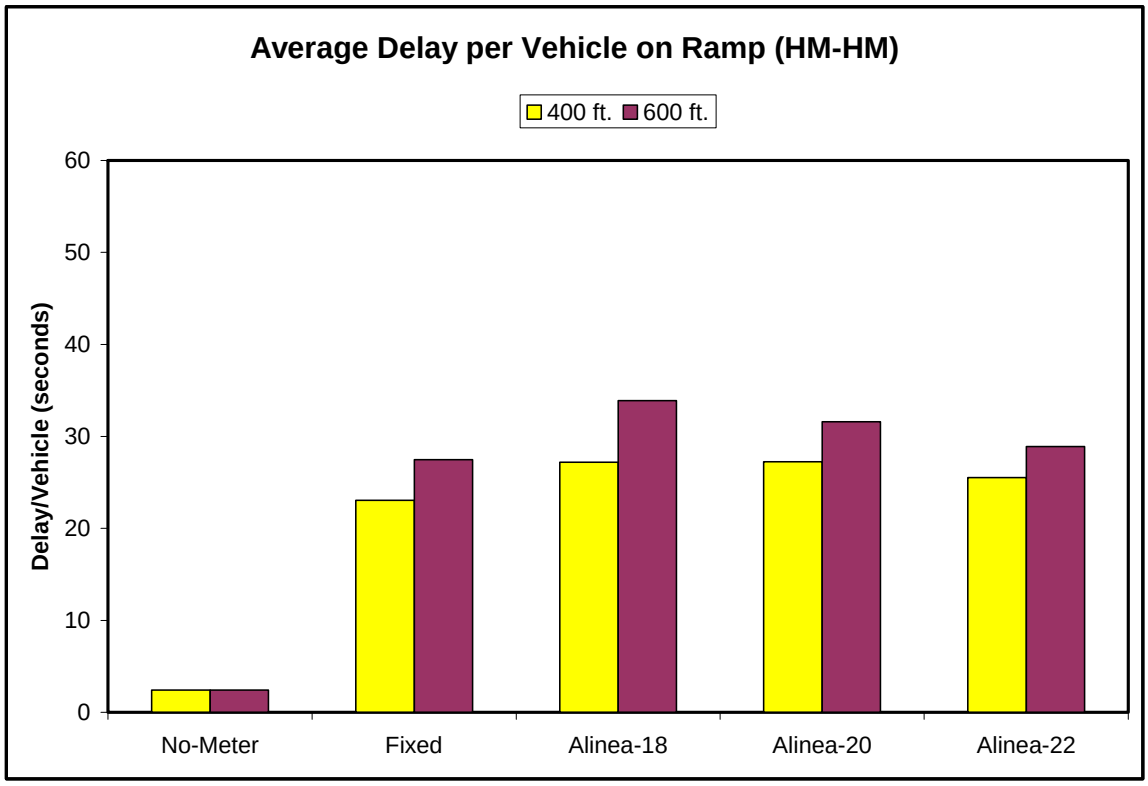
B3. AVERAGE DELAY PER VEHICLE FOR RAMP TRAFFIC

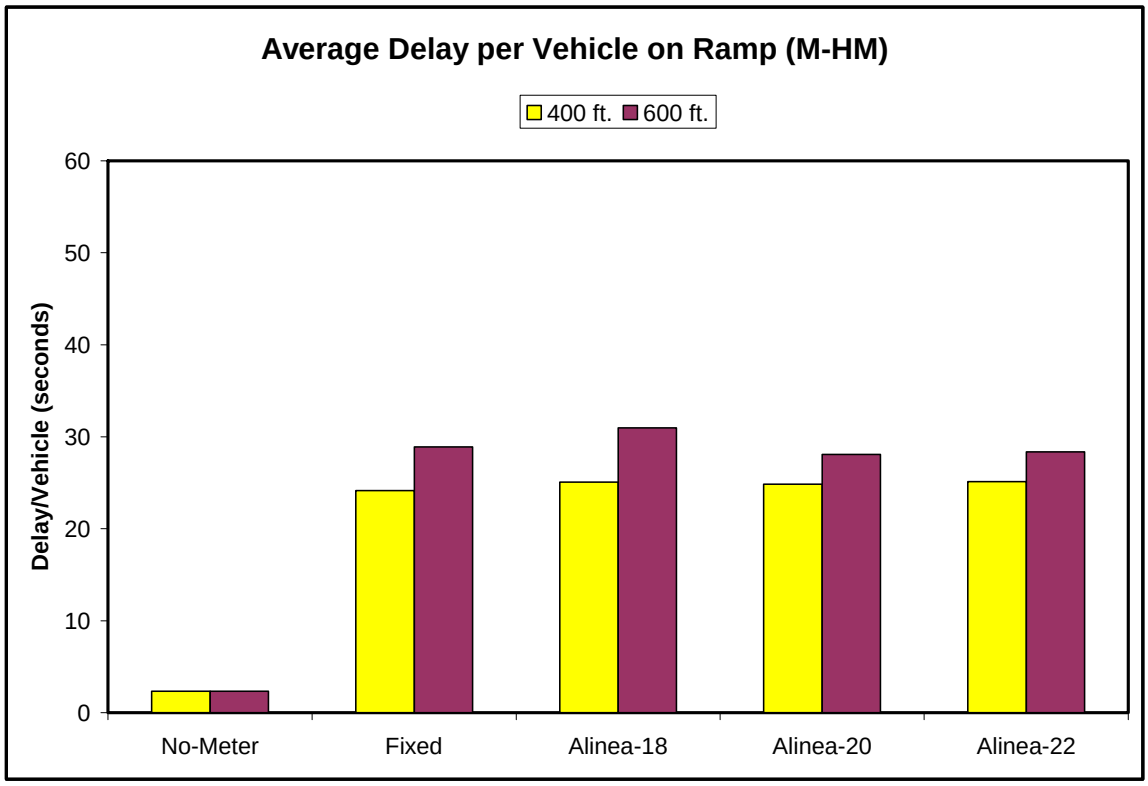


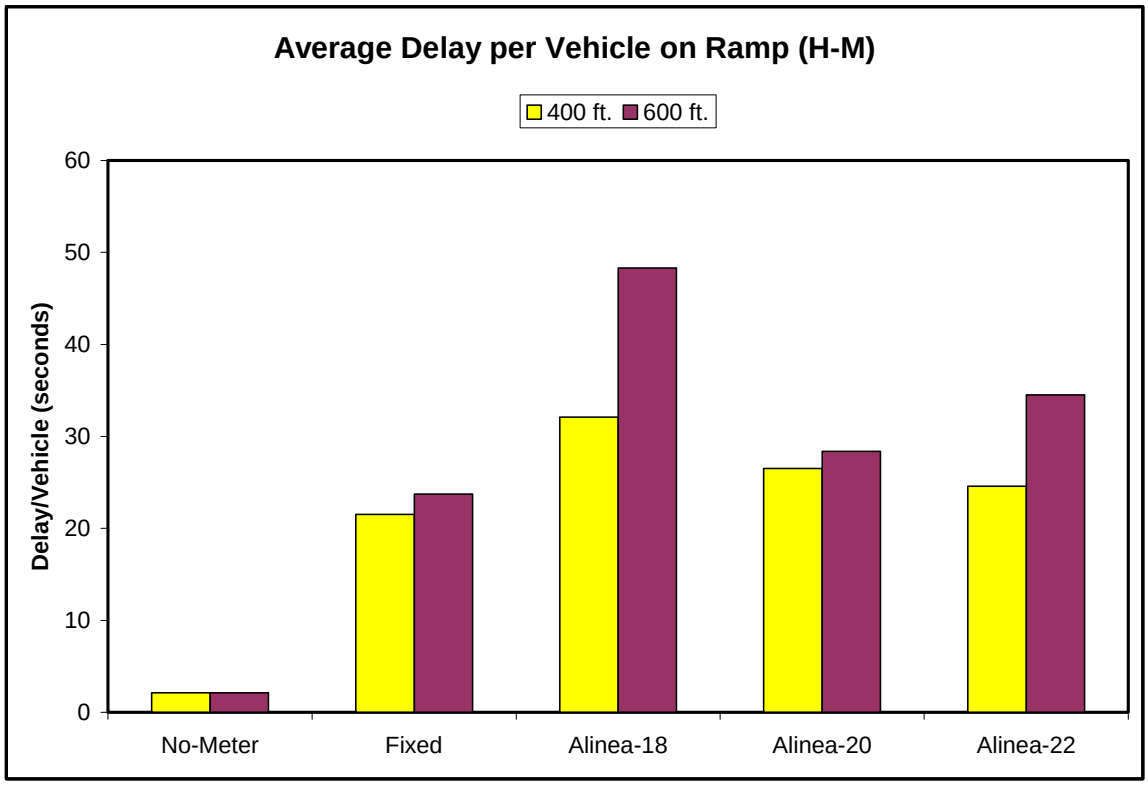


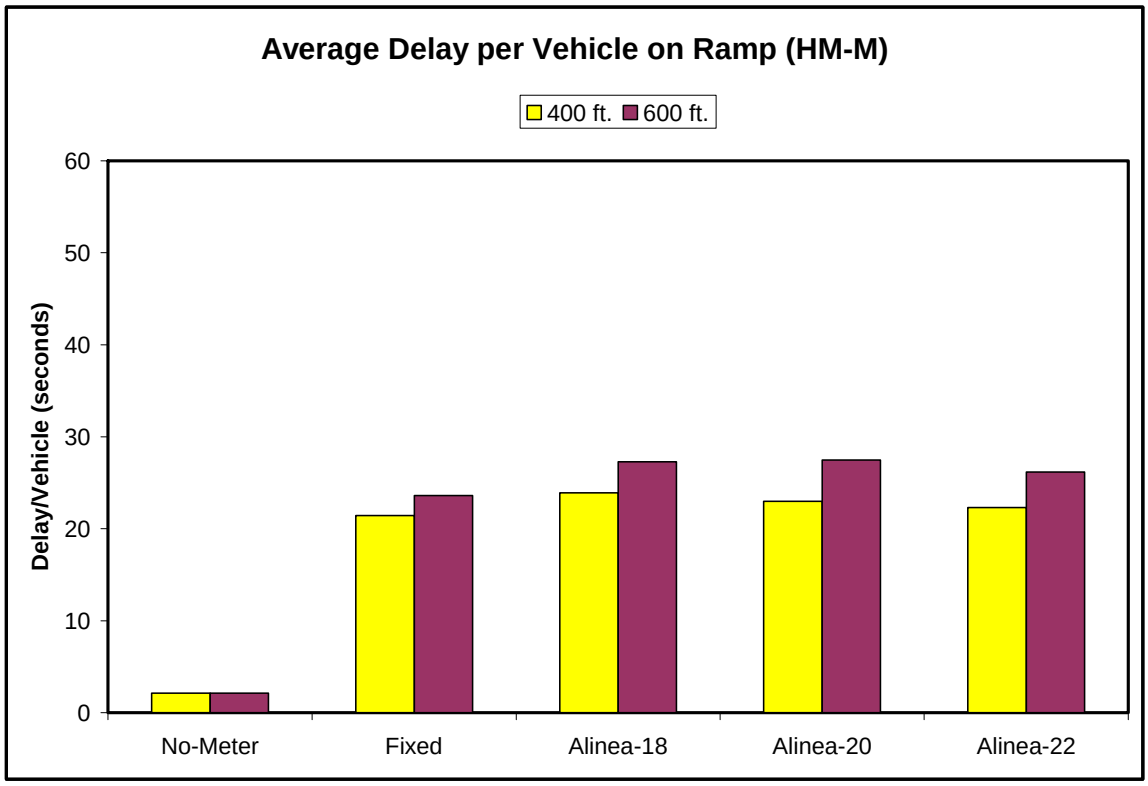

Average Delay per Vehicle on Ramp (M-H)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

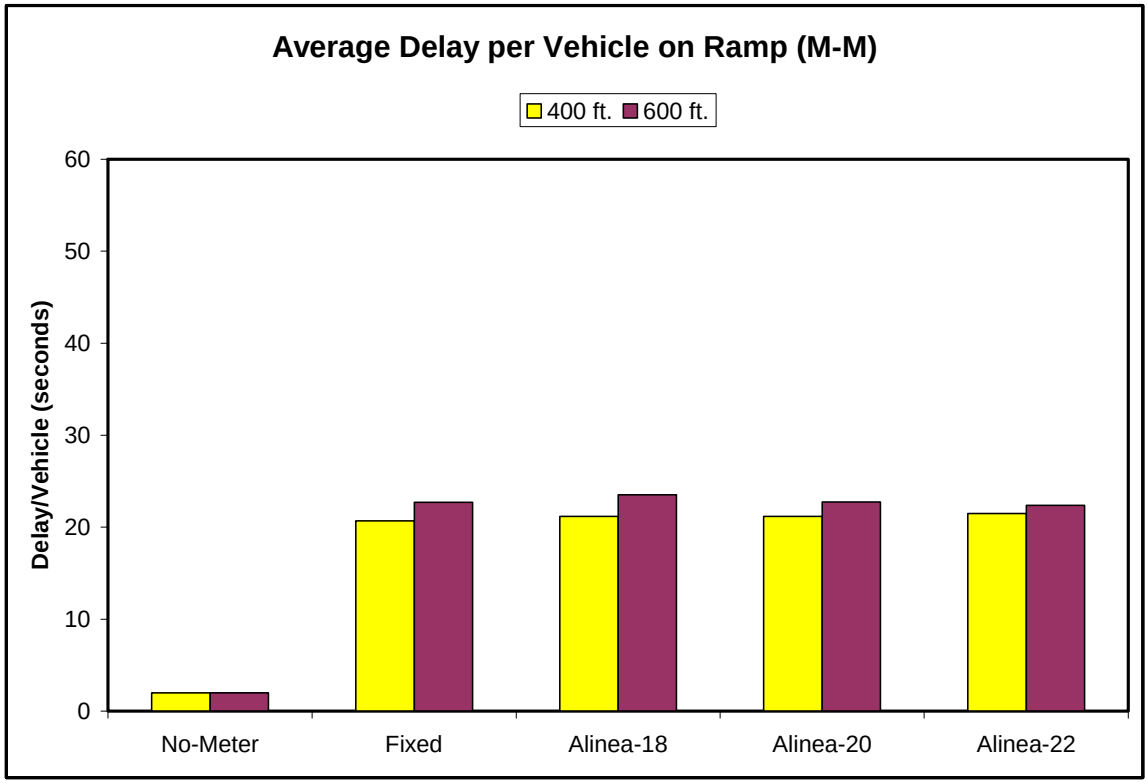

Average Delay per Vehicle on Ramp (H-HM)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22


Average Delay per Vehicle on Ramp (HM-HM)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

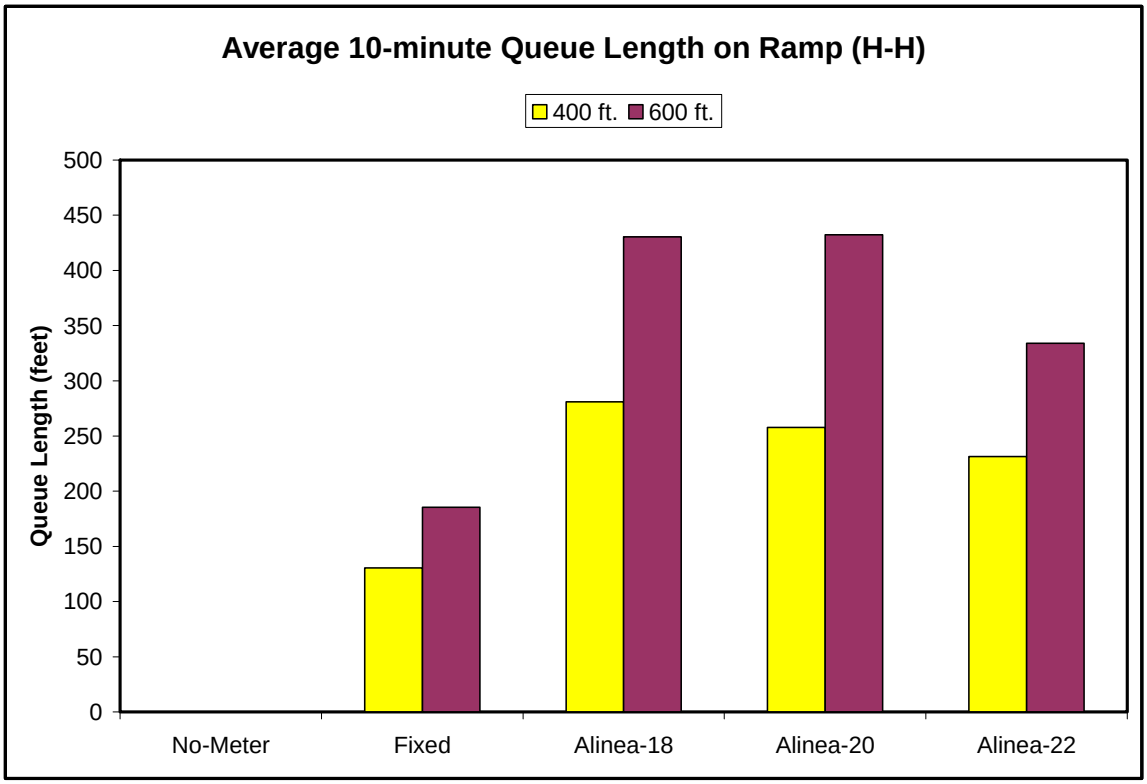

Average Delay per Vehicle on Ramp (M-HM)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

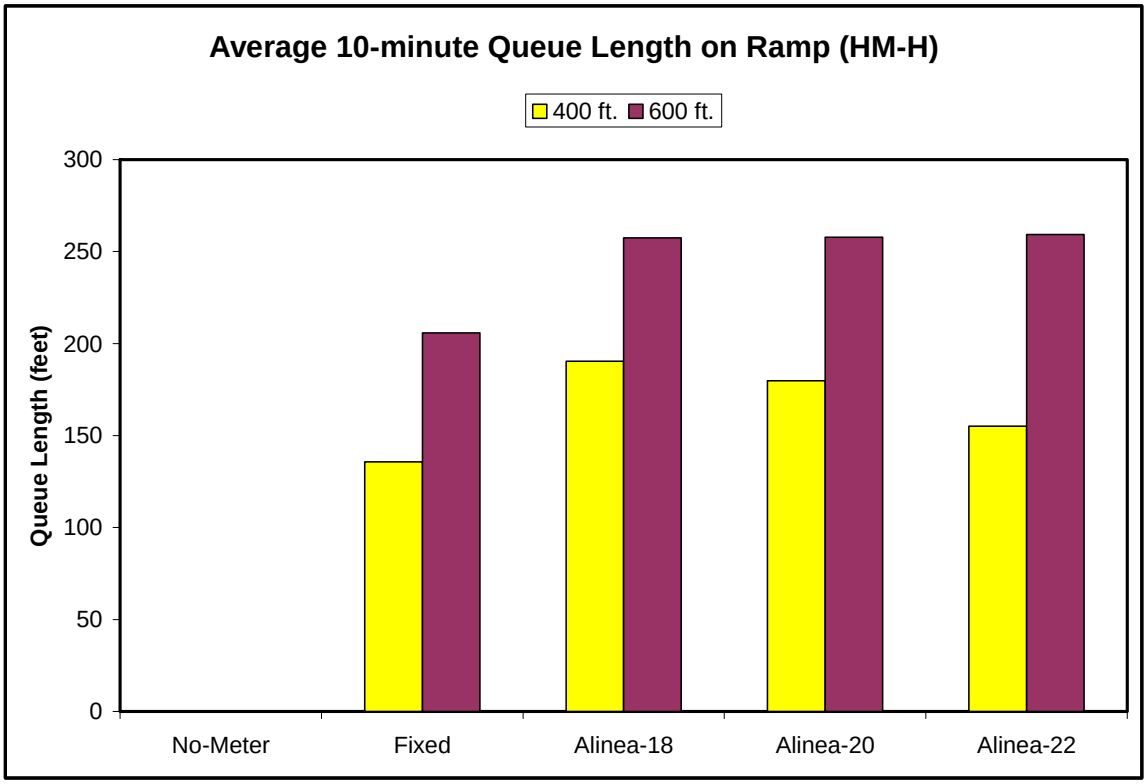

Average Delay per Vehicle on Ramp (H-M)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

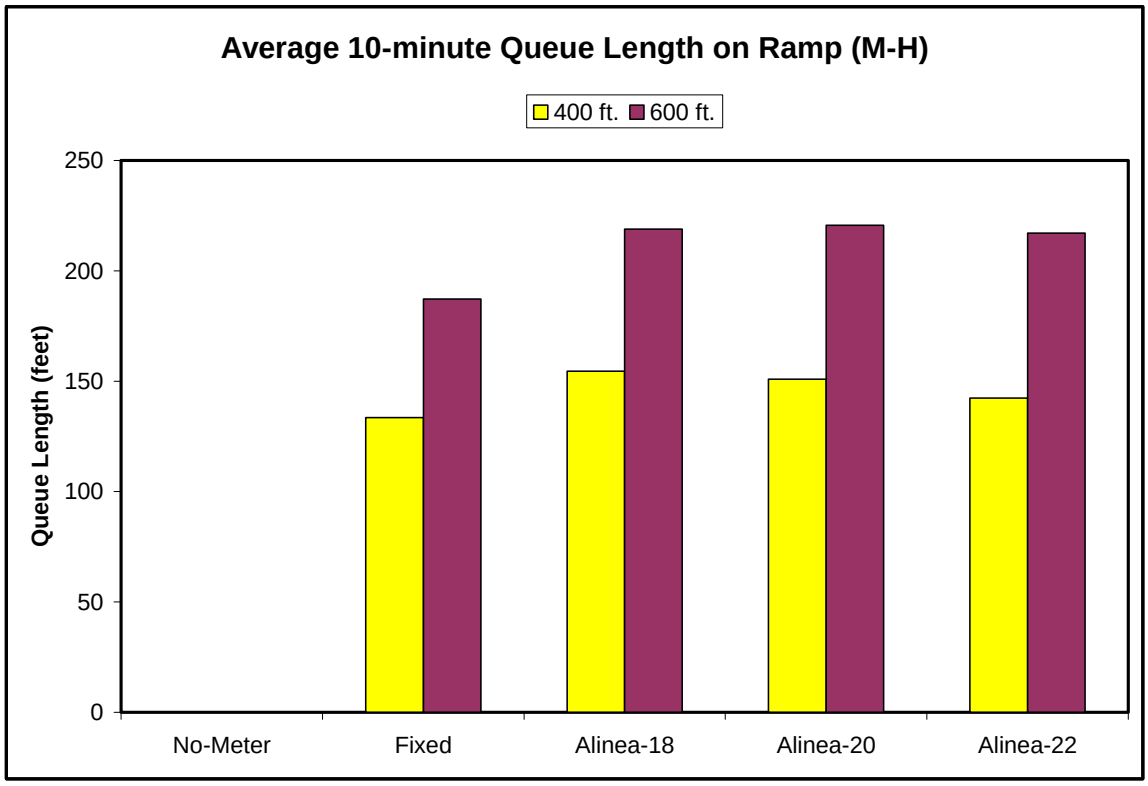

Average Delay per Vehicle on Ramp (HM-M)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

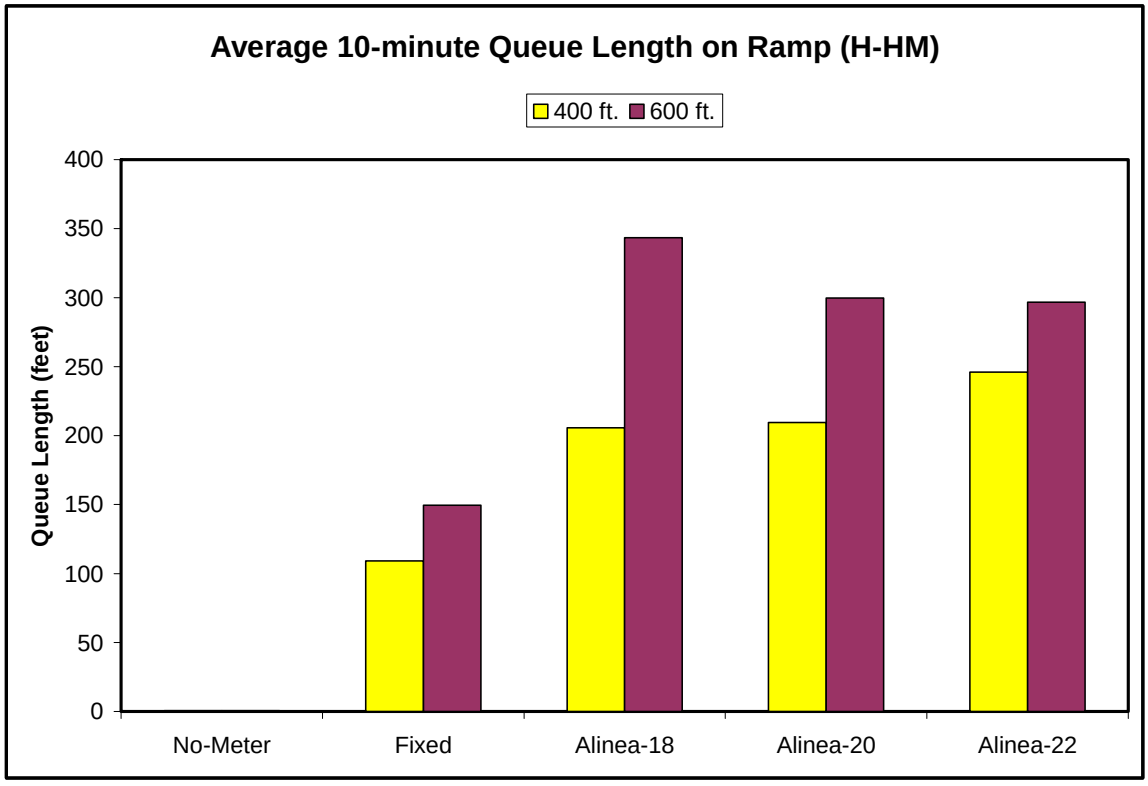

Average Delay per Vehicle on Ramp (M-M)
400 ft.
600 ft.
Delay/Vehicle (seconds)
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

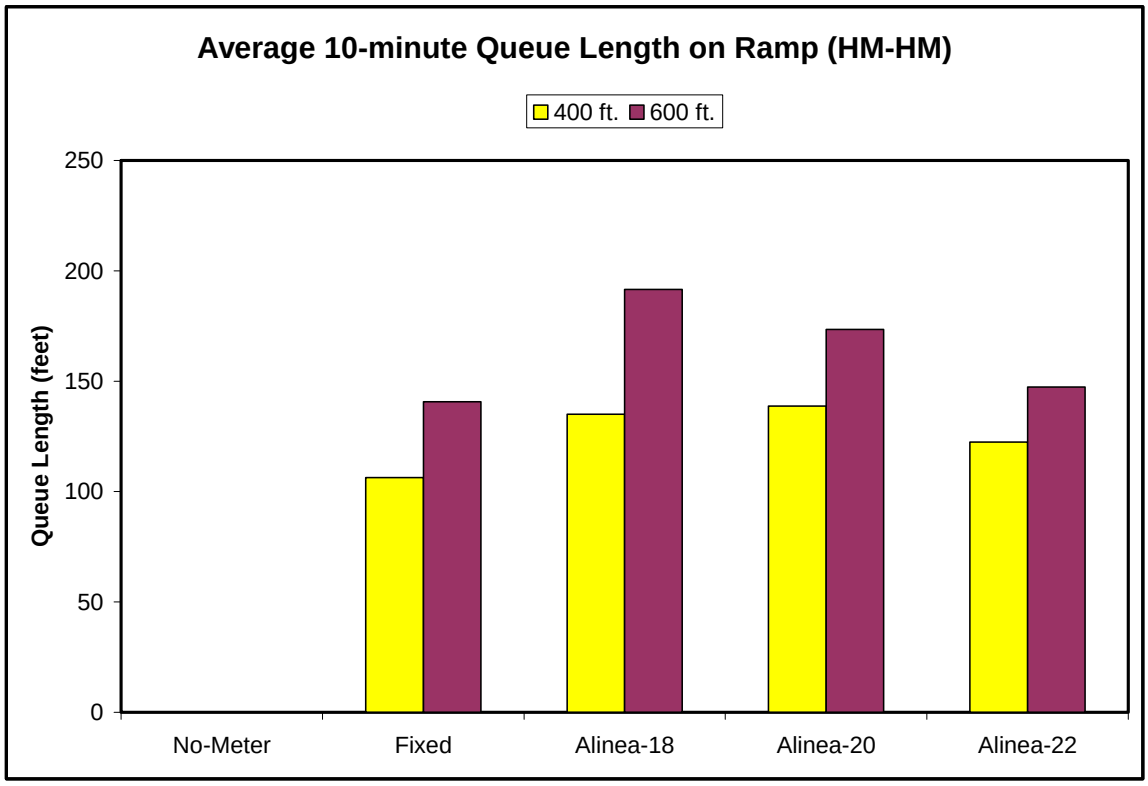
B4. AVERAGE 10-MINUTE QUEUE LENGTH AT RAMP

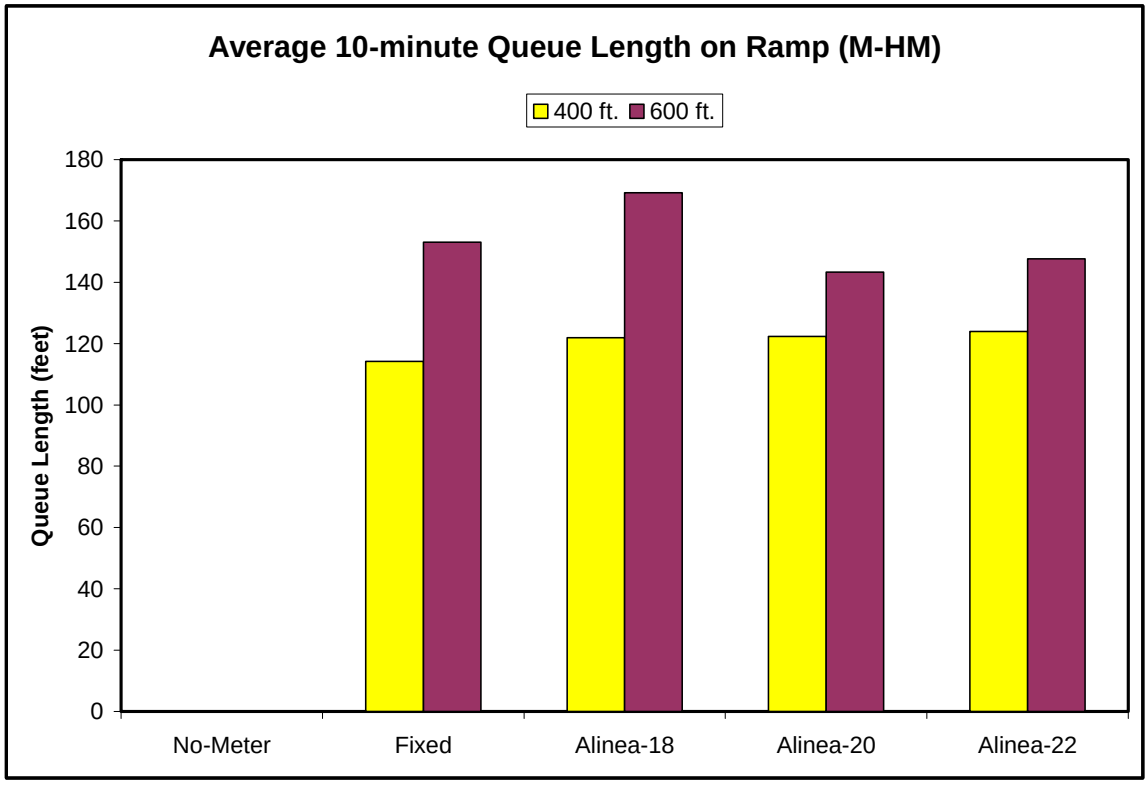


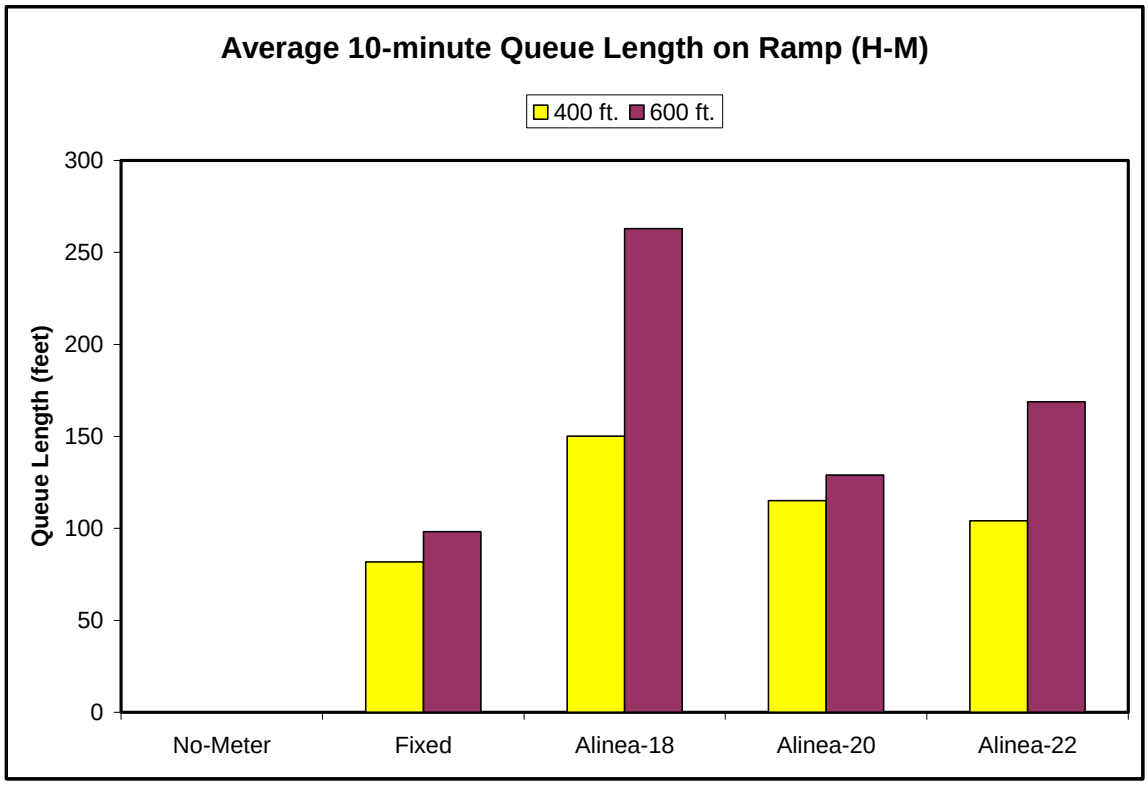


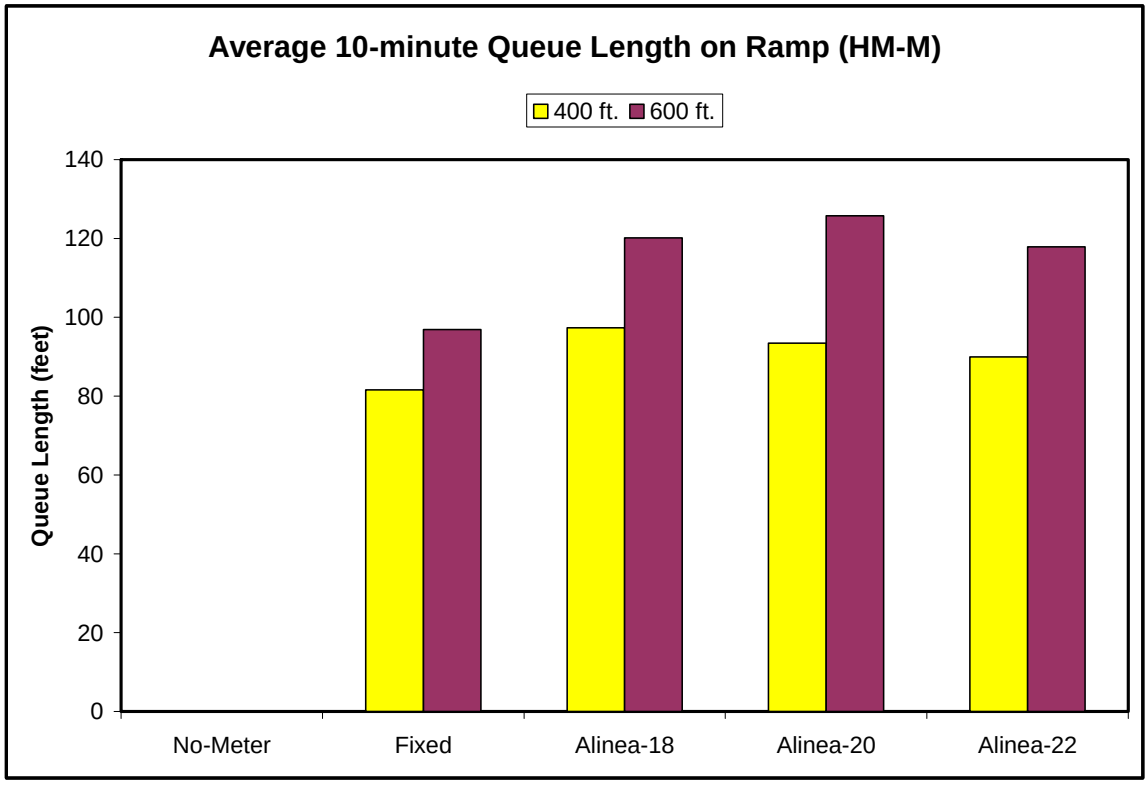

Average 10-minute Queue Length on Ramp (M-H)
400 ft.
600 ft.
Queue Length (feet)
250
200
150
100
50
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

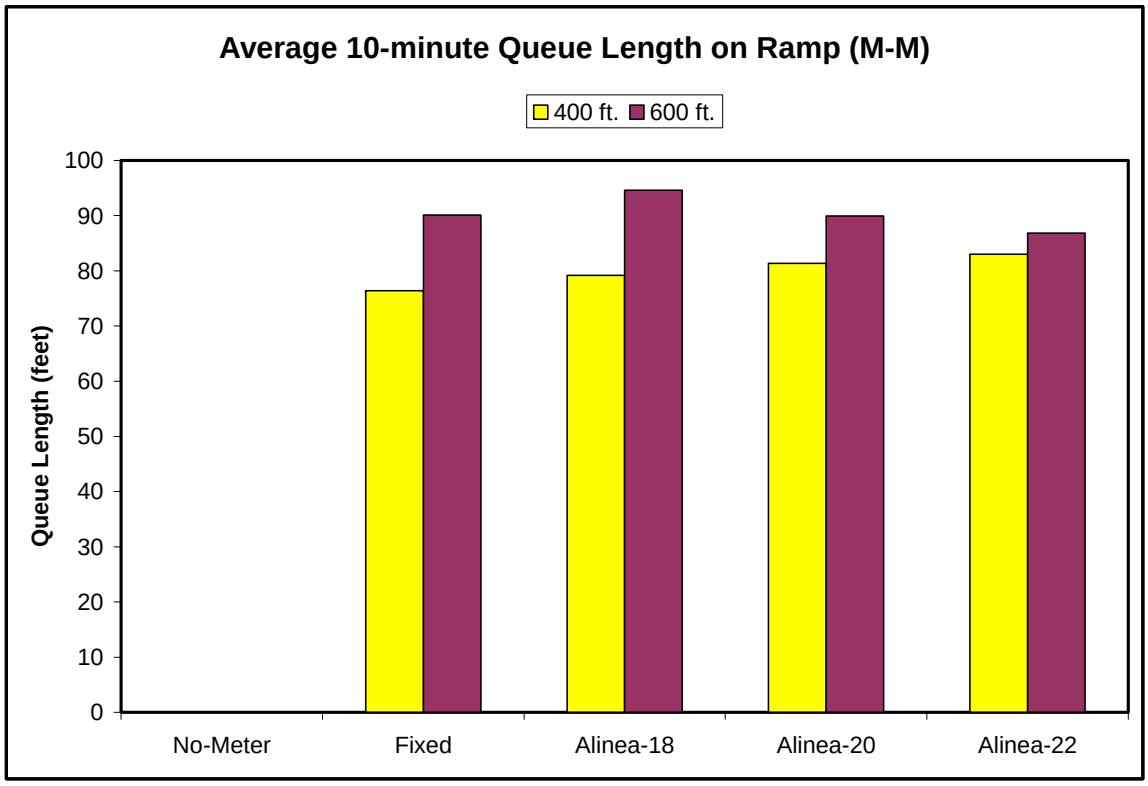

Average 10-minute Queue Length on Ramp (H-HM)
400 ft.
600 ft.
Queue Length (feet)
400
350
300
250
200
150
100
50
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22


Average 10-minute Queue Length on Ramp (HM-HM)
400 ft.
600 ft.
Queue Length (feet)
250
200
150
100
50
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

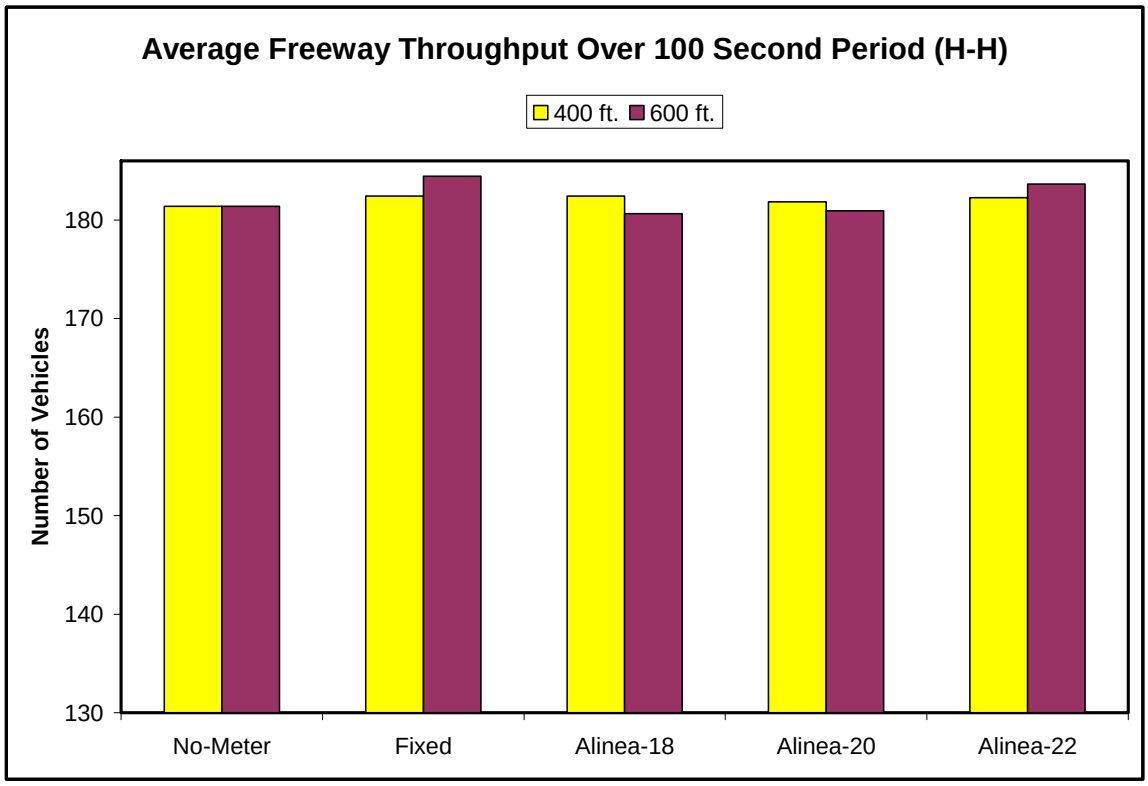

Average 10-minute Queue Length on Ramp (M-HM)
400 ft.
600 ft.
Queue Length (feet)
180
160
140
120
100
80
60
40
20
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

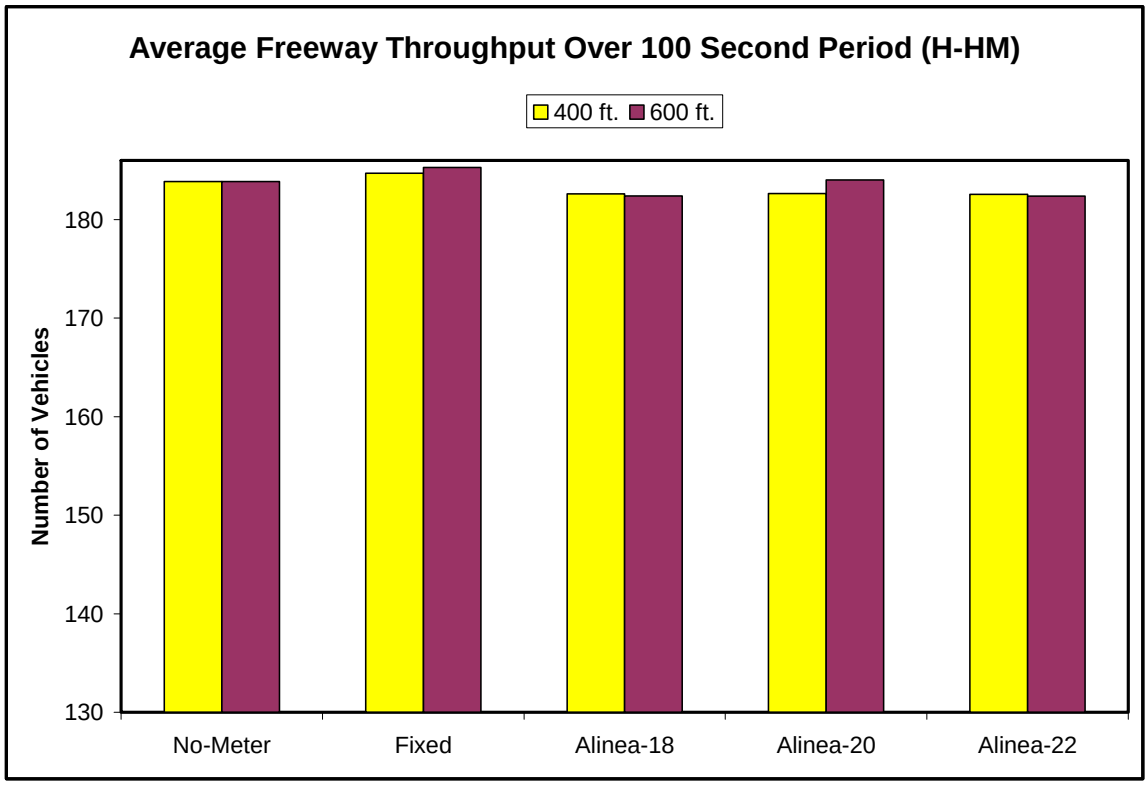

Average 10-minute Queue Length on Ramp (H-M)
400 ft.
600 ft.
Queue Length (feet)
300
250
200
150
100
50
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22


Average 10-minute Queue Length on Ramp (HM-M)
400 ft.
600 ft.
Queue Length (feet)
140
120
100
80
60
40
20
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

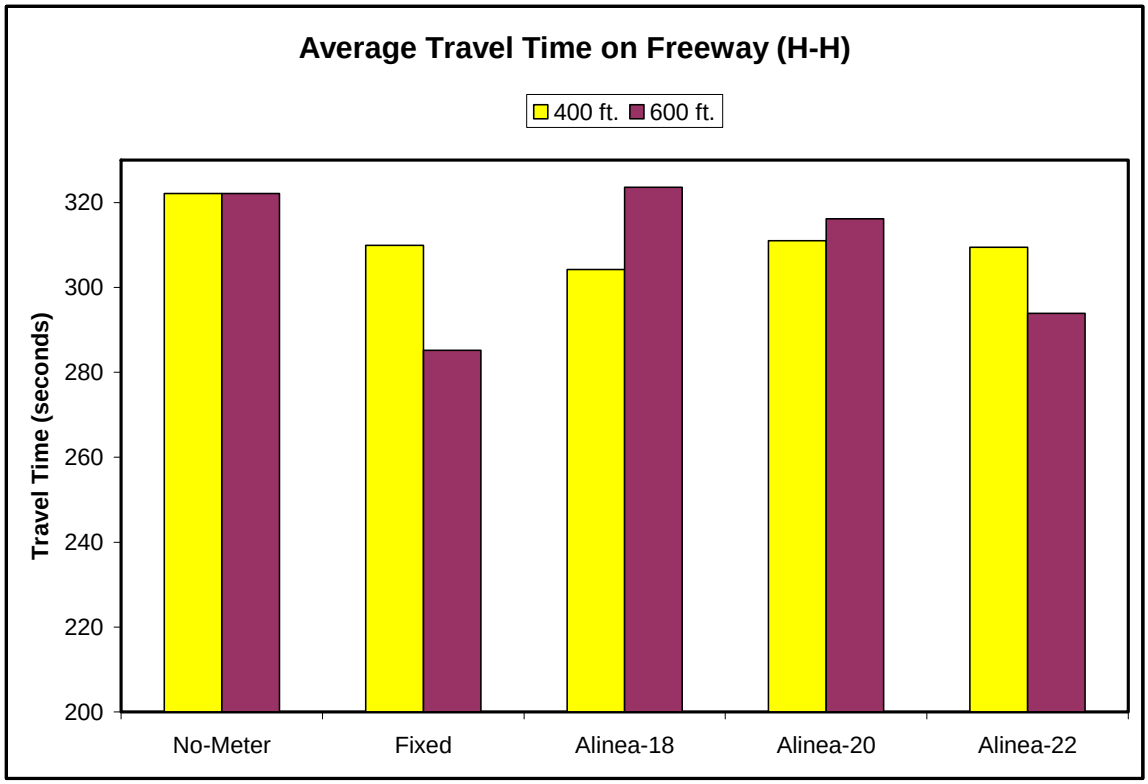

Average 10-minute Queue Length on Ramp (M-M)
400 ft.
600 ft.
Queue Length (feet)
100
90
80
70
60
50
40
30
20
10
0
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22

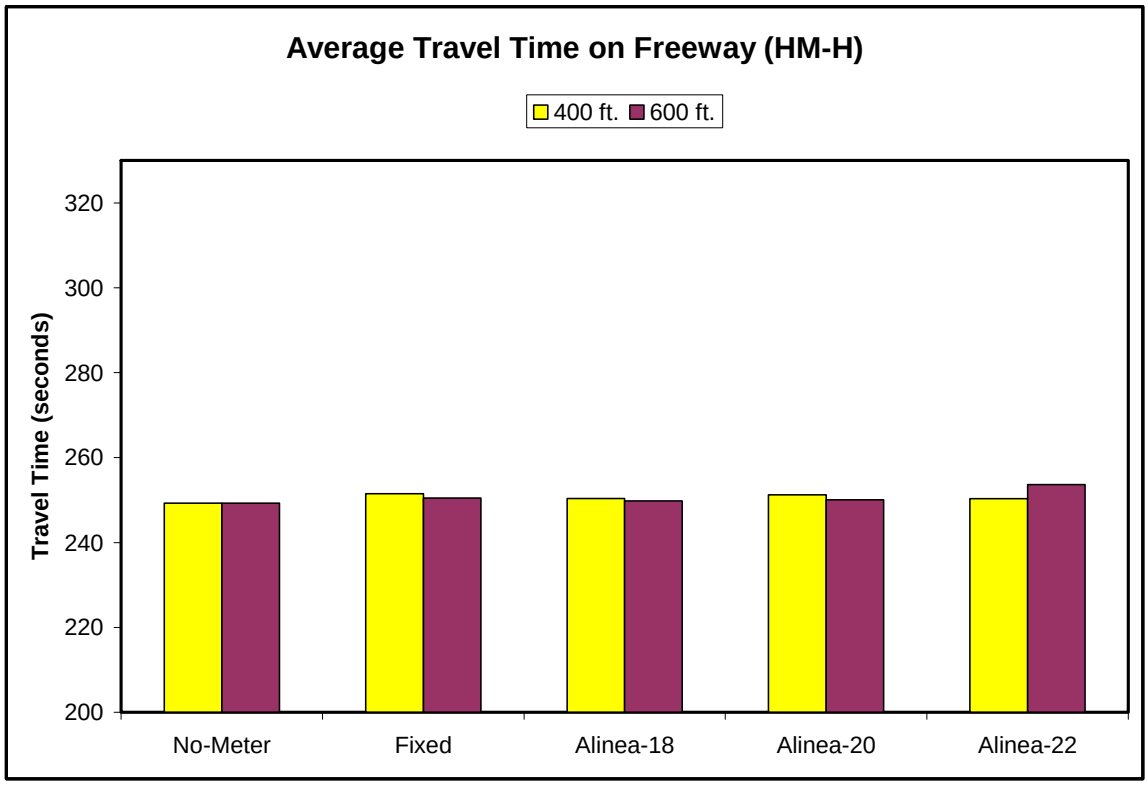
B5. AVERAGE FREEWAY THROUGHPUT FOR HIGH-VOLUME SCENARIOS

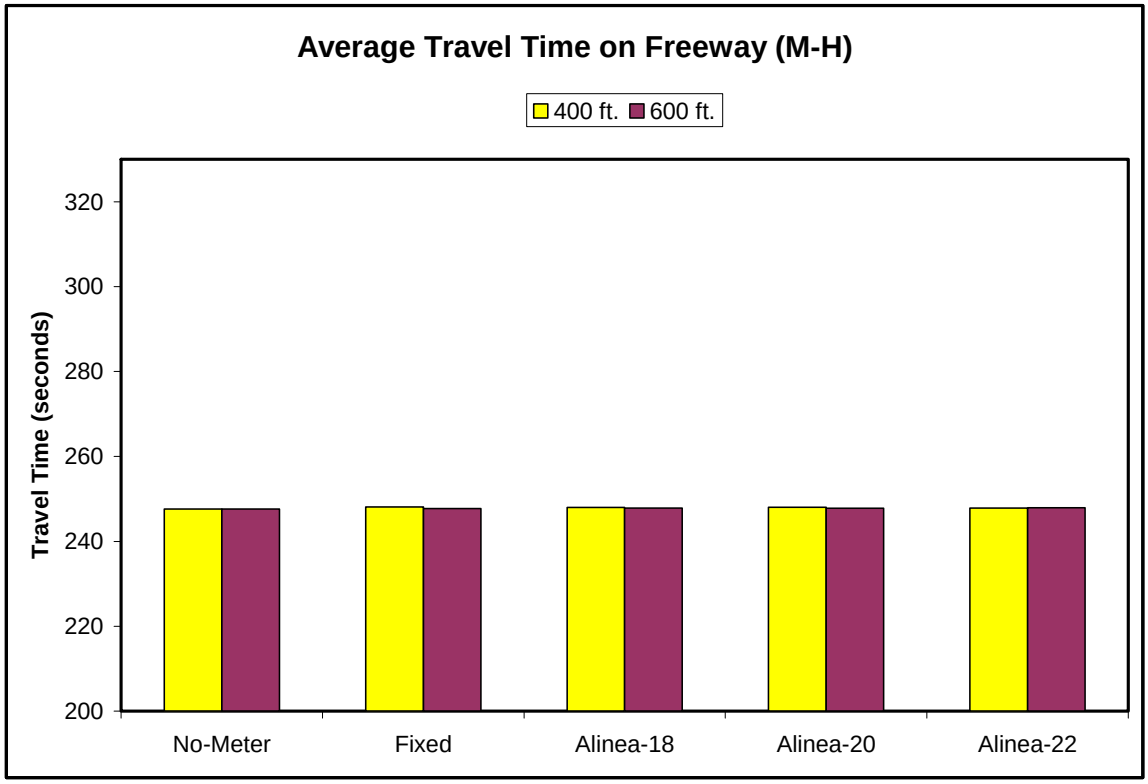


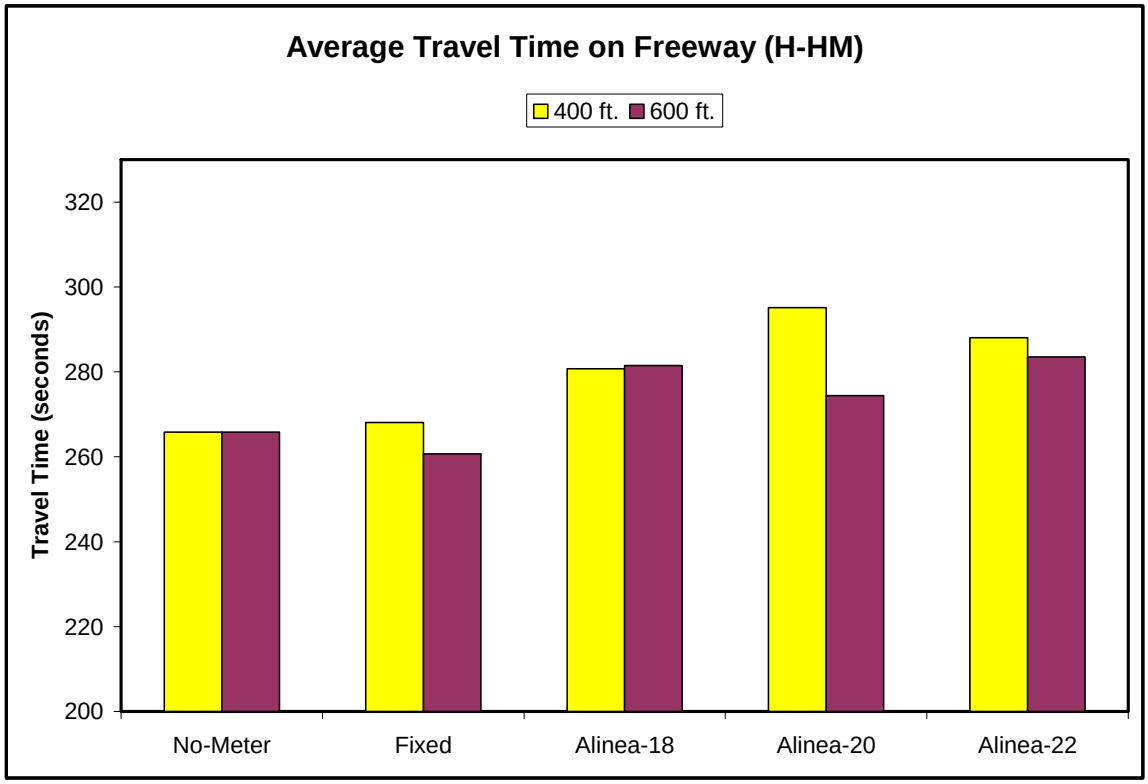


B6. AVERAGE TRAVEL TIME ON FREEWAY






Average Travel Time on Freeway (M-H)
400 ft.
600 ft.
Travel Time (seconds)
320
300
280
260
240
220
200
No-Meter
Fixed
Alinea-18
Alinea-20
Alinea-22


Average Travel Time on Freeway (H-HM)
400 ft.
600 ft.
Travel Time (seconds)
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300
280
260
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200
No-Meter
Fixed
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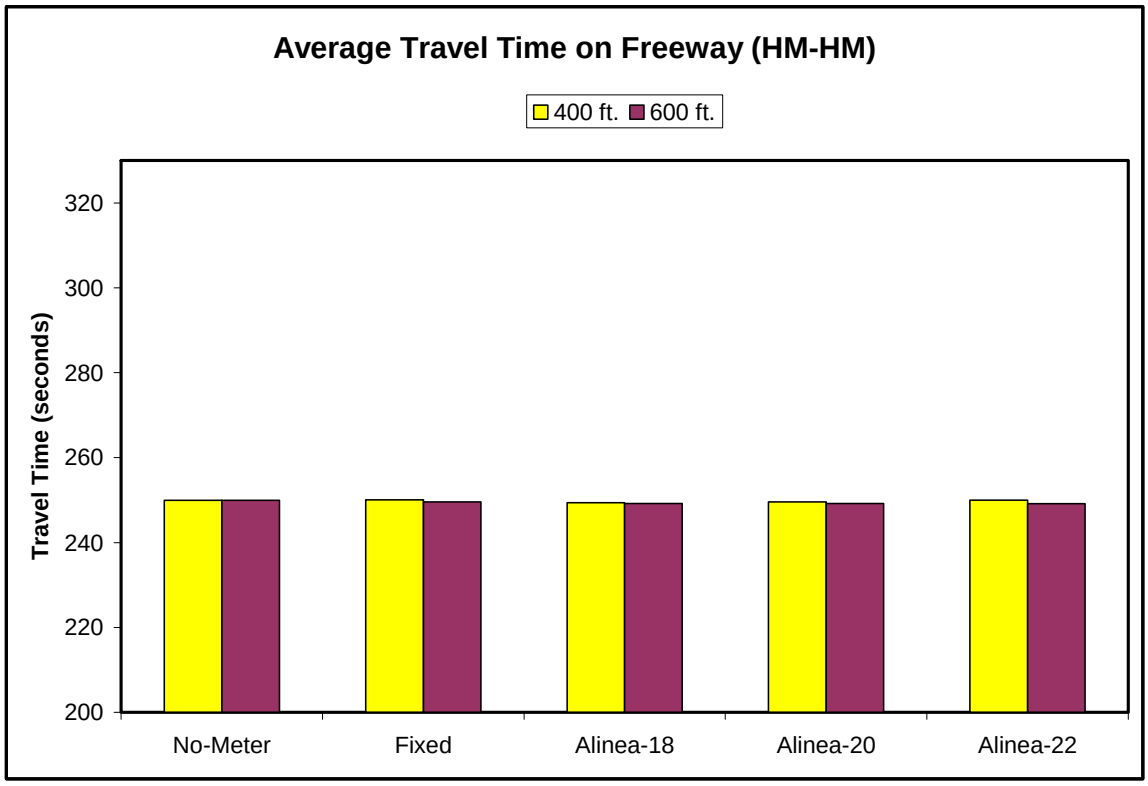
Alinea-22


Average Travel Time on Freeway (HM-HM)
400 ft.
600 ft.
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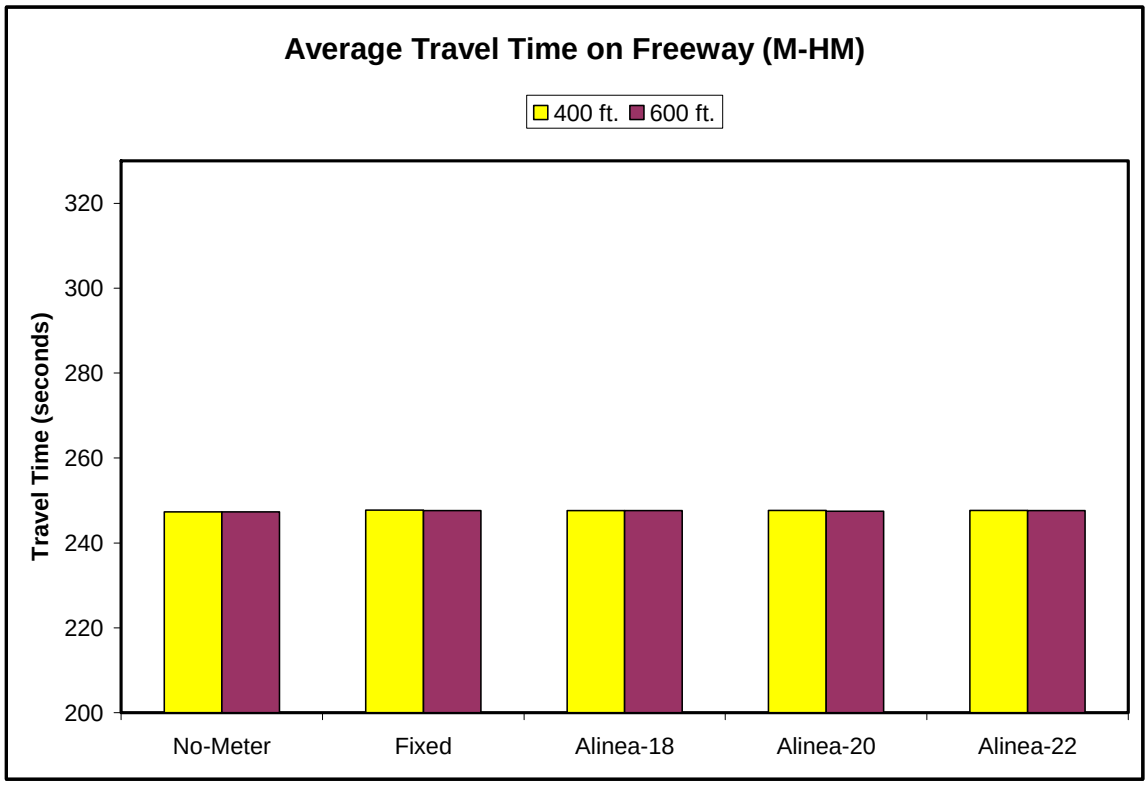
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Fixed
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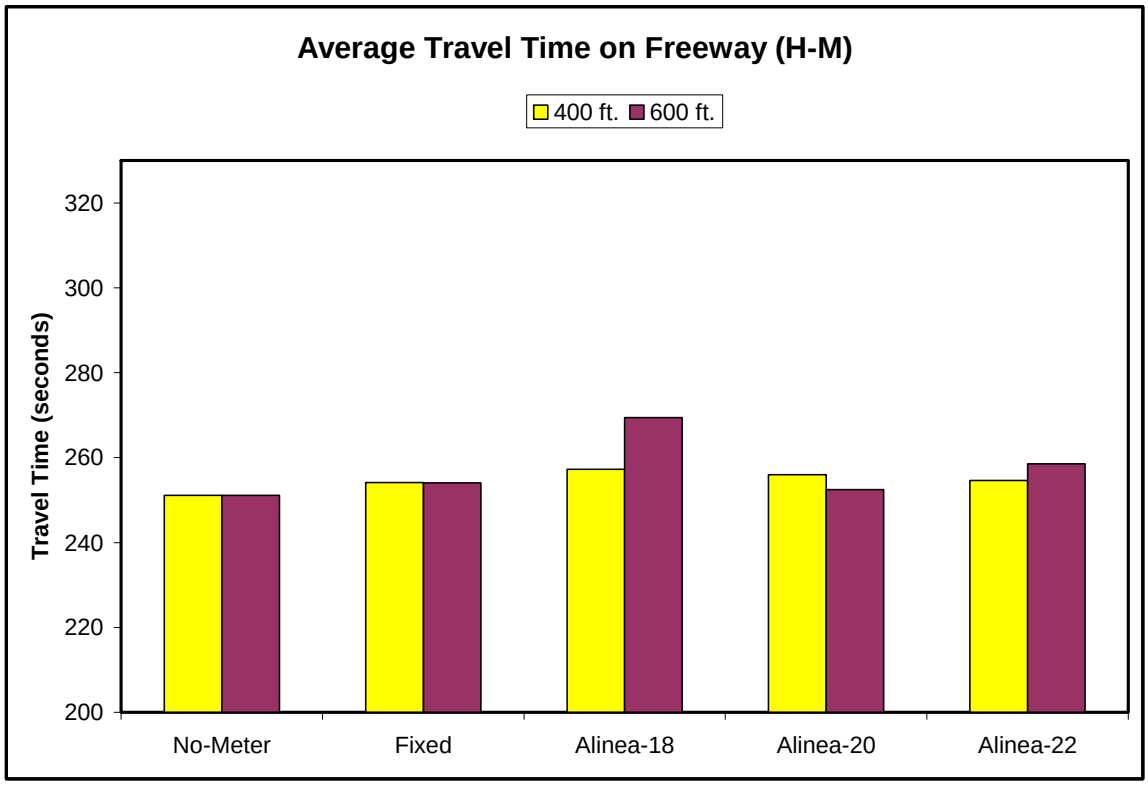
Average Travel Time on Freeway (H-M)
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No-Meter
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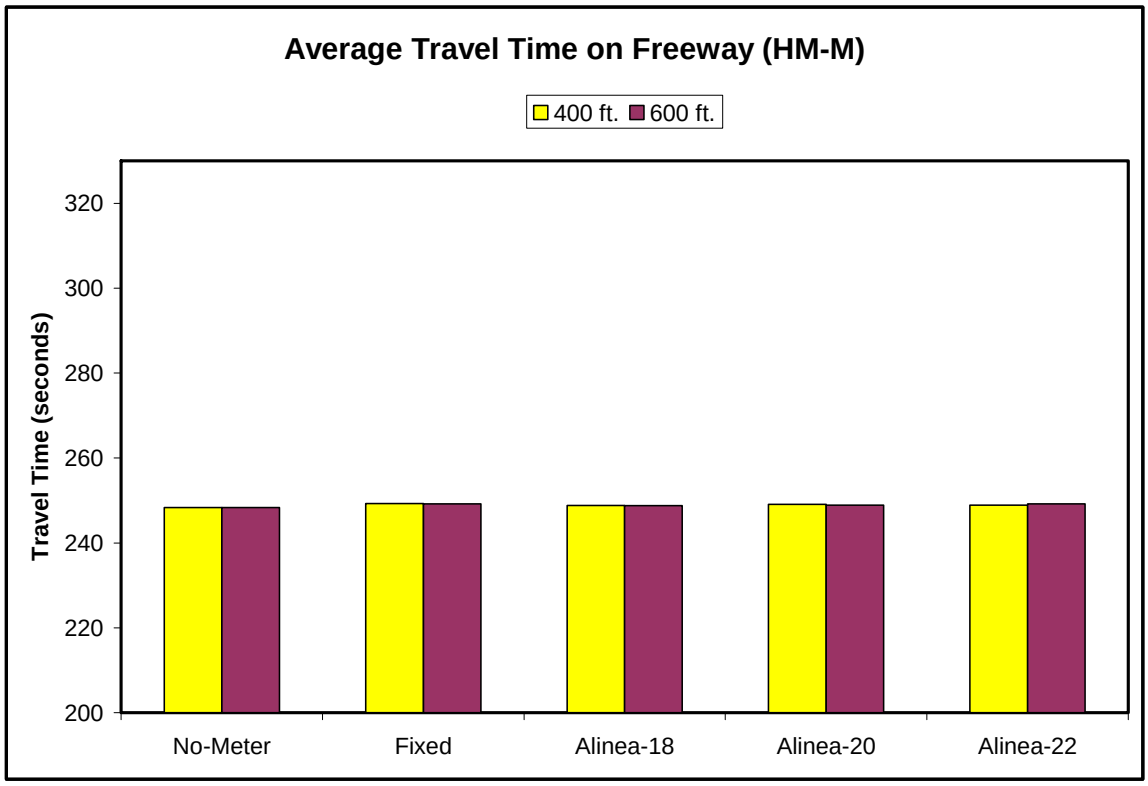
Alinea-20
Alinea-22


Average Travel Time on Freeway (HM-M)
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600 ft.
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No-Meter
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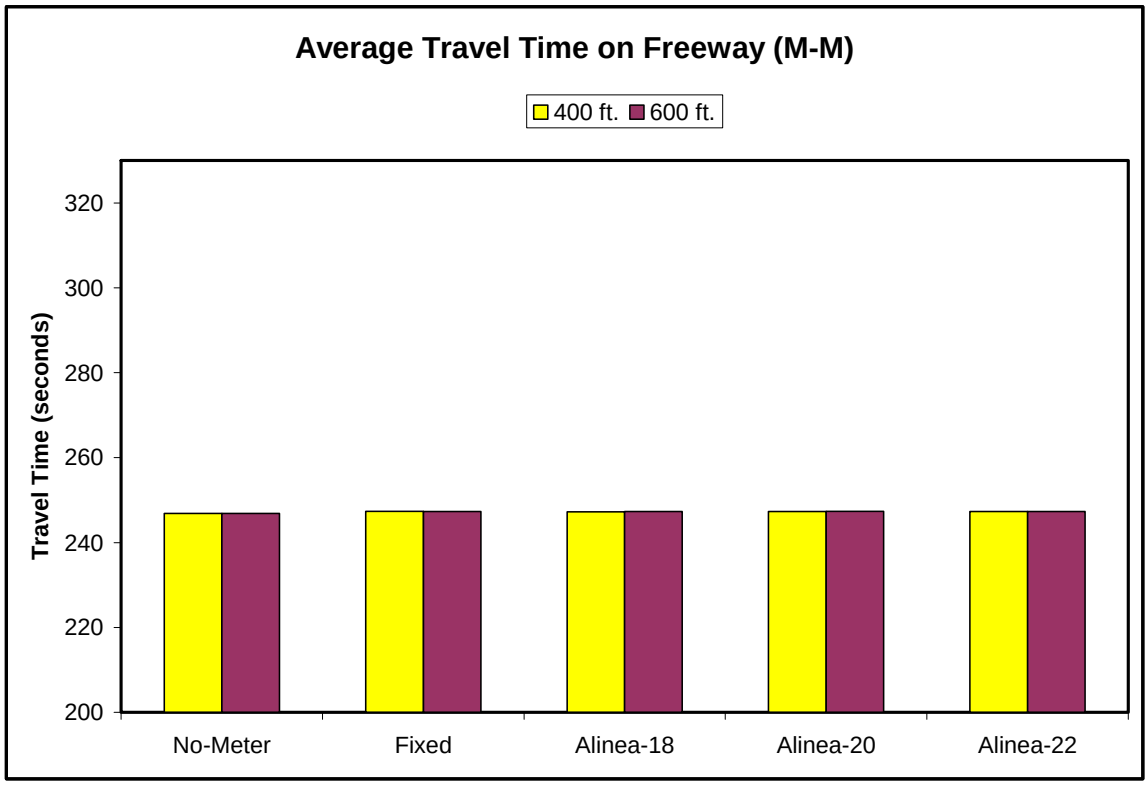
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