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16. Abstract

The primary objective of this project is to develop improved ramp metering design and implementation guidelines for use by TxDOT. These guidelines will provide for more effective design, implementation, and maintenance of ramp-metering systems at existing as well as proposed freeway entrance ramps.

This report documents the results of Tasks 1 and 2 in the proposed work plan. The purpose of these tasks was to study current ramp-metering operations in Texas and other states. Researchers conducted several field studies as part of a review of the ramp metering operations in Texas. This report also presents a summary of results from these field studies. Finally, this report presents a strategy to complete the remaining research.

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RAMP-METERING TECHNOLOGY AND PRACTICE: TASKS 1 AND 2 SUMMARY

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DISCLAIMER

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INTRODUCTION

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

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

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

The purpose of the first objective is to ensure that the total traffic entering a freeway section remains below its operational capacity. The purpose of the second 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 few ramps is usually not sufficient to achieve the first objective. In addition, drivers affected by a small ramp-metering system perceive such a system to be unduly taxing them, favoring those who have entered the freeway at uncontrolled ramps at upstream freeway sections. Thus, ramp-metering should be installed on a sufficiently wide section of a freeway if it is to achieve its expected benefits and keep the motorists happy. When properly installed, ramp metering has the potential to achieve the following benefits:

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

Types of Ramp Metering

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

Single-Lane One Car per Green

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

Single-Lane Multiple Cars per Green

This strategy, also know as bulk metering, allows for two or more vehicles to enter the freeway during each green indication. The most common form of this strategy is to allow two cars per green. Three or more cars can be allowed; however, this will sacrifice the second objective (breaking up platoon). Furthermore, contrary to what one might think, bulk metering does not produce a drastic increase in capacity over a single-lane one car per green operation. This is due to the fact that this strategy requires more green and yellow times as ramp speed increases, resulting in a longer cycle length. Consequently, there are fewer cycles in one hour. For instance, two cars per green strategy requires cycle lengths between 6 and 6.5 seconds and results in metering capacity of 1100 to 1200 VPH. This finding illustrates that bulk metering does not double the benefits and this fact should be noted.

Dual-Lane Metering

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

Ramp-Metering Status in the U.S.

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

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

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

Source: [4]

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

- adequate storage space at the ramp, and
- adequate acceleration distance from the stop-bar to the merge location.

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

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

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

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

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

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

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

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

Ramp-Metering Design and Operational Guidelines

As discussed earlier, over a dozen states are currently using ramp metering as a component of freeway traffic management strategies. Most states use basic implementation guidelines provided in the *Manual on Uniform Traffic Control Devices* (MUTCD) [6]. Some states provide further guidelines in their design manuals. These states include Arizona and Washington. Only a handful of states have specific guidelines readily available for use in designing and operating ramp-metering systems. Even in these cases, a number of design issues are not addressed. The guidelines suggest that these issues be resolved using engineering judgement. This subsection presents three sources that contain useful information.

In 1979, the Illinois DOT published a document dealing with the issue of freeway surveillance and control [7]. This document contains a chapter discussing various issues related to single-lane one vehicle per green ramp-metering operation. Issues discussed include:

- location and number of signal heads,

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

More recently, the Division of Traffic Operations at California DOT (Caltrans) put together specific design guidelines for ramp meters [8]. This document was published in 1989 and contains guidelines for single-, dual-, and three-lane (two regular lanes plus one high occupancy [HOV] lane) metering. Specifically, this document contains the following information.

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

The Washington DOT *Design Manual* dated August 1997 also includes some specific, but very basic, guidelines for ramp metering [9]. Topics discussed include:

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

STATUS OF RAMP METERING IN TEXAS

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

Ramp Meters in Houston

In Houston, ramp meters have been operational for several years. Table 2 provides a summary of operational ramps as of February 2000. All of these ramps operate in an isolated mode on a time-of-day basis. Furthermore, all but two ramps use the single-lane one car per green strategy. One exception is the FM 1960 on-ramp in the inbound direction at SH 290. This ramp has dual-lane metering. The other one is the Kirby ramp in the westbound direction on Highway 59. This is a single-lane ramp with bulk metering.

Table 2: TxDOT Houston District Ramp Metering Locations.

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

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

The Arlington Ramp-Metering System

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

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

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

Field Studies of Operations in Texas

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

Houston Data

I10 WB Blalock Ramp

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

U.S. 290 EB Fairbanks N Ramp

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

U.S. 290 EB Fairbanks N Ramp

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

U.S. 290 EB FM 1960 Ramp (Dual-Lane Operation)

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

- Number of Vehicles: 578
    - Left-lane: 301
    - Right-lane: 277

- Estimated demand: 1156 VPH
    - Left-lane: 602 VPH
    - Right-lane: 554 VPH
- Red violations: 21 times (3.6%)
    - Left-lane: 12 times (4%)
    - Right-lane: 9 times (3.2%)

<u>U.S. 59 WB Kirby Ramp (Bulk Metering)</u>

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

Arlington Data

<u>Abrams Ramp (Flush-on-Green)</u>

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

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

<u>Park Row Ramp (Flush-on-Green)</u>

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

Summary

Field studies show that single-lane, one car per green operation works well when the demand is less than 900 VPH. When ramp demand exceeds 1000 VPH, the effectiveness of this strategy, as indicated by meter availability, is reduced. In such cases, other metering strategies must be considered. The best strategy for high-demand ramps is to implement dual-lane metering. However, it may not be a feasible strategy for high-demand ramps due to the unavailability of space needed for two lanes. When such constraints exist, bulk metering should be considered, since this strategy provides more capacity than the one car per green operations. Furthermore, a comparison between the flush-on-dark and the flush-on-green operations indicates that both modes result in some startup delay at the beginning of the flush period, but the onset of delayed response occurs at different times. In the case of flush-on-dark operation, the delay is generally due to hesitation of the first vehicle; whereas, in flush-on-green operation, the delay results from the second and third vehicles in the queue. Also, researchers observed that, at times, the flush cycle for the Abrams ramp continued for up to 19 seconds in the absence of any vehicle, resulting in an unproductive period at the end of the flush cycle. The controller parameters should be adjusted to minimize the frequency and duration of these unproductive periods.

Texas Ramp Controllers

Unlike most other states in the nation, Texas uses controllers specifically manufactured for ramp-metering operation by Eagle TCS of Austin, Texas. Two versions of Eagle RMC 300 controllers are currently being used in Texas. The older controller runs software version 1.01, dated July 1992. It is simple to use and provides for single-lane operation only. However, it has the following drawbacks:

- Green time for the flush cycle is a preset value of 15 seconds and cannot be changed by the user. Depending on storage space and traffic demand, this may result in a less productive or insufficient startup cycle.

- The startup cycle uses the same values for yellow and red times programmed by the user for the metering cycle. Therefore, the user must carefully select these values, especially the yellow time, to suit the driver expectancy at the end of both these cycles.

The RMC 300 98 version 2.00a (dated February 1998) controller provides several enhancements and is functionally compliant with the draft National Transportation Communication Interface Protocol (NTCIP) standard [10]. This version of the controller is being used on all five ramps in Arlington and some ramps in Houston. Additional features of this controller include functionality to:

- meter up to four lanes;
- program separate green, yellow, and red times for metering and startup cycles;
- adjust metering rates using data from an intermediate queue detector;
- provide a wide range of responsiveness in detecting and responding to a queue; and
- flush in “dark” or “green”.

Consequently, the new version of the RMC 300 controller is also more difficult to program. The simplest way to program this controller is by using the accompanying software provided by the manufacturer. Once the full database has been coded in this DOS-based program, the user can download it to the controller using a serial cable. Furthermore, there is a need to develop a course for training TxDOT staff in the use of this controller.

REMAINING TASKS AND CURRENT RESEARCH DIRECTION

An earlier section provided some details about the ramp metering guidelines developed by some other states in the nation. We can draw from these guidelines and develop a set of guidelines for use in Texas by taking into consideration local needs and priorities. These include the utilization of features available in the Texas Ramp Controller. To this end, we have developed and are using two sets of tools in order to facilitate the research. This section describes these tools.

Spreadsheet-Based Mathematical Models

We programmed a set of mathematical models in a pair of spreadsheets. The purpose of these models is to study the theoretical behavior of ramp metering under various conditions. These issues include:

- storage space, including location of meter and locations of detectors; and
- performance of various ramp-metering strategies under:
  - different levels of ramp demand,
  - various conditions on the freeway, and
  - different settings of controller parameters.

Preliminary testing of these models shows that they provide a good representation of the expected ramp-metering mechanism under various traffic and control scenarios. The next stage of research consists of a more thorough verification/validation of these models using the field data described earlier. However, before this can be done, we need to obtain geometric and controller data for each of these ramps. These data include:

- length of ramp;
- locations of loops, especially the excessive queue detector and the stop bar; and
- database from each controller (signal timing parameters and detector settings).

Once this work is completed, the analysis will be expanded by utilizing a hardware-in-loop simulation setup to study the behavior of the actual controller under various conditions described above.

Hardware-in-Loop Testbed

A hardware-in-loop setup provides the capability to study the behavior of a real traffic controller using simulated traffic data (Figure 1). The testbed consists of an RMC 300 controller connected to the TexSim model running on a personal computer. TexSim is a microscopic simulation model developed by TTI staff for analyzing real-time systems using actual hardware. The second phase of the current research will use this setup.

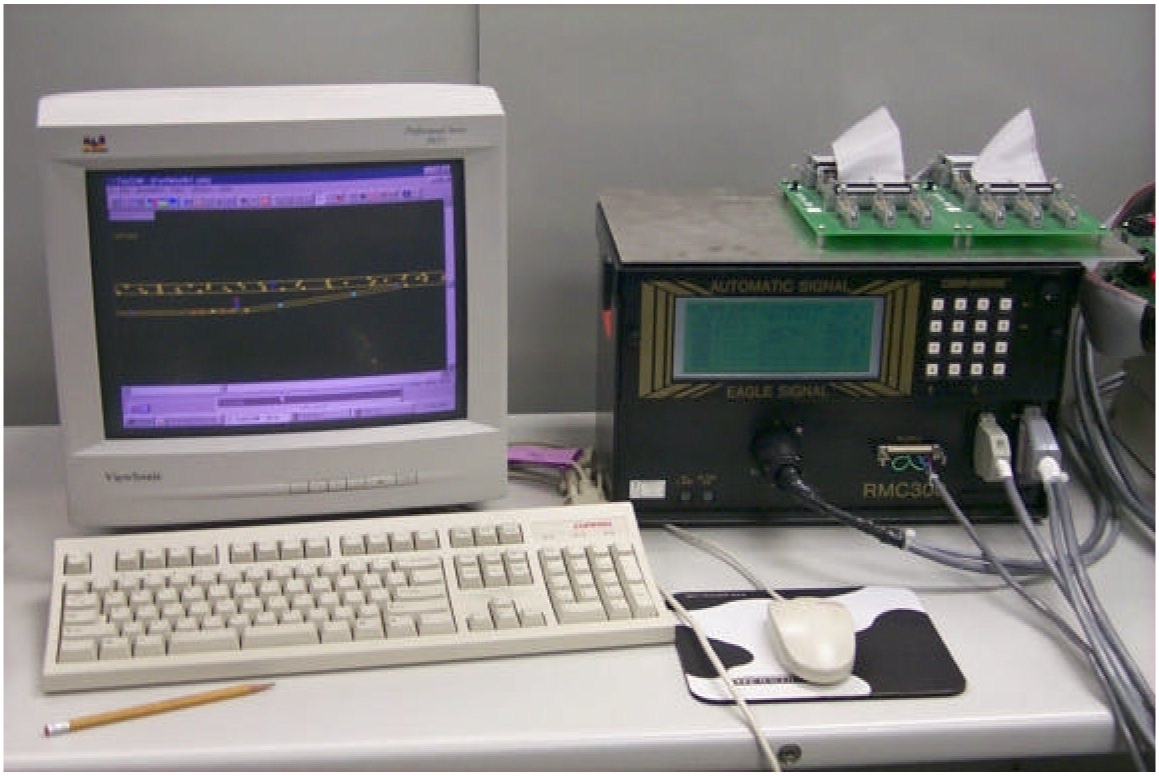

Figure 1: Hardware-In-Loop Testbed.

REFERENCES

1. May, A. D. *Improving Network Operation with Freeway Ramp Control.* 43rd Annual Meeting of the Highway Research Board, Washington, D.C., 1964.

2. McCasland, W. R., D. R. Drew, and J. A. Wattleworth. *Houston Freeway Surveillance and Control Project.* Proceedings, U.S. Bureau of Public Roads, Program Review Meeting, Gaithersburg, MD, 1966.

3. Robinson, J. and M. Doctor. *Ramp Metering Status in North America – Final Report.* Report No. DOT-T-90-01, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., September 1989.

4. Piotrowicz, G. and J. Robinson. *Ramp Metering Status in North America – 1995 Update.* Report No. DOT-T-95-17, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., June 1995.

5. Rigert, J. *Drivers Get Benefits But May Pay a Price.* Special Report on Ramp Meters, Star Tribune, Twin Cities, Minnesota, November 28, 1999.

6. *Manual on Uniform Traffic Control Devices.* 1988 Edition, U.S. Department of Transportation, Washington, D.C., 1988.

7. McDermott, J. M., S. J. Kolenko, and R. J. Wojcik. *Chicago Area Expressway Surveillance and Control: Final Report.* Report No. FHWA-IL-ES-27, Illinois Department of Transportation, Springfield, Illinois, March 1979.

8. *Ramp Meter Design Guidelines.* Division of Traffic Operations, Office of Traffic Operational Systems, Caltrans, July 1989.

9. *Design Manual.* Design Office, Washington Department of Transportation, Olympia, Washington, August 1997.

10. *RMC 300 Ramp Controller Unit Product Manual, Rev. 8.00.* Eagle Traffic Control Systems, Austin, Texas, 1997.