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16. Abstract

With the goal of improving traffic flow and safety on urban freeways, the Texas Department of Transportation initiated a program of installing ramp metering on most freeways in Houston. This research provides advanced methods and strategies for implementing ramp metering, called flow signals in Houston, which will enhance motorist compliance with traffic control and reduce police enforcement requirements.

Report 1295-1 describes the advanced marketing and information strategies employed in preparation for initial turn-on ramp metering in Houston to enhance driver understanding, support, and compliance, given that single-lane ramp metering was used initially.

Report 1295-2 (this report) describes new dual-lane ramp metering strategies recommended for further enhancing freeway traffic operations and driver compliance, and reducing the need for unnecessary or costly advanced enforcement techniques of ramp metering operations. New operational tactics and adaptive detection strategies have been added to advanced multilane metering strategies deployed in the northwestern United States. The design details, both geometric and traffic control, are illustrated for a possible dual-lane demonstration site along the Katy Freeway (IH-10) at Gessner Street in west Houston, Texas.

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A DUAL-LANE FLOW SIGNAL PLAN FOR TEXAS

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IMPLEMENTATION STATEMENT

The Texas Department of Transportation (TxDOT) is currently investigating alternative geometric, traffic control, and operation design strategies for operating flow signals (or ramp meters) on high-volume frontage road/freeway slip ramps with variable traffic arrival patterns. This report investigates the feasibility of designing and operating dual-lane flow signals on urbanized freeways within Texas.

The intent of this research is to provide TxDOT with a dual-lane flow signal implementation plan to initially field test this innovative freeway traffic management strategy by 1998 and hopefully implement this flexible system as appropriate on all urbanized freeways throughout Texas. To achieve this goal, a full-scale demonstration project for a dual-lane flow signal was developed, as illustrated for the Gessner Street on-ramp along the eastbound Katy Freeway (IH-10) in Houston, Texas.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the factual content and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes.

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SUMMARY

The primary objective of this report is to perform a feasibility analysis of the design and operation of dual-lane flow signals on freeway/frontage road slip-ramps and provide an implementation plan for demonstrating dual-lane flow signals in Texas. This objective is based on existing operational issues experienced by the Texas Department of Transportation (TxDOT) in regards to single-lane flow signal operations in Houston, Texas, and the geometric issues associated with freeway/frontage road slip-ramps on urbanized freeways. These operational and geometric issues of single-lane flow signal operations include:

- The inability to effectively meter high-volume (i.e., 1,000 vehicles per hour or greater) on-ramps in metropolitan areas;
- Queue spillbacks onto the upstream frontage road, off-ramp, and/or signalized interchange terminals, which create a higher possibility of accidents;
- A lack of operational flexibility in providing preferential lanes for high-occupancy vehicles and high-volume discharge rates; and
- The inability to widen or lengthen ramps to accommodate the storage, acceleration, and merge areas of a metered on-ramp because of constraints related to the distance between the freeway and frontage road.

Based on the geometric, traffic control, and operational design elements investigated as part of this research, the researchers determined that dual-lane flow signals can be designed and operated effectively on frontage road/freeway slip-ramps in the state of Texas. In addition, the recommended dual-lane flow signal design strategy can improve the operation and safety provided by the single-lane flow signal design used today. The dual-lane flow signal design strategy provides the following benefits as compared to the traditional single-lane flow signal design strategy:

- The ability to meter up to approximately 1,800 vehicles per hour compared to the 900 vehicles per hour limitation associated with single-lane configurations;
- The ability to store 100 to 130 percent more vehicles in the same queuing distance;
- The enhanced opportunity to provide preferential lane assignments for carpools, vanpools, and transit;

- The flexibility to accommodate various on-ramp volumes and arrival patterns; and
- A reduction in flow signal violations by ramp motorists.

The proposed dual-lane flow signal design concept, as illustrated for the Gessner Street on-ramp located along the eastbound Katy Freeway (IH-10) in Houston, is recommended to be developed into a field demonstration project. This demonstration project is recommended to further evaluate the geometrics, traffic control, and traffic operations associated with dual-lane flow signal operations on frontage road/freeway slip-ramps before more extensive deployment of multiple-lane flow signals in Texas is considered. This recommendation is based on the operational successes of dual-lane flow signals noted for traditional diamond- and parclo-type interchanges located in other states and upon the analyses conducted as part of this research.

1. INTRODUCTION

In response to continued increases in traffic congestion on urbanized freeways in Texas, the Texas Department of Transportation (TxDOT) is evaluating a variety of design, control, and operation strategies in an attempt to increase the efficiency of the current urban freeway system through ramp metering. With the recent opening and operation of the advanced Transportation Management Centers (TMCs) in Houston (TranStar) and San Antonio (TransGuide), ramp metering will again serve a prominent role in Texas freeway management strategies. Ramp metering of freeways allows TMCs and jurisdictions an opportunity to regulate the amount of traffic entering the freeway system based on the ability of the freeway to handle additional traffic (i.e., the available capacity). This regulation is accomplished by signalizing the on-ramps to the freeway and monitoring the amount of traffic traveling on the freeway using inductive loop detectors. The metering of traffic at the on-ramps also provides a uniform distribution of traffic entering the freeway traffic stream, which allows for improved freeway efficiency and enhanced use of available capacity. Ramp metering can also provide incentives for increased use of carpools, van pools, and public transit through preferential lane assignments (i.e., high occupancy vehicle [HOV] bypass lanes) that offer time savings to HOVs at freeway on-ramps (*1*). Finally, ramp metering can provide an effective freeway management tool for TMC controllers to use when responding to freeway incidents.

Ramp meters have been used in a variety of freeway applications in Texas, beginning in the mid 1960's. Traditional single-lane ramp meters were installed in Austin, Dallas, Fort Worth, Houston, and San Antonio. However, during the past two decades, most of these ramp meters were removed during extensive freeway reconstruction projects (*2*). Due to very recent implementation efforts, TxDOT now operates and maintains approximately 54 single-lane ramp meters in Houston along Interstate 10 (Katy Freeway), Interstate 45 (North Freeway), and U.S. 290 (Northwest Freeway), and one single-lane ramp meter on U.S. Highway 281 in San Antonio. The majority of these ramp metering systems are controlled by an RMC-300 controller unit (manufactured by Eagle Signal), which was introduced in 1992 (*3*). In general, TxDOT freeway managers feel that properly operated ramp meters provide an effective tool to manage freeway congestion during peak hour periods. Several studies conducted by the Texas Transportation Institute (TTI) and TxDOT have shown improved freeway operations and safety after the installation of ramp meter signals (*4*). However, concerns have been expressed by TxDOT regarding the operational limitations of single-lane ramp metering on high-volume ramps (i.e., for volumes in excess of 900 vehicles per hour).

As the number of motorists entering Texas freeways during the rush hours has grown, arrival rates at several on-ramps now exceed 1,200 vehicles per hour. These high volume ramps, when combined with the current limited metering capabilities of the RMC-300 controller, may result in continuous queues that spill back onto the upstream frontage roads and intersections. These spillback conditions may also pose potential operational and safety problems. To address these issues, the operation of several single-lane flow signals in Houston is discontinued during portions of the peak period to clear excessive queues. The need to turn off the meters during peak periods is primarily attributed to the typical frontage road/freeway slip-ramp configuration used in Texas, which provides a minimal queue storage area upstream of the flow signal. In addition, the current RMC-300 controller specification can only meter up to 1,161 vehicles per hour. To address these issues, an effective high-volume flow signal design specification and operational control system are needed to provide a more efficient freeway traffic management program for Texas.

BACKGROUND

TxDOT is in the process of installing new single-lane flow signals that will provide the necessary communication technology to operate an integrated ramp metering system along large sections of urbanized freeway in several metropolitan areas. To date, TxDOT has installed 54 single-lane flow signals in Houston; 106 additional meters are expected to be operational by the end of 1998. TxDOT is also planning to install five flow signals in Arlington over the next year. In conjunction with this effort, TTI has developed the Ramp Adaptive Metering Bottleneck Optimization (RAMBO) program to provide freeway managers with interactive tools used to develop and evaluate flow signal timing plans. TxDOT's primary objective in the latest installment of ramp metering systems is to link the newly developed TMCs with the individual flow signals to provide a fully interactive freeway management system that can effectively observe and manage entire freeway systems.

As the metropolitan areas throughout Texas continue to advance in their implementation of freeway management strategies, the need to develop high-volume ramp metering capabilities is paramount to providing TMCs and TxDOT with the essential tools to effectively manage freeway-related congestion. The current single-lane ramp metering design and specifications do not provide an effective freeway management tool at on-ramp locations where traffic demands exceed 900 vehicles per hour. Single-lane flow signals with signal cycle lengths of less than four seconds (i.e., the headway corresponding to a metering discharge rate of 900 vehicles per hour) have been found to be ineffective in Texas and throughout the nation because this minimal headway does not provide sufficient time to bring vehicles formed in a single lane to a complete stop at the flow signal stop-bar. Therefore, to provide TxDOT and the TMC controllers with an effective freeway management tool, a high-volume ramp metering system should be developed.

Multiple-lane ramp meter systems used in California, Minnesota, Oregon, Washington, and other states have been found to provide effective ramp meter control strategies, including the capability to meter on-ramp traffic demand volumes of up to approximately 1,700 vehicles per hour (*5,6,7,8*). These multiple-lane systems include single-lane and dual-lane ramp meters with and without HOV-bypass lanes. In addition, these ramp meter systems are typically installed and operated on traditional diamond- or parclo-type interchange on-ramps. These types of interchanges normally provide a sufficient amount of distance for vehicles to accelerate from the ramp meter stop-bar and queue between the upstream intersection (interchange terminal) and the freeway merge point. Since sufficient queue storage and acceleration distance are provided, the primary operating objective is to meter traffic in order to meet the needs of the current freeway conditions (i.e., higher occupancy detection on the freeway, lower metering levels at the on-ramps) rather than to focus on the potential of queue spillbacks into the upstream intersection.

However, the existence of frontage roads along most of the urban freeways in Texas presents three specific areas of concern regarding the use of dual-lane flow signals: the availability of space between the freeway and frontage road to construct a dual-lane ramp geometric configuration, the ability to prevent queue spillbacks into the frontage road and upstream intersection, and the ability to provide a flow signal controller that can manage both freeway conditions and queuing conditions effectively.

The need to develop an effective freeway management tool, given the geometric constraints associated with the frontage road/freeway slip-ramp configurations in Texas, warrants the need to evaluate the feasibility of designing a safe and effective dual-lane ramp metering system.

RESEARCH OBJECTIVES

The primary objective of this research work was to determine the feasibility of designing and operating a dual-lane flow signal system under the frontage road/freeway slip-ramp configuration commonly used throughout Texas. Accordingly, the research focused on three specific topics: the design, control, and operational elements necessary to implement dual-lane flow signals under this geometric constraint.

Design Elements

Potential geometric configurations were evaluated with respect to their ability to: provide effective transition of traffic from the frontage road to the freeway under both metered and non-metered conditions, maximize the size of the queue storage area between the flow signal stop-bar and the frontage road egress point, and maintain sufficient acceleration area between the flow signal stop-bar and the freeway merge area to allow motorists to reach freeway speeds. This evaluation included a brief review of the typical geometric conditions present along the Katy Freeway and other freeways in the Houston area (e.g., frontage road/freeway offset distances and on-ramp to off-ramp transition distances). Multiple-lane ramp meter design practices used in other states were also examined. Based on these evaluations, recommendations were made regarding the geometric requirements (e.g., storage area, transition, channelization) desired to efficiently operate a dual-lane flow signal under frontage road/freeway slip-ramp configurations commonly found in Texas cities.

Control Elements

The flow signal control requirements were examined to provide a range of metering rates up to 1,800 vehicles per hour. This examination included a review of the current metering specifications for the RMC-300 controller unit used in Texas and other controller specifications for dual-lane metering used throughout the nation. Based on this review, identified were the components (e.g., loop detectors) necessary to effectively operate a dual-lane flow signal system under the slip-ramp configuration commonly used in Texas. The operational performance of single-lane versus dual-lane flow signals was compared using microscopic simulation. This simulation analysis was used to evaluate the ability of a dual-lane flow signal controller to: adjust metering levels to prevent queue spillbacks into the frontage road and upstream signalized intersection, adjust metering levels to accommodate changes in freeway conditions (i.e., relate freeway mainline detector occupancy to the metering rate), and accommodate fluctuations in freeway conditions and on-ramp arrival patterns. Based on the results of the simulation analysis and state-of-the-practice review, placement locations and operational requirements for mainline, merge, demand, primary queue, and secondary queue detectors were recommended.

Operation Elements

The operation of the recommended design and control elements for a dual-lane flow signal system under a frontage road/freeway slip-ramp configuration was analyzed using microscopic simulation. This analysis focused on the changes in freeway, on-ramp, and frontage road operation and relative safety (i.e., qualitative evaluation) related to the possible installation of a dual-lane flow signal at one study site location. In addition, this research was used to develop new design and operational concepts, as illustrated for possible demonstration on the Gessner Street entrance ramp located on the eastbound Katy Freeway (IH-10) on the west side of Houston.

SCOPE OF WORK

This research focuses primarily on the design, control, and operational elements of dual-lane flow signals located on frontage road/freeway slip-ramps on urbanized freeways in Texas. Based on the evaluation results, a plan for designing and operating dual-lane flow signals was developed. The primary investigation, regarding the feasibility of the design of dual-lane flow signal meters, concentrates on the inbound segment of Interstate 10 (Katy Freeway) located east of the Sam Houston Tollway (State Highway 8) and west of Interstate 610 (West Loop) in west Houston. The findings and recommendations summarized in this research report will expand the potential freeway management strategies available to TxDOT.

2. STATE OF THE PRACTICE

This chapter summarizes the geometric, traffic control, and operational features of single-lane and multiple-lane ramp meters. Using this information, a comparative analysis of the two ramp meter configurations was conducted to ascertain the similarities and differences in the geometric, traffic control, and operational characteristics between the two design strategies. From this research and analysis, application guidelines were proposed for single-lane and multiple-lane ramp meters.

It should be noted that the information presented in this section is based on a survey of dual-lane ramp metering conducted by the Texas Transportation Institute (TTI), telephone interviews conducted as part of this research (see Appendix A), and a review of the available literature on ramp metering.

CURRENT MULTIPLE-LANE RAMP METER SYSTEMS

With the opening of several advanced traffic management centers across the United States over the past decade, the geometric design, traffic control, and operation of ramp meters have become more sophisticated and their application more wide-spread. As of 1995, ramp metering systems were operational in 23 metropolitan areas in North America (*2*). In addition to these 23 metropolitan areas, 10 other cities are designing or planning new ramp meter systems that will be operational by 2001 (*2*).

Our research survey determined that the 10 states of Arizona, California, Colorado, Illinois, Minnesota, New York, Oregon, Virginia, Washington, and Wisconsin currently operate some type of dual-lane ramp meters. Table 1 shows the number of multiple-lane meters currently operating in these states.

In addition to the states shown in Table 1, Florida, Georgia, Maryland, New Jersey, Pennsylvania, and Utah are in the process of planning or installing ramp meter systems which may include multiple-lane ramp meters. Texas is not included in this assessment.

Table 1. Summary of Operational Multiple-Lane Ramp Meters in North America

State (*Reference*)	Single-Lane + HOV	Dual-Lane	Dual-Lane + HOV	Total Number of Multiple-Lane Meters
Arizona (*9*)	7	3	-	10
California (*10*)	576	491	40	1,097
Colorado (*11*)	1	19	5	25
Illinois (*12*)	-	1	-	1
Minnesota (*13*)	-	350	50	400
New York (*14*)	2	2	-	4
Oregon (*15*)	2	63	1	66
Virginia (*16*)	-	4	-	4
Washington (*17*)	40	2	10	52
Wisconsin (*18*)	17	7	4	28

Control Techniques

Ramp meter systems use three primary control techniques to manage on-ramp traffic: fixed-time, local traffic responsive, and system control systems. Fixed-time ramp control provides the basic function of breaking up platoons of traffic. A fixed-time controlled on-ramp can either operate in a continuous cycle or under a detection-based configuration. The detection-based, fixed-time control configuration uses a one or two detector layout to regulate on-ramp traffic. An inductive loop detector (demand detector) is used to identify the presence of vehicles, and a passage detector is used by some agencies to terminate the metering cycle. The metering rate for fixed-time controlled on-ramps is based on average conditions and does not regulate volumes based on the current freeway conditions. However, fixed-time controlled ramps provide even distribution of traffic into the freeway stream and reduce merge-related accidents (*2*).

The second type of ramp meter control is local traffic responsive. This control system uses mainline detection on the freeway in the vicinity of the on-ramp to determine current traffic conditions and adjusts the ramp metering rates to obtain a specified operating level (or target). By continually measuring the freeway traffic, the controller is able to regulate traffic more effectively than a fixed-time system.

The most sophisticated ramp meter control technique is system (integrated) control. This control technique is traffic responsive, but is not limited to an isolated on-ramp along a freeway. This control technique evaluates segments of a freeway to determine the best overall metering strategy for an entire section of freeway; for example, a series of ramp meters are programmed together to adjust and maintain freeway traffic volume levels. Under an integrated control mode, the metering rates and strategies are calculated in an on-line real-time process that is able to adjust to existing traffic conditions (*19*). Metering rates and strategies are updated continuously on a system-wide approach based on the control algorithms selected for the given system. This type of control should function well within Intelligent Transportation Systems (ITS), having sophisticated traffic management centers and area-wide data collection, because it can regulate input flow and also provide the ability to improve incident detection and management.

Design Strategies

Ramp meter systems use various control techniques, including fixed-time, local traffic responsive and system control, to determine the appropriate metering rates for vehicles desiring access to a freeway facility. However, many departments of transportation have experienced operating conditions in which the metering of a single-lane approach is not adequate for the prevailing conditions or operational policies (i.e., preferential treatment for HOVs). The typical on-ramp configuration in the United States consists of a single-lane ramp design that accesses the freeway through a traditional diamond interchange or similar interchange facility. Meters installed on single-lane ramps are found effective only at vehicular demands of 900 vehicles per hour or less. This maximum threshold is based on the ability of the traffic control device to bring each vehicle to a complete stop at the ramp meter's stop-bar. At metering rates in excess of 900 vehicles per hour (i.e., a four second vehicular headway), the time between successive green signal displays becomes too small to effectively stop vehicles operating in a single lane. Therefore, vehicles tend to roll through the metered ramp, and the benefit of dispersing platoons at the merge point deteriorates. Correspondingly, the enforcement of the ramp meter becomes difficult at low vehicular headways because officers cannot effectively differentiate legal movements from illegal movements. In addition to the operation and enforcement issues, single-lane ramps reduce the benefits of exclusive high-occupancy lanes on the freeway because all vehicles must wait their respective turn under a single-lane ramp meter configuration with mixed flow traffic.

To address the design and operational issues associated with single-lane ramp meters, California, Minnesota, Oregon, Washington, and other states have developed a variety of ramp meter control strategies to handle both high-volume on-ramps and high-occupancy vehicles. Table 2 lists examples of the control strategies currently used throughout the nation (*20*).

Table 2. Summary of Alternative Ramp Meter Control Strategies

Ramp Meter Control Strategy	Description
Single-Lane (Multiple Vehicle Release)	Two or more vehicles are released per green displayed.
Single-Lane + HOV	A parallel or separate HOV-lane is provided for carpools, vanpools, and transit in addition to the mixed-traffic lane. This lane may provide varying degrees of preferential treatment and control.
Dual-Lane	Two lanes are formed upstream of the ramp meter stop-bar and vehicles are released independently by lane or coordinated between lanes.
Dual-Lane + HOV	Two lanes are formed upstream of the ramp meter for mixed traffic and a parallel or separate HOV-lane is provided for carpools, vanpools, and transit.

As shown in Table 2, the alternative ramp meter control strategies provide a high degree of flexibility for agencies to operate ramp meter systems under various operational situations while still promoting other transportation programs such as transportation demand management through exclusive HOV and transit lanes.

California, Minnesota, Oregon, and Washington transportation officials have indicated that dual-lane ramp meters are capable of metering on-ramp demand volumes of up to 1,700 vehicles per hour effectively and provide the ability to implement various control strategies throughout the day and over time (i.e., mixed traffic versus preferential HOV assignments) (*5,6,7,8*). As a result of these demonstrated operational benefits, these four states and several others have adopted multiple-lane ramp metering as their recommended design standard for new ramp meter installations.

DESIGN ELEMENTS OF DUAL-LANE RAMP METERS

The typical dual-lane ramp meter configuration used in California, Minnesota, Oregon, and Washington has been developed on traditional single-lane on-ramps at diamond and parclo-type interchanges. These single-lane approaches have been modified with either signage or striping to create two side-by-side storage lanes during metered periods. Figure 1 shows the typical dual-lane ramp meter configuration and traffic control element used throughout the nation (*20, 21*).

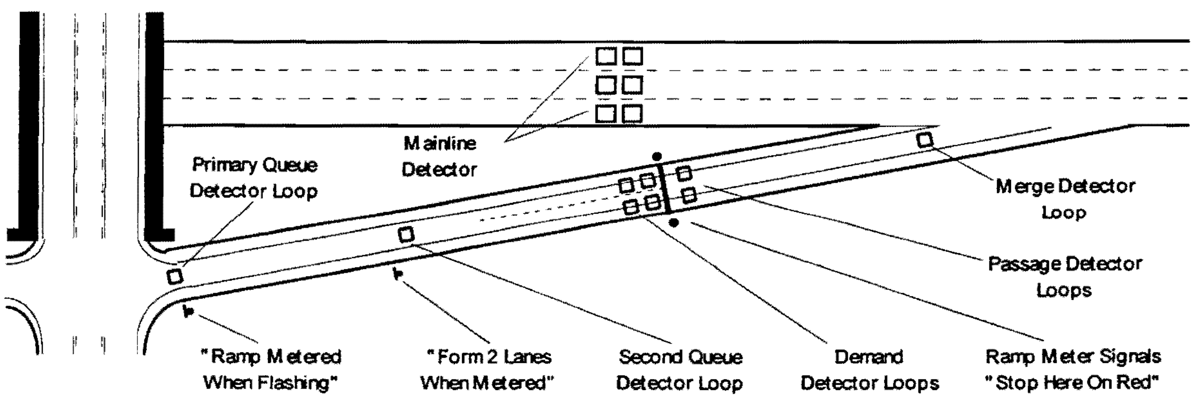


Figure 1. Typical Dual-Lane Ramp Meter Geometric and Traffic Control Plan

As shown in Figure 1, the dual-lane ramp meter configurations maintain geometric and traffic control elements similar to those of a traditional single-lane ramp meter. However, the dual-lane configuration requires several traffic controller advancements and additional pavement width and lateral clearance when compared to the traditional single-lane ramp meter. These geometric and traffic control elements are described below.

Geometric Elements

The single-lane and multiple-lane ramp meters require three physical areas: the queue reservoir, the acceleration area, and the merge area. The queue reservoir is the area located between the ramp meter stop-bar and the upstream intersection, service road, or freeway. To develop multiple-lane ramp meters, the single-lane queue storage reservoir is modified with either signage or striping to create two side-by-side storage lanes during metered periods. The queue reservoir can either be striped as one or two lanes, depending on the available geometry. Under a traditional on-ramp configuration, the queue reservoir is divided into two lanes through signing that informs motorists to form two lanes during metered operations. As a result, the multiple-lane (dual-lane) ramp meter queue reservoir can accommodate approximately twice the number of vehicles as the traditional single-lane ramp meter.

The queue storage area upstream of the ramp meter stop-bar may maintain either one or two lanes during non-metered periods and should be sufficiently long to accommodate the expected queues during the metered periods. Locations with insufficient storage should be outfitted with excessive queue detectors and control strategies capable of increasing the metering rate until the queue clears. To estimate the queue during the metered periods, the existing or forecast on-ramp volumes and freeway volumes must be known. Using the freeway volumes, the expected metering rate during the peak on-ramp arrival period can be determined using a local traffic-responsive, occupancy-based approach. In turn, the expected queue length can be determined using the on-ramp arrival patterns. Once this process is accomplished, the queue storage reservoir required to contain the expected on-ramp demand volumes can be determined.

Under the dual-lane ramp meter configuration, a minimum of 50 meters of queue storage is recommended to allow vehicles to switch lanes when approaching the stop-bar. It is important to also note that the queue reservoir should be designed with excessive queue detectors (i.e., initial and advance) even if a sufficient queue reservoir can be developed. These detectors will ensure proper operation and safety of the upstream interchange terminal, service road, or freeway, even under unexpected changes in either the freeway or on-ramp arrival patterns and volumes.

Unlike the single-lane ramp meter that can be installed at nearly all on-ramp locations, the dual-lane ramp meter configuration requires additional pavement width to provide space for two lanes of vehicles within the queue storage reservoir. The Oregon and Washington Departments of Transportation recommend that 7.3 to 8.0 meters, respectively, of pavement be provided within the queue storage reservoir and an absolute minimum width of 6.7 meters be maintained for dual-lane ramp metering. This width allows passenger cars, trucks, and buses to safely queue and meter side-by-side.

The acceleration area is the distance between the stop-bar and the freeway merge point necessary for vehicles to accelerate to freeway speed. Additional merging length may be provided to allow motorists to find an acceptable gap in the traffic stream. The additional merging distance can be provided by lengthening the ramp, providing additional downstream merging area, or by adding an auxiliary lane between entrance and exit ramps.

Traffic Control Elements

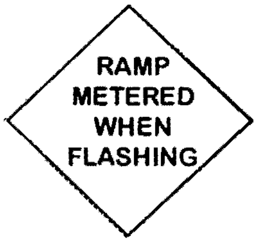
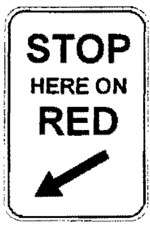
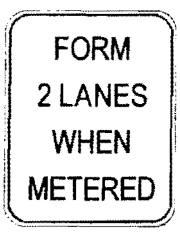
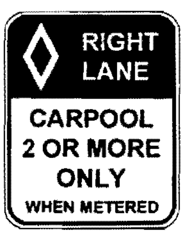
To inform motorists of the ramp meter operations and movement protocols, the metered ramp maintains a series of loop detectors, signs, and traffic control devices to effectively communicate the necessary information to motorists and ensure the safety and integrity of the freeway management system. Six sets of loop detectors are required to provide data necessary to operate fixed-time, local traffic-responsive, or system-controlled ramp meter systems. These include the mainline, merge, passage, demand, initial queue, and advanced queue detectors. Table 3 provides a description of each detector's location and specific application within the control system. The merge, passage, and initial queue detectors are not necessary to operate the three described control systems; however, these detectors provide additional features that several agencies currently use in their ramp metering operations.

Table 3. Placement and Application of Ramp Meter Detectors

Type of Detector	Location	Application
Mainline	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	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.
Initial 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.
Advanced Queue	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.

In addition to the detectors used with dual-lane ramp meters, a series of warning and regulatory signs are used to convey the intent of the freeway management system. Table 4 provides an illustration of the various ramp meter signs used under single-lane, multiple-lane, and multiple-lane with preferential lane assignment configurations.

Table 4. Ramp Meter Signing Conventions

Sign	Location	Application
	Placed near the entrance of the on-ramp.	This warning sign is accompanied by a yellow flashing beacon that is activated during metered periods to alert motorists of the upcoming controlled ramp. May be internally illuminated without beacon with a message of "Ramp Signal On."
	Placed on both sides of the on-ramp at the ramp meter stop-bar. This sign is placed on the signal pole under the post-mounted configuration.	This regulatory sign identifies the ramp meter stop-bar location and is used to align drivers over the demand detectors placed upstream of the stop-bar. May be internally illuminated.
	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 ramp-metered conditions.
Dual-Lane Ramp Signage		
	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 ramp meter operations.
Preferential Lane Assignments		
	This optional preferential lane assignment sign is located in conjunction with the "Form 2 Lanes When Metered" sign and sometimes repeated near the stop-bar.	This type of regulatory sign is used to specify lane restrictions at the ramp meter for various carpool occupancies, vanpools, and transit vehicles. Either the right- or left-side lane may be assigned.

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 facility. Figures 2 and 3 illustrate the typical post and mast-arm ramp meter control conventions, respectively, for multiple-lane ramp meters. It should be noted that single-lane ramp meters use similar control conventions but provide only a single approach lane.

Figure 2. Typical Dual-Lane Ramp Meter Post-Mounted Traffic Control Configuration

Figure 3. Typical Multiple-Lane Ramp Meter Mast-Arm Mounted Traffic Control Configuration

As shown in Figure 2, the dual-lane ramp meter post-mounted traffic control configuration consists of two separate sets of traffic signals located on the right and left sides of the metered on-ramp. These signals are normally placed within three meters downstream of the stop-bar and control each lane separately. The upper three-section head traffic signal is intended to inform arriving motorists that the ramp meter is operational, while the lower two- or three-section head traffic signal is oriented towards the driver at the stop-bar. In addition to the traffic signals, two regulatory signs, "Stop Here On Red" and "One Vehicle Per Green" are affixed to the signal pedestal to indicate the proper lane control and operation to be observed under metered conditions. Under a single-lane design, the signals can be displayed on one or two posts to fit existing geometry.

The multiple-lane ramp meter with mast-arm mounted design is illustrated in Figure 3. This design represents the second ramp meter traffic signal configuration commonly used. This configuration is similar to the traditional traffic signal mounting design used at signalized intersections. The mast-arm is typically located within 12 to 22 meters of the stop-bar and has a single three-section head traffic signal over each metered lane. The mast-arm design is normally accompanied by regulatory signing near the stop-bar indicating the appropriate lane control and stop position. The on-ramp illustrated includes an exclusive HOV bypass lane (right side) in addition to two lanes of mixed traffic.

Operational Elements of Dual-Lane Ramp Meters

The operational features of dual-lane and single-lane ramp meters reveal the greatest difference between the two freeway traffic management design strategies. Traditional single-lane ramp meters cycle at the specified metering rate using either a red-green-red or red-green-yellow-red sequence when vehicles are present. Most states allow one vehicle to proceed during each green signal display; however, some states have been forced to allow multiple vehicles to be released to accommodate high ramp volumes at some on-ramp locations. In general, most states will only operate single-lane ramp meters up to a maximum discharge rate of 900 vehicles per hour, which represents a four-second headway between successive vehicles. As discussed previously, agencies have found that headways of less than four seconds do not effectively bring vehicles to a complete stop. This can create enforcement problems because motorists continually move through the ramp meter.

The dual-lane ramp meter operational strategies employed throughout the country differ significantly, from vehicles in each lane being released simultaneously to release being evenly alternated between lanes. The existence of a second lane allows multiple-lane ramp meters to meter traffic up to approximately 1,800 vehicles per hour, while maintaining four seconds or longer headways in each lane. In addition, priority phasing can be given to preferential lanes at a ramp meter. These two capabilities give multiple-lane ramp meters a significant advantage in operational flexibility over single-lane ramp meters. This operational flexibility is a further advantage where excessive queues occur.

The two types of ramp meter design strategies have contrasting operation and traffic control capabilities for dealing with excessive queues. Single-lane ramp meters can only effectively meter traffic up to approximately 900 vehicles per hour, and excessive queues can only be cleared by discontinuing metering. In contrast, multiple-lane ramp meters can increase the discharge rate up to nearly the saturation flow rate of the on-ramp to clear queued vehicles. This operational flexibility allows multiple-lane ramp meters to continuously regulate and evenly distribute vehicles into the freeway traffic stream, whereas the single-lane design strategy allows a large platoon of traffic to enter the traffic stream whenever metering is interrupted to clear queues. The multiple-lane ramp meter design strategy can accommodate approximately 100 to 130 percent more vehicles within the queue reservoir than the single-lane ramp meter (*13*).

OPERATIONAL BENEFITS OF DUAL-LANE RAMP METERS

Based on the results of the surveys and the telephone interviews, the 10 agencies operating dual-lane ramp meters were determined to prefer the dual-lane ramp meter design over the traditional single-lane ramp meter configuration for the following reasons:

- Dual-lane ramp meters provide the ability to meter a wide range of on-ramp demand volumes from approximately 200 to 1,800 vehicles per hour, compared with the traditional single-lane configuration, which can only effectively accommodate up to approximately 900 vehicles per hour;

- The additional queue storage (queue reservoir) area provided under the dual-lane configuration nearly doubles that available under the single-lane design and provides the ability to handle platoon arrivals from upstream traffic signals more effectively;
- Dual-lane ramp meter configurations allow agencies to provide preferential lanes to carpools, vanpools, and transit vehicles. This promotes single-occupancy vehicle reduction in accordance with the Clean Air Act (CAA) of 1990 and the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991; and
- A better self-enforcement environment is provided by dual-lane ramp meters when compared to single-lane configurations because of the presence of motorists next to one another.

3. DEVELOPMENT OF DUAL-LANE FLOW SIGNAL PLAN FOR TEXAS

A detailed survey of dual-lane ramp meter systems currently operating in the United States was conducted to develop a dual-lane flow signal plan for Texas. This survey was intended to provide current information on the geometric, traffic control, and operational elements of dual-lane ramp meters and to identify design criteria and strategies for potential implementation in Texas.

Using the survey and TxDOT's experience and operational testing of recently installed single-lane flow signals in Houston, geometric, traffic control, and operation design criteria were developed to design and operate dual-lane flow signals on freeway/frontage slip-ramps in Texas. The geometric constraints and operational considerations associated with frontage road/freeway slip-ramps used throughout Texas were also considered in the design criteria. On the basis of these design criteria, a proposed dual-lane flow signal plan was developed.

GEOMETRIC DESIGN CRITERIA

To properly design a dual-lane flow signal system in Texas, the frontage road/freeway slip-ramp should provide three primary operating areas for vehicles to queue, accelerate, and merge under metered conditions. The slip-ramp should also provide the proper transition design to operate effectively under both metered and non-metered conditions. This section will establish recommended design criteria covering the three ramp operational areas: the queue storage reservoir, acceleration area, and merge together with desired transition distances and lateral clearances within a dual-lane flow signal system.

Queue Storage Reservoir

The queue storage area upstream of the flow signal stop-bar may maintain either one (the typical configuration in Texas) or two lanes during non-metered periods and should be sufficiently long to accommodate the expected queues during the metered periods. Locations with insufficient storage should provide excessive queue detectors and control strategies capable of increasing the metering rate until queues clear. To estimate the queue during the metered periods, the existing or forecast on-ramp volumes and freeway volumes must be known. Using the freeway volumes, the expected metering rate during the peak on-ramp arrival period can be determined based on a local traffic-responsive, occupancy-based approach. The expected queue length can be determined using the on-ramp arrival patterns so that the queue storage reservoir required can be determined.

Even if a sufficient queue reservoir can be developed, the queue reservoir should be designed with excessive queue detectors. These detectors will ensure proper operation and safety of the upstream frontage road, signalized intersection, and off-ramp (under a reverse, X-ramp, interchange configuration), even under unexpected changes in either the freeway or on-ramp arrival patterns and volumes.

Acceleration/Merge Areas

The area downstream of the flow signal stop-bar should provides sufficient length for motorists to accelerate to freeway speeds, transition into a single lane prior to reaching the merge area, and merge into the freeway travel stream. This distance can be determined through a fundamental flow equation given as Equation 1 (*22*). The American Association of State Highway and Transportation Officials recommends an acceleration rate of three meters per second per second (10 feet per second per second) (*23*). The desired distance is:

$$d = \frac{v_f^2}{2a} \tag{1}$$

where:

d = distance traveled (meters);
v_f = freeway speed (meters per second); and
a = vehicular acceleration rate (meters per second per second).

In addition to the acceleration area, vehicles may need additional time in which to find an acceptable gap in traffic into which to merge. Research conducted by TTI estimates that an additional 1.5 seconds of travel time at freeway speeds is necessary for a driver to find an acceptable gap within the freeway traffic stream (*24*). Using the acceleration equation above and the merge time defined by TTI, the required acceleration/merge area relative to freeway operating speed is illustrated in Figures 4 (metric units) and 5 (English units).

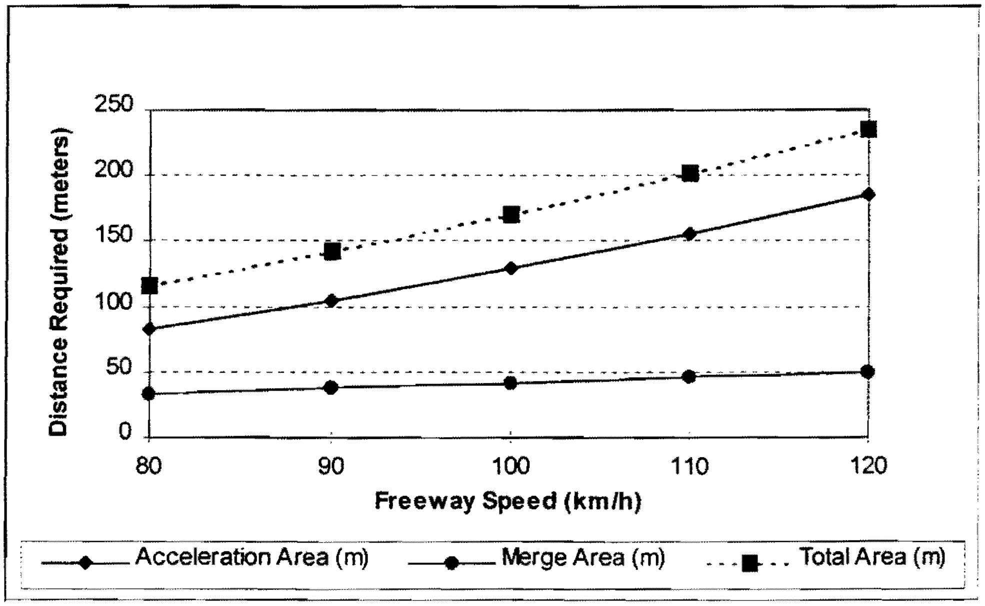


Figure 4. Required Acceleration/Merge Area versus Freeway Speed

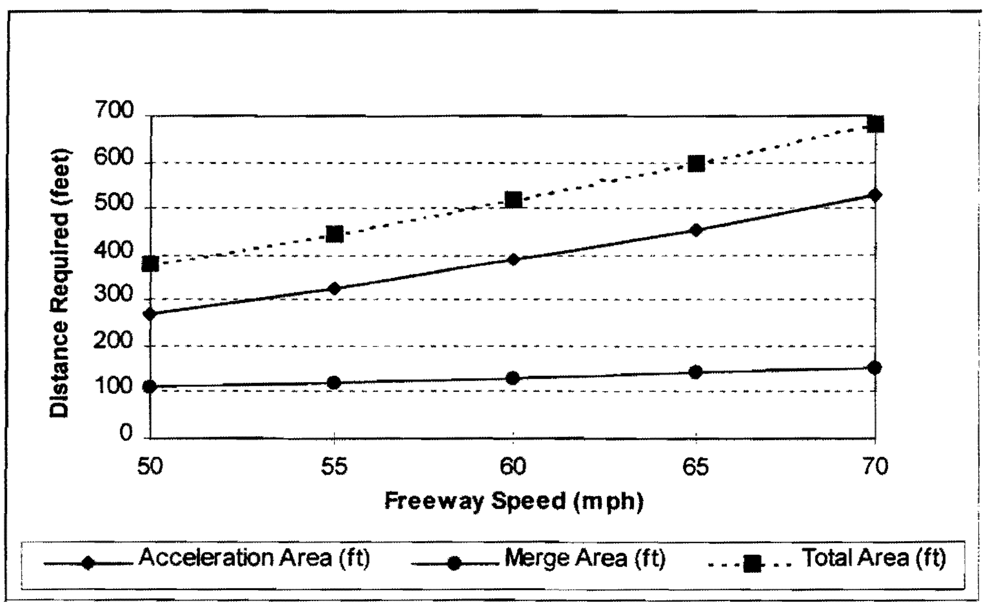


Figure 5. Required Acceleration/Merge Area versus Freeway Speed

Lateral Clearances

The development of dual-lane flow signals requires additional lateral clearances both on the on-ramp and between the freeway and frontage road, when compared to traditional single-lane configurations. Most states recommend between 7.3 and 7.9 meters (24 and 26 feet) of pavement width for dual-lane metering on single-lane ramps upstream of the stop-bar. This width provides adequate room for large trucks and buses to queue side-by-side under a dual-lane configuration. Oregon and Washington have developed and operated dual-lane ramps on 6.7-meter (22-foot) -wide pavement sections. However, both agencies indicate that additional precautions should be taken to ensure that proper setbacks are provided for traffic control devices, luminaire poles, and other obstructions in the vicinity of the on-ramp. Therefore, it is recommended that frontage road/freeway slip-ramps in Texas desirably maintain a 7.3 meters (24 feet) minimum pavement width, with an absolute minimum of 6.7 meters (22 feet) minimum width upstream of potential dual-lane flow signal on-ramp locations.

In addition to the on-ramp pavement width upstream of the flow signal stop-bar, the ramp needs to provide proper clearance for the traffic control devices from the freeway, frontage road, and on-ramp. Because of the limited lateral distances between the inside frontage road and outside freeway travel lanes in Texas, the typically required 9.1 meters (30 feet) of lateral clearance cannot be provided. Therefore, safety measures such as breakaway sign posts, attenuators, and longitudinal barriers should be employed along with raised curbing along the frontage road and on-ramp lanes for dual-lane flow signal designs with restricted lateral clearance.

TRAFFIC CONTROL DESIGN CRITERIA

To ensure the operational integrity and benefits of dual-lane flow signals, several traffic control elements need to be properly addressed. These elements include the traffic signal placement, configuration, and display; the loop detector placement and operation; warning and regulatory signage requirements; and on-ramp channelization. This section establishes the traffic control design criteria for dual-lane flow signals in Texas.

Traffic Signals

Dual-lane flow signals should use either a post or mast-arm mounting technique to display flow signal traffic signals. Post-mounted signals should be located on both sides of the on-ramp in the vicinity of the stop-bar (1.5 to 3.0 meters downstream) to control the adjacent approach lane during metering operations. Each post-mounted standard should maintain two sets of signals: the upper three-section traffic signal head should be directed up the ramp to notify approaching motorists of the flow signal operation; and the lower two- or three-section traffic signal head should be oriented toward the driver compartment of the first vehicle in the queue. The post-mounted design has been prone to vehicular damage in other states if not properly set back from the on-ramp and protected through raised curbing or other longitudinal barriers (e.g., guard rails). The departments surveyed indicated that 0.6 to 1.0 meters (2.0 to 3.0 feet) of horizontal clearance should be maintained between the edge of pavement and the nearest traffic control device.

The mast-arm design is similar to the traditional signalized intersection mast-arm design, where the traffic signals are located downstream of the stop-bar and aligned over each controlled lane of traffic. The mast-arm mounted traffic signals should be placed between 12 and 20 meters (40 and 65 feet) downstream from the stop-bar. A single three-section traffic signal head should be used to control each lane of metered traffic on the ramp. The mast-arm design provides additional protection to the flow signals and related signing; however, this design is typically more expensive than the post-mounted design.

Loop Detectors

To ensure the operational integrity of a metered on-ramp, the positioning and maintenance of several inductive loop detectors is required for fixed-time, local traffic-responsive, and system-controlled systems. Table 5 outlines the placement and application of required and optional inductive loop detectors under a dual-lane flow signal configuration.

For dual-lane flow signal configurations, the initial queue and advance queue detectors appear to be essential to properly contain queues on slip-ramps. This feature is needed because queue spill back at slip-ramp configurations can potentially impact traffic operations

Table 5. Placement and Applications of Required and Optional Loop Detectors

Type of Detector	Location	Application
Mainline	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	Placed upstream of the merge area in the on-ramp (downstream of the stop-bar).	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	Placed immediately upstream of the stop-bar in both specified lanes.	Senses a vehicle's presence at the stop-bar and initiates the green traffic signal display for that specific lane under the selected metering strategy.
Initial Queue	Placed approximately half-way between the stop-bar and the on-ramp entrance point in both lanes.	Adjusts the metering rate to control growing queues within the queue storage reservoir.
Advanced Queue	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.

and safety of the adjacent frontage road, interchange terminal, or upstream off-ramp under a reverse diamond interchange.

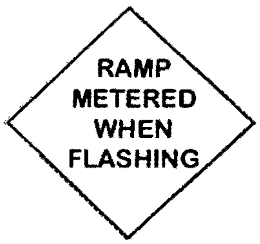
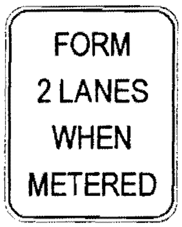
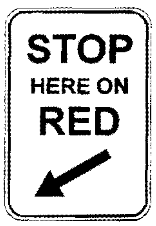
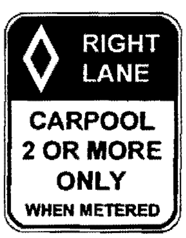
Signage

The dual-lane flow signal configuration requires a specific signing convention to inform motorists of the intended on-ramp operation and vehicle movements. Table 6 outlines the required and optional signing for a freeway/frontage road slip-ramp that maintains a dual-lane flow signal configuration. Some states provide internally illuminated signs, red-on-black, which are adaptations of these passive signs.

Channelization

The operational integrity and safety of the metered slip-ramp is highly dependent on the effectiveness of the on-ramp channelization used (i.e., striping and raised curbing). The most important aspect of slip-ramp channelization is to provide a delineated path that motorists can follow during both metered and non-metered periods. Most states have found that single-lane on-ramps converted to dual-lane queue storage reservoirs are best controlled by modifying the existing, non-metered striping at the stop-bar location. The stop-bar should maintain a standard 0.3-meter (12-inch) white stripe that extends across the entire ramp and is accompanied by a 3.0- to 9.0-meter-long (10- to 30-feet), 0.1- or 0.2 meter-wide (4.0- or 8.0-inches) white line that extends upstream from the center of the stop-bar to properly delineate the two queue storage lanes during flow signal operation (*25*). According to staff who were interviewed from several states, additional lane striping for metered conditions can cause more confusion than direction and creates additional maintenance.

Table 6. Dual-Lane Flow Signal Signing Locations and Applications

Sign	Location	Application
	Placed on the left-side of the frontage road approximately 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.
	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.
	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.
	This optional preferential lane assignment sign is located in conjunction with the "Form 2 Lanes When Metered" sign and sometimes repeated near the stop-bar.	This type of regulatory sign is used to specify lane restrictions at the flow signal for various carpool occupancies, vanpools, and transit vehicles. Either lane may be assigned.

OPERATIONAL DESIGN CRITERIA

In addition to the geometric and traffic control design criteria, the dual-lane flow signal configuration needs to provide a wide range of operational design criteria deemed to be desirable in Texas. These operational design criteria are primarily associated with the flow signal controller hardware and software elements, including metering capabilities, queue containment, and enforcement. This section describes each of the three operational design criteria.

Metering Capabilities

For dual-lane flow signals in Texas to properly operate, the flow signal controller should possess the capabilities to function well during various on-ramp arrival conditions, to produce the discharge rates necessary to effectively accommodate a wide-range of traffic volumes, and to address excessive queues. The existing single-lane flow signals in urbanized areas do not adequately accommodate platoon arrivals and/or on-ramp demand volumes exceeding 900 vehicles per hour. To address these deficiencies, dual-lane flow signals should be able to process a wide range of ramp arrival patterns and demand volumes up to approximately 1,800 vehicles per hour.

To meet the various objectives of ramp metering, the dual-lane flow signal controller should release one vehicle per lane and alternate between the two queue storage reservoir lanes to maintain consistent vehicular headways that correspond to the desired hourly discharge rate. The traffic signals should sequence from green-to-yellow-to-red-to-green, and they should also dwell on red while the demand detectors in each approach lane are unactuated. Finally, the dual-lane flow signal controller needs to be capable of operating under either isolated (local) or system (integrated) control.

Queue Containment

Due to the operation and safety issues associated with frontage road/freeway slip-ramps under traditional- and reverse-diamond interchange configurations, the dual-lane flow signal controller should be able to contain queued vehicles within the on-ramp storage area under various arrival patterns and demand volumes. Therefore, the dual-lane flow signal system should maintain initial queue (a secondary queue detector in Texas) and advance queue detectors (a primary queue detector in Texas) that manage the on-ramp queue during minor and major fluctuations, respectively, in arrival patterns and demand volumes. The secondary queue detector should manage the queue through minor adjustments to the metering rate when queues are detected at the end of the dual-lane queue storage reservoir. Furthermore, the flow signal controller needs to manage on-ramp queues under either isolated or system control.

To properly control on-ramp queues, the metering rate provided through either local traffic-responsive or system control is adjusted by either the secondary queue or primary queue detectors to accommodate fluctuations in arrival patterns and demand volumes that temporarily exceed the programmed metering rate. This queue management strategy is designed to address the operation and safety issues associated with the restrictive storage areas on the slip-ramp, while maintaining the overall objective of ramp metering. Figure 6 illustrates an example of the queue management strategy for a dual-lane flow signal using either a local traffic responsive or system-specified metering rate of 900 vehicles per hour.

As shown in Figure 6, the activation of the secondary queue detector from growing queues in the queue storage reservoir results in an increased metering rate by one metering level. This process continues until the secondary queue detector does not detect any queued vehicles. At this point, the metering level is reduced by one for a specified period of time (defined by the user) until the flow signal controller either reaches the target metering level (i.e., 900 vehicles per hour) or the secondary queue detector is again activated (i.e., detects a queued vehicle).

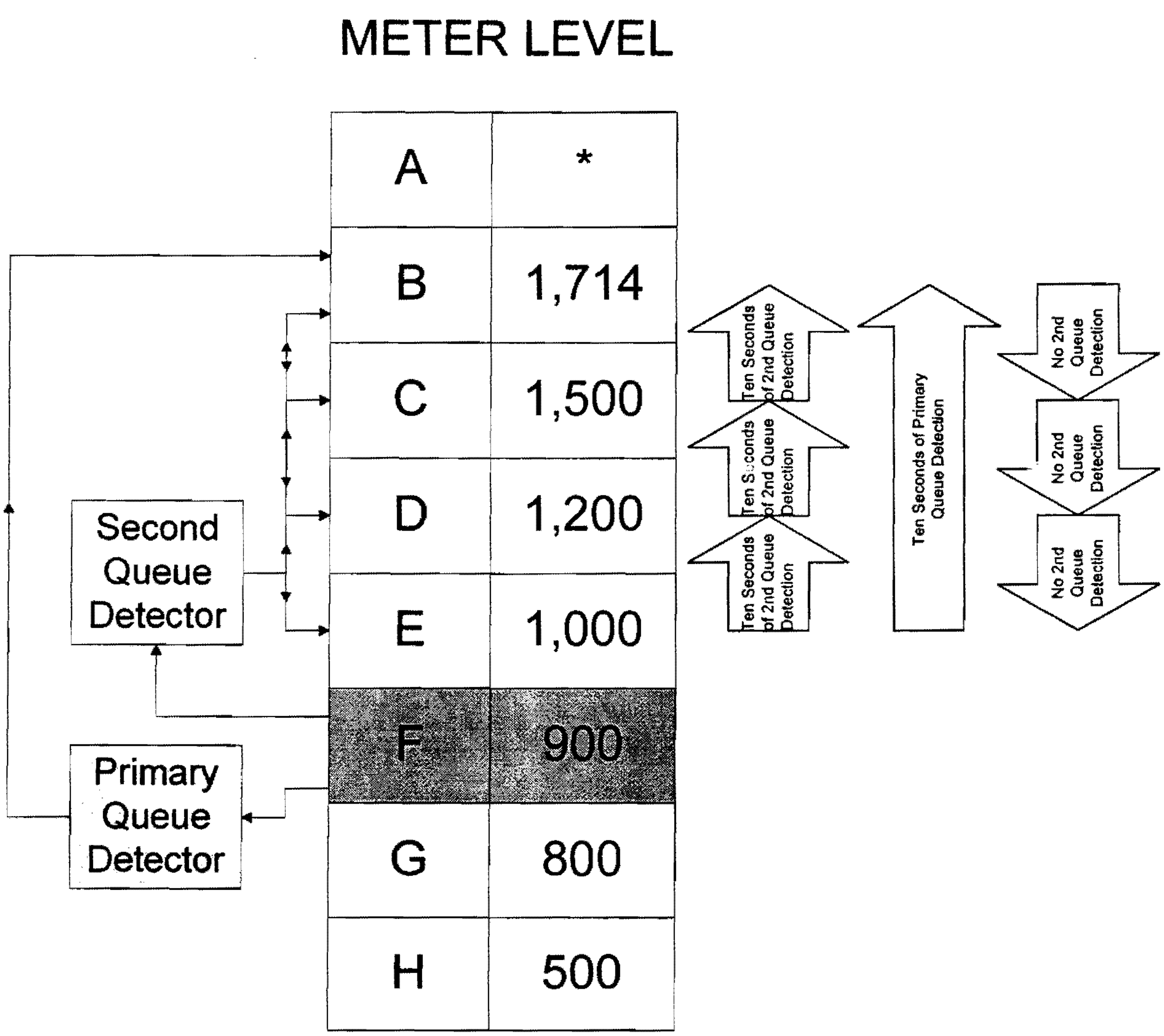


Figure 6. An Example of the Queue Management Strategy for Dual-Lane Flow Signals Using a Selected Metering Rate of 900 Vehicles Per Hour

In addition, as shown in Figure 6, the activation of the primary queue detector by an excessive queue results in an increase in the metering level to the maximum specified metering rate. The maximum metering rate is maintained until the secondary queue detector does not detect any queued vehicles. At this point, the secondary queue detector reduces the metering rate by one meter level as discussed above.

PROPOSED DUAL-LANE FLOW SIGNAL PLAN FOR TEXAS

Using the geometric, traffic control, and operational design criteria established throughout this chapter, a proposed dual-lane flow signal plan was developed to design and operate this advanced freeway traffic management strategy on freeway/frontage road slip-ramps in Texas. The proposed plan employs many of the geometric, traffic control, and operational elements that have proven successful in other states. The plan also accounts for the geometric constraints and operational issues associated with frontage road/freeway slip-ramps in Texas. Figure 7 illustrates the proposed dual-lane flow signal plan for Texas based on this research's detailed survey.

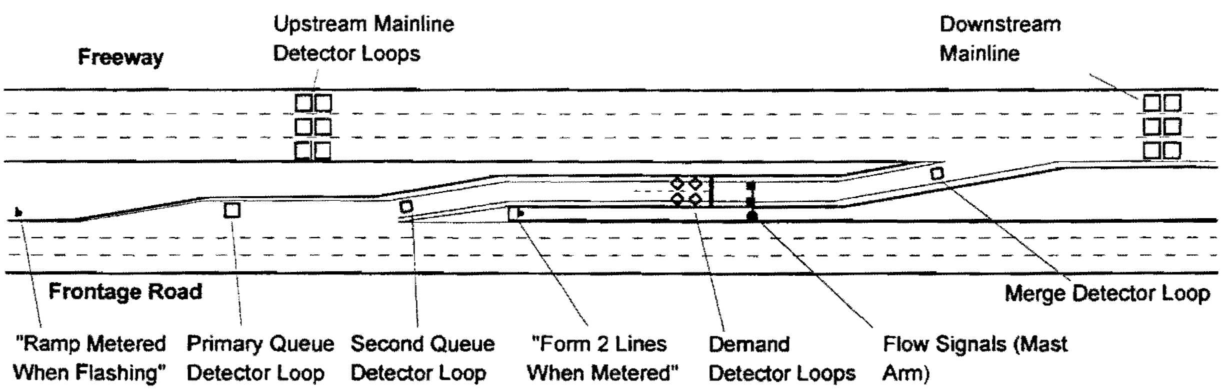


Figure 7. Proposed Dual-Lane Flow Signal Design Strategy

Geometric Guidelines

To address the storage and lateral clearance issues associated with frontage road/freeway slip-ramps, the typical on-ramp area will be lengthened and widened to provide adequate room for the dual-lane queue storage reservoir. The on-ramp ingress point will be modified to provide additional storage during metered periods through the development of a short auxiliary lane (i.e., similar to a left-turn bay at an intersection). This 35- to 50-meter auxiliary lane will allow approximately four to six additional vehicles to queue outside the frontage road travel lanes without disrupting the transition patterns of vehicles using the ramp during non-metered periods. The on-ramp will transition towards the freeway at the end of the auxiliary lane and then parallel the freeway and frontage road to allow for the dual-lane queue storage reservoir and traffic control equipment. The dual-lane queue storage reservoir will require a minimum pavement width of 6.7 meters, preferably 7.3 meters, and a length of 50 meters between the on-ramp transition area and the stop-bar. In addition, proper clearance should be provided between the edge of pavement and the nearest traffic control device to reduce potential maintenance and safety issues. From the stop-bar location, the on-ramp should have an acceleration/merge area that satisfies the design criteria defined in Figures 4 and 5. Due to the typically constrained lateral area between the freeway and frontage road in Texas, the freeway, frontage road, and on-ramp should include raised curbs and other longitudinal barriers to provide a safe refuge for queued vehicles and the traffic control devices associated with the flow signal.

Traffic Control Guidelines

The traffic control design elements should be consistent with the design criteria established within this chapter and TxDOT's current Manual of Uniform Traffic Control Devices (MUTCD) guidelines. The dual-lane flow signal should be controlled through either post- or mast arm-mounted traffic signals, depending on the local conditions. The approach and on-ramp signing will include an upstream "Ramp Metered When Flashing" warning sign, a "Form 2 Lines When Metered" regulatory sign at the beginning of the dual-lane queue storage reservoir, and "Stop Here On Red" and "One Vehicle Per Green" regulatory signs placed on both sides of the on-ramp at the stop-bar (assuming a post-mounted design).

The channelization of new or existing single-lane slip-ramps should only be altered to accommodate the added auxiliary lane, and a stop-bar will be placed upstream of the merge point based on the acceleration/merge area geometric design criteria. The on-ramp will maintain mainline, merge, demand, secondary, and primary queue detectors to provide the required data information to the flow signal controller under either local traffic-responsive or system control.

Operation Guidelines

The operational design elements of the proposed design strategy are consistent with the operational design criteria established in this chapter. The flow signal controller should permit one vehicle per green to go and alternate green signal displays equally between each queued lane to maintain consistent vehicular headways. The signal displays should dwell on red when the demand detectors are momentarily unactuated. The controller should be capable of metering low, medium, and high volume on-ramp arrival/discharge rate conditions and support a queue-responsive strategy that can contain the queue within the on-ramp area during metered operations when downstream freeway conditions permit. The dual-lane flow signal controller should be designed to operate under either local traffic-responsive or system control.

4. EVALUATION OF THE PROPOSED DUAL-LANE FLOW SIGNAL PLAN

INTRODUCTION

This chapter outlines the methodology used to evaluate the feasibility of the proposed dual-lane flow signals in Texas. The evaluation included a qualitative and quantitative analysis of the dual-lane flow signal design strategies developed in Chapter 3. A comparative analysis of single-lane and dual-lane flow signal systems was also performed based on actual field comparisons and microscopic simulation analysis runs. These analyses were based on the design and operation of an existing single-lane flow signal location in Houston.

This chapter also provides a detailed description of the study site, data collection and reduction procedures, and evaluation criteria. Study techniques used for the geometric design and construction evaluation, comparative analysis of single-lane and dual-lane flow signals, and the microscopic simulation analysis of the two flow signal options are described.

Study Site

The design and operation aspects of the existing Gessner Street eastbound (inbound) on-ramp located on Interstate 10 (Katy Freeway) in Houston, Texas were selected as the basis for the evaluation of the feasibility of dual-lane flow signals. This site was selected because of the variation in operational conditions encountered during the weekday morning rush hour, the lateral and longitudinal geometric constraints, and the existence of a single-lane flow signal where long queues and corresponding flow signal termination sequences occur during metered periods. In addition, this on-ramp location is within view of TxDOT's closed-circuit television cameras; therefore, an aerial perspective of the current operational conditions is also provided. Figure 8 illustrates the Gessner Street/Katy Freeway eastbound on-ramp study site location.

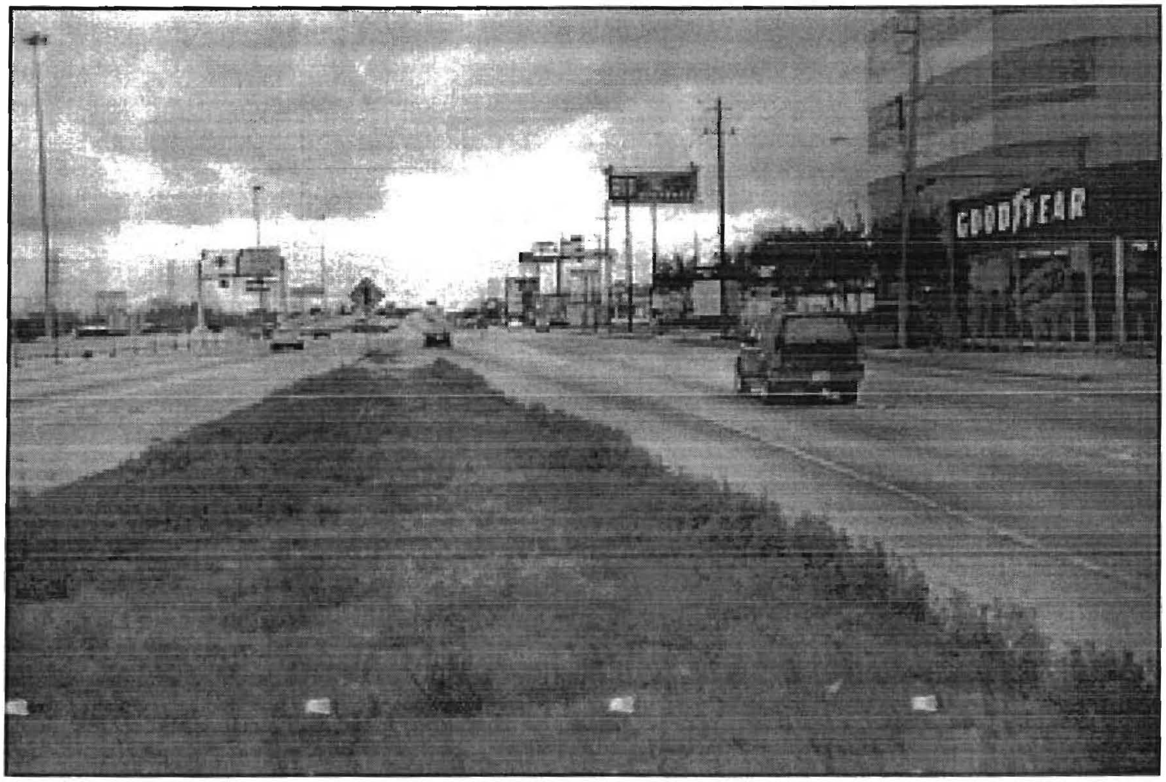


Figure 8. Gessner Street/Katy Freeway Eastbound On-Ramp, Houston, Texas

The Gessner Street/Katy Freeway eastbound on-ramp is located approximately 520 meters east of the signalized Gessner Street/Katy Freeway interchange terminal and 670 meters west of the signalized Bunker Hill Street/Katy Freeway interchange terminal along the eastbound Katy Freeway three-lane frontage road. This segment of the Katy Freeway maintains reverse diamond interchanges; therefore, the Bunker Hill Street off-ramp is located upstream of the Gessner Street on-ramp on the frontage road. The off-ramp and on-ramp are separated by approximately 110 meters, transition taper to transition taper, along the eastbound frontage road. The on-ramp currently accommodates approximately 12,000 to 14,000 vehicles per day. In the site vicinity, the Katy Freeway has a posted speed of 95 kilometers per hour and carries approximately 180,000 vehicles per day (two-way), while the eastbound frontage road has a posted speed of 65 kilometers per hour and carries approximately 20,000 vehicles per day downstream of the ramp weaving section. The frontage road provides multiple access points to the Memorial City Shopping Center located near the Gessner Street/Katy Freeway eastbound on-ramp.

Data Collection

Information about the existing design and operation of the Gessner Street/Katy Freeway eastbound on-ramp was collected to provide the data necessary to evaluate the dual-lane flow signal design strategy. First, an on-site investigation and review of "as-built" construction plans provided by TxDOT were used to ascertain information about the on-ramp, frontage road, and freeway geometrics. The timing plans for the single-lane flow signal controller and the Gessner Street/Katy Freeway signalized interchange terminals were obtained from TxDOT and the city of Houston, respectively. Finally, the on-ramp demand volumes and queues were recorded during the weekday morning metered period.

The on-ramp demand volumes and queues were recorded between 6:30 and 9:30 A.M. during typical Tuesday, Wednesday, and Thursday metered periods in May 1997. The on-ramp demand volumes were recorded at one-minute intervals and counted when the vehicle reached either the flow signal stop-bar or the back of the queue during queued conditions. The vehicular queues were observed at 15-second intervals; the number of vehicles counted in the queue included each vehicle stopped in the queue and those vehicles approaching the back-of-the-queue and traveling at 25 kilometers per hour (15 miles per hour) or less. In addition to the demand volume, queue counts, and observations, qualitative observations were made regarding the operation and traffic control elements of the existing single-lane flow signal. Appendix B provides a summary of the demand volume and queue data collected as part of this effort.

Data Reduction

To properly reduce the operational data recorded in the field, the one-minute demand volume counts and 15-second queue observations were used to generate 15-minute demand volume profiles and 15-minute queue profiles. In addition, this information was used to determine the on-ramp peak hour and corresponding demand volumes for the Tuesday, Wednesday, and Thursday morning metered periods. The average queue, queue variance, maximum queue, and average control delay were determined for both the weekday A.M. peak hour and three-hour metered periods to provide an operational baseline for the single-lane metered Gessner Street/Katy Freeway eastbound on-ramp.

From the queue and demand volume data collected, the average control delay was calculated based on the newly adopted 1997 Highway Capacity Manual (HCM) update to Chapter 9 methodology. The 1997 HCM calculation is provided in Equation 2 (*26*).

$$d = \frac{I \times \sum v_{iq}}{V_{tot}} \times 0.9 \qquad (2)$$

where:

d	=	average control delay per vehicle (seconds);
I	=	interval between vehicle-in-queue counts (seconds);
Σv_{iq}	=	sum of vehicle-in-queue counts (vehicles);
V_{tot}	=	total number of vehicles arriving during study period (vehicles); and
0.9	=	adjustment factor for the consistent tendency of field observers to overestimate vehicle-in-queue counts.

The average control delay was calculated for the peak hour and overall three-hour metered periods for each day. These data were then used to develop 15-minute control delay profiles.

DUAL-LANE FLOW SIGNAL FEASIBILITY ANALYSIS

To evaluate the feasibility of designing and operating dual-lane flow signals in Texas, three evaluation criteria were established to compare and measure the effectiveness of the proposed dual-lane flow signal strategy. These evaluation criteria are described below:

- *Geometric Design and Construction Feasibility:* The first evaluation criterion was established to determine if the dual-lane ramp configuration could be constructed under the typical frontage road/freeway slip-ramp configuration used in Texas. This determination is based on the dual-lane design strategy's compliance with TxDOT's engineering, safety, and economic requirements;
- *Operational Flexibility:* The second evaluation criterion was established to evaluate the operational flexibility of the proposed traffic control and operational design strategy. The proposed strategy was evaluated with respect to its ability to operate under a wide range of arrival patterns and low, medium, and high demand volumes. Secondly, using this criterion, the ability of the proposed design strategy to operate under both local traffic-responsive and system control was examined; and

- *Queue Containment:* The third evaluation criterion established was queue containment. Using this criterion, the dual-lane strategy was evaluated with respect to its ability to prevent the vehicular queues from interfering with the operation of or resulting in the potential degradation of the safety of the frontage road, freeway off-ramp, and signalized interchange terminals in the vicinity of the on-ramp.

Using the three evaluation criteria presented above, the feasibility of the proposed dual-lane flow signal strategy was analyzed through a geometric design and construction evaluation that examined the potential design and construction issues associated with the frontage road/freeway slip-ramp found in Texas. The analysis included a comparative analysis of single-lane and dual-lane flow signals that qualitatively and quantitatively evaluated the operational flexibility and queue containment criteria and a microscopic simulation analysis that evaluated the operational and queue containment criteria established through comparing the traffic control and operational characteristics of single-lane and dual-lane flow signals. In addition, the microscopic simulation analysis tested the queue management strategy of the dual-lane flow signal traffic control strategy. From these analyses and evaluations, the feasibility of designing and operating dual-lane flow signals in Texas was determined.

Geometric Design and Construction Evaluation

To evaluate the feasibility of designing and constructing dual-lane flow signals in Texas, the proposed design strategy outlined in Chapter 3 was used to prepare a conceptual design of a dual-lane flow signal demonstration project for TxDOT at the Gessner Street/Katy Freeway eastbound on-ramp. The proposed project design was reviewed by TTI and TxDOT engineers for actual field installation. This review included an evaluation of the proposed design using geometric design and construction feasibility criterion. Appendix C includes an illustration of the proposed dual-lane demonstration project for the Gessner Street/Katy Freeway eastbound on-ramp.

Comparative Analysis of Single- and Dual-Lane Flow Signals

To properly evaluate the operational flexibility and queue containment criteria established as part of this research, the existing single-lane flow signal at the Gessner Street/Katy Freeway eastbound on-ramp was compared to the proposed dual-lane flow signal demonstration project. This analysis was based on a qualitative comparison of the two systems' metering capabilities and available queue storage areas. Differences in the capabilities of the single-lane and dual-lane metering systems were determined based on the operational performance data obtained through the survey discussed in Chapter 3. The percentage of observed queues that each system could accommodate within the on-ramp storage area during the weekday morning metered periods was also compared.

Microscopic Simulation Analysis of Traffic Control and Operational Characteristics

To evaluate the traffic control and operation elements of a dual-lane flow signal configuration on a frontage road/freeway slip-ramp, the operational flexibility and queue containment of the proposed dual-lane flow signal design strategy was also analyzed using microscopic simulation. The microscopic simulation analysis focused on a comparison of the operational performance of single-lane and dual-lane flow signals and the operational flexibility of the proposed dual-lane design strategy and queue management strategy. This analysis was based on the measured demand volumes and artificially developed arrival patterns to simulate the traffic control and operational characteristics of the Gessner Street/Katy Freeway eastbound on-ramp.

To compare the existing single-lane and proposed dual-lane flow signal configurations at the Gessner Street/Katy Freeway eastbound on-ramp, the existing Tuesday, Wednesday, and Thursday morning peak hour metering period operations were analyzed using microscopic simulation. This comparison was based on an evaluation of the following three geometric and traffic control scenarios:

- A single-lane flow signal configuration with a fixed-time metering rate of 900 vehicles per hour (consistent with the existing Gessner Street/Katy Freeway eastbound on-ramp geometry and flow signal timing plan);

- A dual-lane flow signal configuration with a fixed-time metering rate of 900 vehicles per hour (consistent with the proposed dual-lane flow signal demonstration project design and the existing Gessner Street/Katy Freeway eastbound on-ramp flow signal timing plan); and
- A dual-lane flow signal configuration with a fixed-time metering rate of 900 vehicles per hour and the proposed queue management strategy described in Chapter 3 (consistent with the proposed dual-lane flow signal demonstration project design and the existing Gessner Street/Katy Freeway eastbound on-ramp flow signal timing plan).

Using the three geometric and traffic control scenarios described above, the operational performance of the existing single-lane flow signal configuration and timing plan was compared to the proposed demonstration project geometric configuration with and without the queue management strategy. This comparative analysis examined the average queue, maximum queue, and average control delay for each period. In addition, the queue containment was evaluated according to the percent of time that the vehicular queue could be managed within the on-ramp area.

The operational flexibility and queue responsiveness of the proposed dual-lane flow signal control strategy was demonstrated and reviewed qualitatively by systematically increasing the on-ramp demand volume through simulation using a normally distributed arrival pattern. The dual-lane flow signal demonstration project design for the Gessner Street/Katy Freeway eastbound on-ramp was tested using five successive 10-minute demand volumes of 800, 950, 1,050, 1,250, and 1,600 vehicles per hour. The specified local metering rate was established at 900 vehicles per hour. The simulation run was evaluated primarily to demonstrate the ability of the dual-lane flow signal design strategy to efficiently operate under various arrival demands and reliably contain the ramp queues within the on-ramp queue storage reservoir.

The single-lane/dual-lane comparative analysis and dual-lane flow signal flexibility analysis were both conducted using the metering levels and the secondary/primary queue detector settings shown in Tables 7 and 8, respectively.

Table 7. Meter Levels for the Microscopic Simulation Analysis

Meter Level	Discharge Rate	Meter Level	Discharge Rate
A	(Dark Phase - Off)	E	1,000 vph
B	1,714 vph	F	900 vph
C	1,500 vph	G	800 vph
D	1,200 vph	H	500 vph

Table 8. Queue Detector Settings for the Microscopic Simulation Analysis

Secondary Queue Detector Settings		Primary Queue Detector Settings	
Unactuated Time	5 seconds	Actuated Time	5 seconds
Occupancy Threshold	50%	Unactuated Time	5 seconds
Occupancy Interval (time between successive checks)	10 seconds		

DUAL-LANE FLOW SIGNAL EVALUATION RESULTS

The analysis and evaluation results of the dual-lane flow signal design strategy are presented in this section. These results positively address the three evaluation criteria previously established in this chapter: geometric design and construction feasibility, operational flexibility, and queue containment.

Geometric Design and Construction Evaluation Results

Analysis of the proposed dual-lane flow signal design revealed that a dual-lane flow signal configuration can be implemented on a frontage road/freeway slip-ramp similar to the Gessner Street/Katy Freeway eastbound on-ramp if the design complies with the proposed geometric elements of the design strategy. This finding was verified by the TxDOT and TTI operational specialists' and designers' review of the proposed demonstration project. According to their review, the proposed demonstration project includes the necessary geometric, traffic control, and operational features that will likely provide a safe and functional freeway management system. Furthermore, the proposed demonstration project design developed from the strategy was approved by TxDOT staff for field implementation and testing in late 1997.

Based on the geometric design and construction analyses, it was determined that a 12-meter lateral separation in cross-section represents the absolute minimum lateral separation between the outside freeway and inside frontage travel lanes at the meter required for dual-lane flow signal operations having post-mounted flow signals. This distance is required to effectively construct and operate a dual-lane post-mounted flow signal configuration on frontage road/freeway slip-ramps. A ramp separation of 15 meters or more would be preferred for developing dual-lane flow signals.

Results of the Single-Lane And Dual-Lane Flow Signal Comparative Analysis

Review of the dual-lane ramp meter survey and the Gessner Street/Katy Freeway eastbound on-ramp geometric, traffic control, and operational results revealed that the dual-lane flow signal design strategy provides significant improvements in overall operational flexibility compared to the existing single-lane flow signal design used in Houston. The following benefits and findings indicate that the dual-lane design is feasible and could provide wide-range operational flexibility:

- The dual-lane configuration can provide discharge rates up to approximately 1,800 vehicles per hour based on the operational performance experienced in California, Minnesota, and Washington;
- The queue storage reservoir provides approximately 100 to 130 percent more storage capacity than the traditional single-lane configuration (*13*); and
- Because of the operational flexibility of the dual-lane design strategy, continuous operation can be maintained under a wide range of demand volumes and various on-ramp arrival patterns.

The evaluation of the queue containment capabilities of the single- and dual-lane flow signal design configurations at the Gessner Street/Katy Freeway eastbound on-ramp revealed that the proposed dual-lane demonstration project design provides approximately twice the available queue storage area as the existing single-lane configuration [i.e., 18 to 20 vehicles under the dual-lane configuration versus 8 - 10 vehicles under the single-lane configuration assuming approximately 9 meters (30 feet) per vehicle]. The percentage of queues contained within the on-ramp area was also calculated for both the single-lane and dual-lane designs. This calculation was based on the distribution of the observed 15-second interval queues at the Gessner Street/Katy Freeway eastbound on-ramp.

Figures 9 through 11 illustrate the observed queues and the calculated containment (percentage of time all queued vehicles are stored within the on-ramp queue storage reservoir) under each flow signal configuration for Tuesday, Wednesday, and Thursday morning metering periods, respectively.

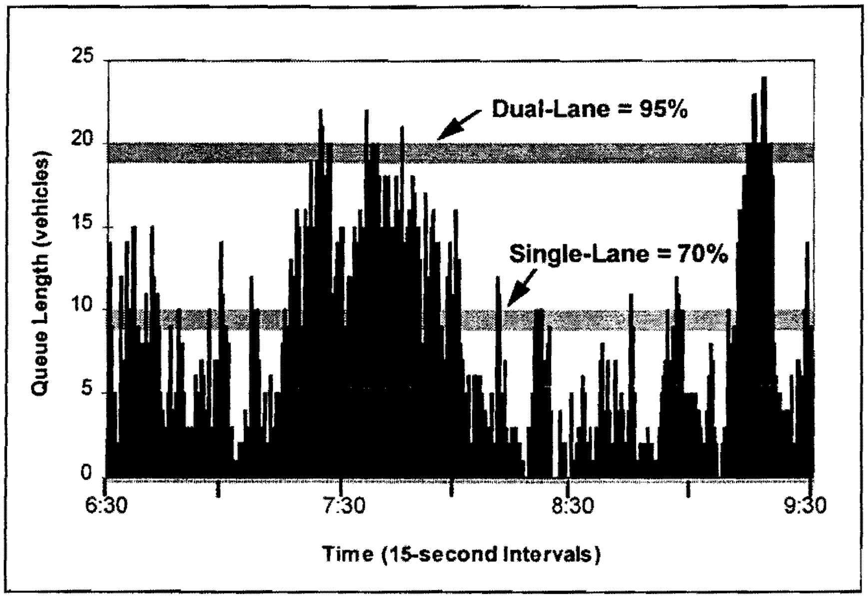


Figure 9. Comparative Analysis of Observed Physical Queue Containment at Gessner Street/Katv Freeway Eastbound On-Ramp (Tuesday Morning Metering Period)

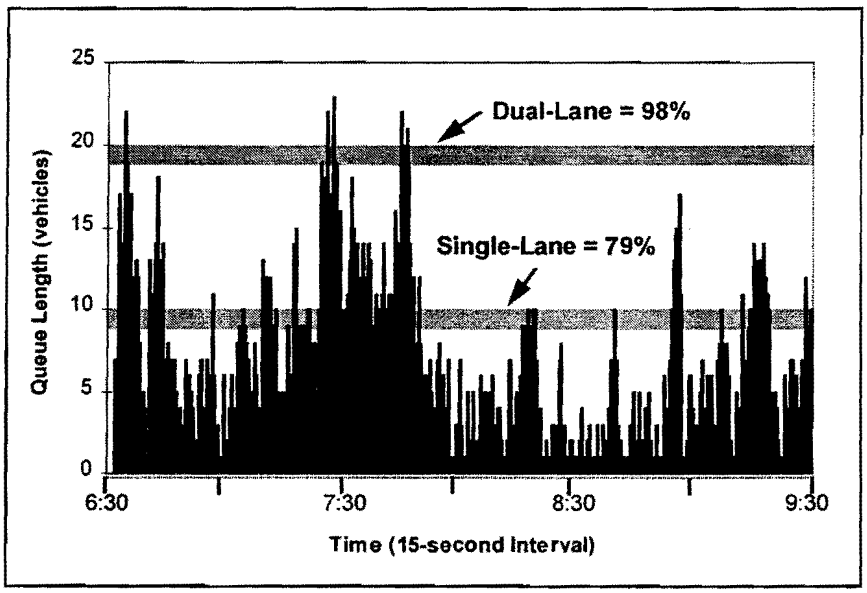


Figure 10. Comparative Analysis of Physical Observed Queue Containment at Gessner Street/Katy Freeway Eastbound On-Ramp (Wednesday Morning Metering Period)

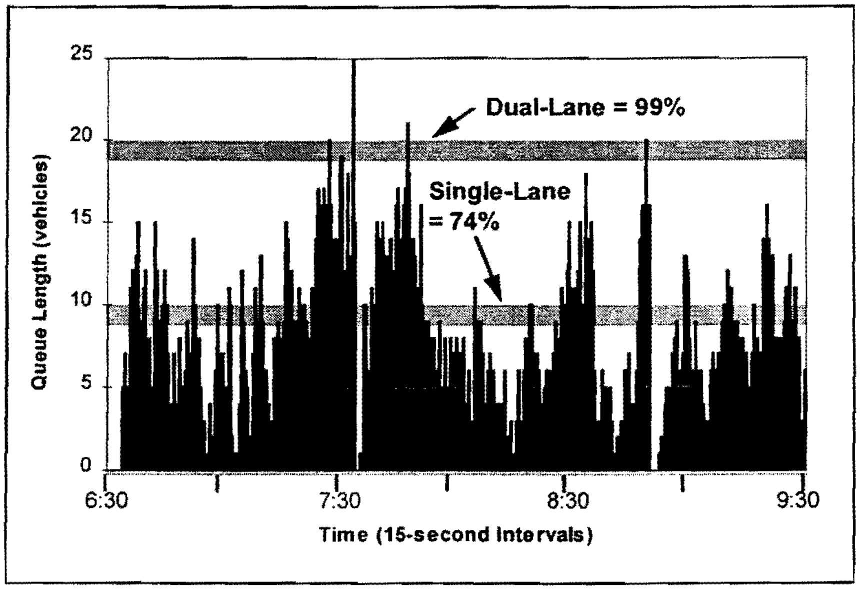


Figure 11. Comparative Analysis of Observed Physical Queue Containment at Gessner Street/Katy Freeway Eastbound On-Ramp (Thursday Morning Metering Period)

As shown in Figures 9 through 11, the existing single-lane design can only accommodate 70 to 79 percent of the queues that occur during a typical morning peak period (using a metering rate of 900 vehicles per hour). The remaining 21 to 30 percent of the queues spill back onto the frontage road. However, the proposed dual-lane flow signal configuration can accommodate between 95 and 99 percent of the queues that occur during a typical weekday morning metering period at the Gessner Street/Katy Freeway eastbound on-ramp. Therefore, the dual-lane design represents an improvement of approximately 25 percent in queue containment and nearly eliminates all queue spillbacks onto the adjacent frontage road based on the existing weekday morning metering period conditions.

The above comparisons are based solely on the physical storage space of the two flow signal design configurations and do not account for the increased efficiency of the queue responsive traffic control elements that can be provided by the dual-lane flow signal design strategy (i.e., the proposed queue management strategy). The combination of the queue responsive traffic control elements and the operational flexibility of metering up to approximately 1,800 vehicles per hour indicates the potential benefit of adopting a dual-lane flow signal design configuration for frontage road/freeway slip ramps.

Microscopic Simulation Analysis Results of Traffic Control and Operational Characteristics

As part of the microscopic simulation analysis process, field data were used in an attempt to calibrate TTI's TexRAMBO model to reflect existing traffic control and operational conditions at the Gessner Street/Katy Freeway eastbound on-ramp. This calibration process included loading recorded one-minute demand volumes and adjusting the timing of an upstream traffic signal on the frontage road to generate the arrival patterns observed in the field. In addition, a traffic controller and loop detectors were modeled to simulate the existing flow signal controller timing plan and demand detector placements. The objective of the calibration was to generate queues and control delays from TexRAMBO that resembled those measured in the field and presented earlier in this chapter.

From the calibration process, it was determined that the simulated queue and delay results were consistently underestimated. This can be attributed to TexRAMBO's inability to generate the highly variable arrival patterns observed in the field. In addition, several other modeling issues were discovered that limited the capabilities to model the existing Gessner Street/Katy Freeway traffic control and operation conditions, including:

- The placement and response of demand detectors in the model appear to provide more efficient service to vehicles queued at the flow signal location. This more efficient service may be attributed to the fact that vehicles in the field do not always actuate the demand detector immediately following the departure of the vehicles from the stop-bar. Therefore, the actual maximum service rate in the field is probably less than 900 vehicles per hour. This response/service rate issue may be responsible for the reduced measures in delays and queue lengths in the simulated model; and
- The simulation does represent the demands of densely packed platoons arriving at the flow signal. In TexRAMBO, the arrivals are more indicative of uniform arrival patterns during the one-minute increments, whereas the actual arrival patterns observed in the field are highly variable. This problem is reflective of the highly variable arrival patterns discussed earlier. This results in reductions in the delays and queues estimated through simulation.

Based on the issues discussed above, it was determined that the present version of TexRAMBO could not emulate the highly variable arrival patterns experienced at the study site. However, it was also determined that the model could provide a comparative analysis between different geometric and traffic control conditions.

The results of the simulation analysis demonstrating the operational flexibility of the proposed dual-lane flow signal strategy are summarized in Figures 12 through 14. Figure 12 illustrates the increasing demand volumes and the corresponding flow signal discharge rates generated by the queue management strategy to contain queues within the dual-lane flow signal queue storage reservoir.

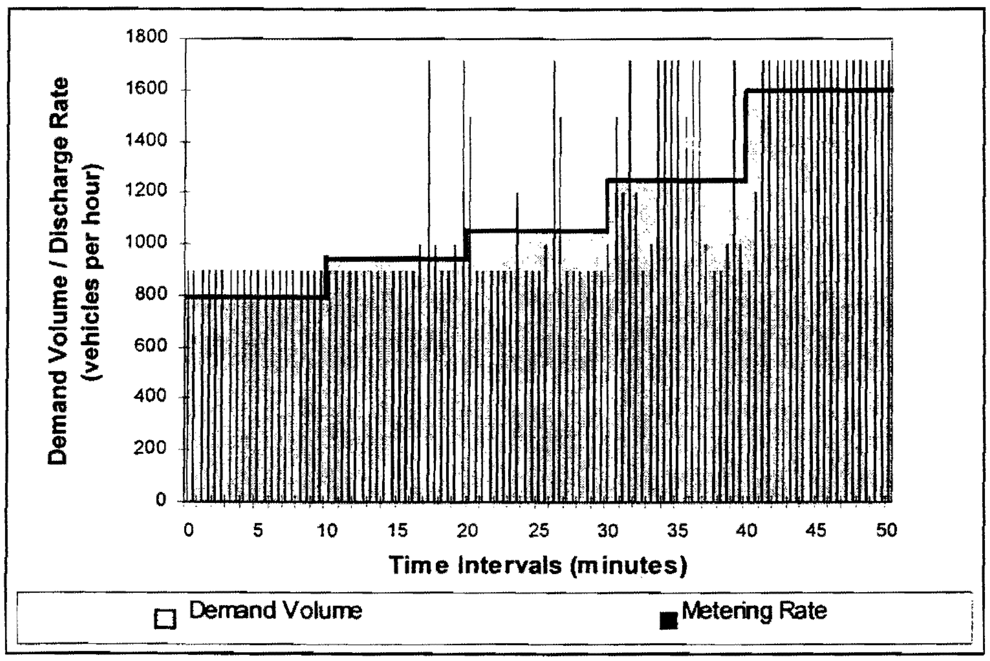


Figure 12. Demonstration of the Metering Rate Queue Adjustments Versus Increasing Demand Volumes

As Figure 12 illustrates, the modeled dual-lane flow signal configuration for the Gessner Street/Katy Freeway eastbound on-ramp maintains a target metering rate of 900 vehicles per hour with slight adjustments under medium-demand volumes (i.e., 600 to 1,200 vehicles per hour). However, the target rate cannot be effectively maintained under high-demand volumes.

To measure the performance of the flow signal system under various demand volumes, the freeway management technique reliability was calculated for each 10-minute period. The reliability is computed as the percentage of time the flow signal is able to produce the target metering rate (i.e., 900 vehicles per hour). Table 9 indicates the reliability results for the traffic control strategy demonstration.

Table 9. Demonstration of the Flow Signal Reliability Versus Increasing Demand Volumes

Demand Volume	Reliability
800 vph	100%
950 vph	75%
1,050 vph	70%
1,250 vph	25%
1,600 vph	10%

Figures 13 and 14 overlay the averaged 30-second queue length results and control delays, respectively, on the demand volume/metering discharge rate plot shown previously in Figure 12. As shown in Figures 13 and 14, the microscopic simulation analysis demonstrates that queues can be contained effectively under the proposed dual-lane ramp geometric and traffic control design strategies. In addition, the average queue length and control delay results demonstrate the operational flexibility of the design strategy. However, it is important to remember that these demonstrations do not fully account for the high variability in on-ramp arrivals experienced at the study site location.

Due to the current limitations in the TexRAMBO, Version 4.0, simulation model, additional arrival distributions should be developed to enhance the accuracy of the model.

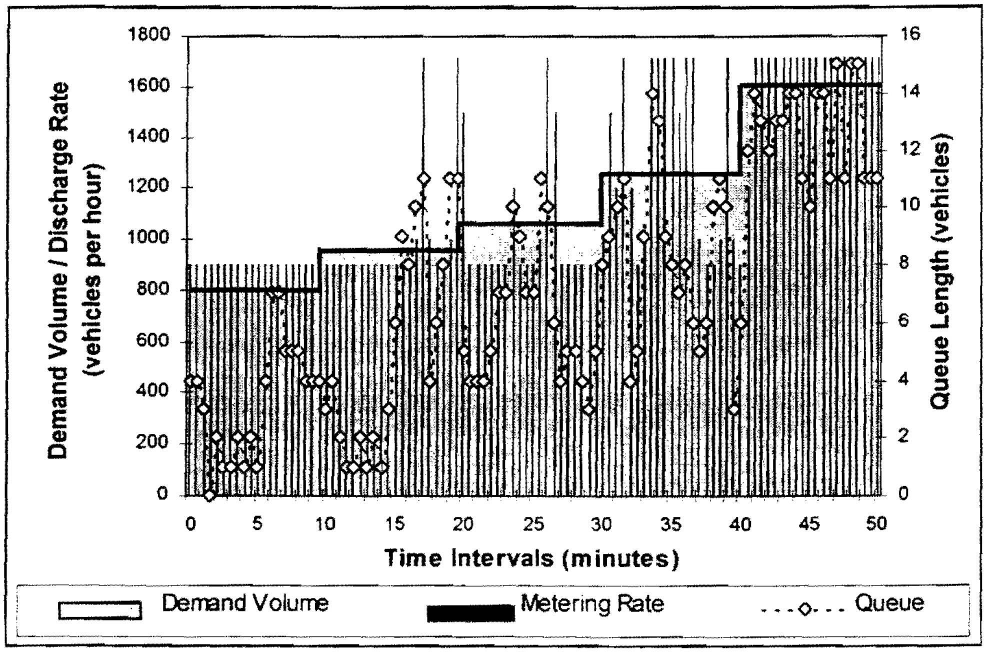


Figure 13. Simulated Queue Containment Demonstration

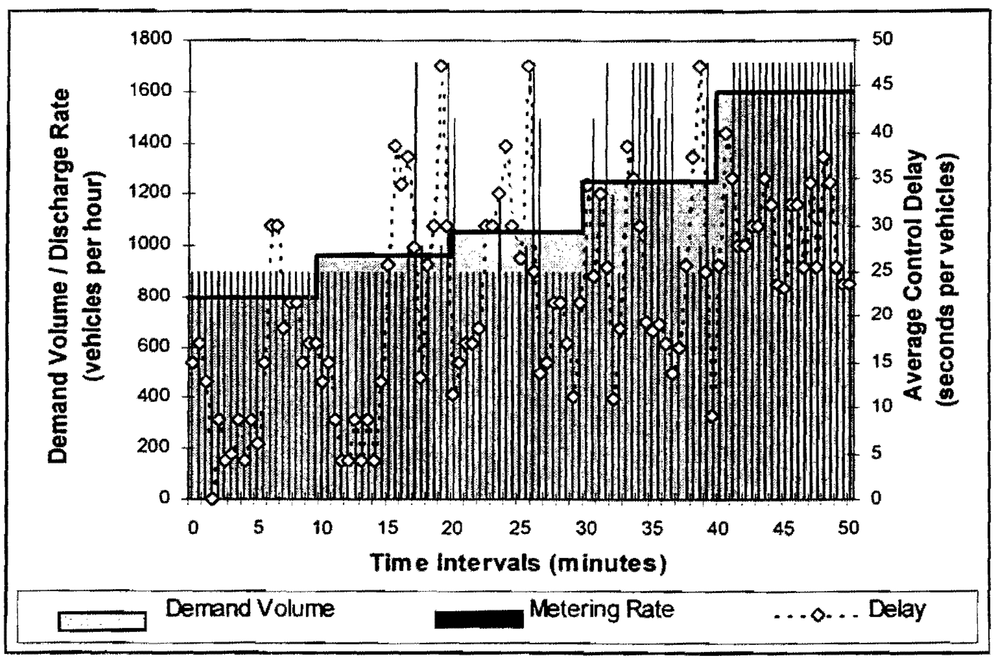


Figure 14. Simulated Operational Flexibility Demonstration

DISCUSSION OF RESULTS

A review of the analysis and evaluation results presented in this chapter reveal that the proposed dual-lane flow signal design strategy achieves the three evaluation criteria established. The analysis also reveals that the dual-lane flow signal design strategy provides a superior freeway traffic management system compared to the single-lane flow signal configuration. Table 10 is a summary of the established evaluation criteria and research findings comparing the two flow-signal configurations.

Table 10. Summary of Evaluation Criteria

Evaluation Criteria	Single-Lane Flow Signals	Dual-Lane Flow Signals
Geometric Design and Construction	Can be readily designed and constructed on frontage road/freeway slip-ramps.	Requires a minimum of 12 meters (preferably 15 meters) of lateral clearance to design and operate on frontage road/freeway slip-ramps.
Operational Flexibility	Cannot effectively meter vehicles at discharge rates above 900 vehicles per hour. Excessive queues cause lapses in metering during peak hour periods. Preferential lane priority for carpool, vanpools, and/or transit cannot be provided.	Capable of metering demand volumes up to approximately 1,800 vehicles per hour. Queue responsive traffic control elements allow for continuous metering. Preferential lane treatments can be provided in the second lane for carpools, vanpools, or transit.
Queue Containment	Not capable of managing medium-to-high demand volumes with platoon or pulse arrival patterns.	Available storage area and queue responsive traffic control features allow for the accommodation of a variety of demand volumes and arrival patterns.

Based on the findings summarized in Table 10, the proposed dual-lane flow signal conceptual design (see Appendix C) is recommended to be developed as a demonstration project to evaluate and refine the geometric, traffic control, and operational elements presented in Chapter 3.

Other Operational Issues

In addition to the findings summarized in Table 10, the prior analysis suggests that the general assumptions (e.g., Poisson arrivals and platoon adjustment factors) used to analyze delays and queues at signalized intersections are not directly applicable to flow signals. The generalizations used in the HCM regarding arrival patterns can significantly affect the calculated delays depending on the selected arrival type and the proportion of vehicles which arrive on red. These issues, as discussed by Olszewski, can lead to the possibility of either significantly underestimating or overestimating the delay at signalized intersections (*27*). As part of Olszewski's research, he suggested that a more precise step arrival model should be employed to eliminate the errors incurred by the selection of an appropriate arrival type. This model would require users to measure the proportion of vehicles that arrive on red and provide better estimates of average control delay experienced. However, neither the HCM nor the proposed step-arrival model provide the ability to estimate delays or queues at flow signals.

Unlike traditional traffic signals, the red and green indications used in flow signals are typically short (e.g., 2.0 to 4.0 seconds). At traffic signals, the arrival pattern during the red period does not significantly influence the total queue length at the beginning of the green phase assuming identical demand volumes within that same period. The amount of vehicles (or demand volume) during the red period defines the queue length. Therefore, the analyst must only know the approximate distribution in arrival rates during discrete periods to adequately estimate the queue length because queues are typically dissipated during each cycle when conditions are undersaturated. However, a flow signal does not discharge the entire queue at one time, rather the queue is serviced at a predetermined metering rate. This difference makes it more difficult to determine the queue length and subsequently the control delay at a flow signal without more specific arrival pattern information.

Another important factor to remember in evaluating single-lane flow signals similar to those operated in Texas or the dual-lane flow signal design strategy proposed by this research is that the capacity provided by the flow signal is equal to the demand at the flow signal. Flow signals only discharge vehicles when they are detected and, conversely, will accommodate high-demand volumes (i.e., excessive queues) by either terminating the metering (existing single-lane method) or increasing the metering rate (proposed dual-lane, queue management strategy). This unique operational situation in which the demand equals capacity raises several issues in regards to estimating the delays and queues at flow signals.

Based on the discussion above, further research should be conducted regarding the estimation of arrival patterns at flow signal locations. The research would provide a better understanding of the expected delays and queues at single-lane and dual-lane flow signals. In addition, the TexRAMBO simulation model should be updated to provide a better range of distribution patterns to help researchers estimate highly variable arrival patterns similar to those observed at the Gessner Street/Katy Freeway eastbound on-ramp.

5. CONCLUSIONS AND RECOMMENDATIONS

As recurrent congestion and the number of vehicles on urban freeways in the state of Texas have increased, the ability to effectively meter traffic using single-lane flow signals has diminished. Other state departments of transportation experiencing similar conditions have developed and implemented multiple-lane flow signals to address the increased demand volumes and variable on-ramp arrival patterns. These multiple-lane systems have increased operational flexibility and available storage area as compared to traditional single-lane flow signals. As a result, TxDOT is interested in evaluating the feasibility of designing dual-lane flow signals on frontage road/freeway slip-ramps commonly found in Texas.

This research's primary objective was to evaluate the feasibility of designing and operating dual-lane flow signals on frontage road/freeway slip-ramps in a safe and efficient manner. For this reason, the geometric, traffic control, and operational elements necessary to operate this freeway management strategy were reviewed and analyzed.

To evaluate the proposed dual-lane flow signal design strategy, an existing single-lane flow signal location was selected in Houston. This site was used to compare the design and operation of the existing single-lane and the proposed dual-lane flow signal configurations.

Based on an analysis of the single-lane flow signal traffic control parameters and operations, three primary evaluation criteria were established to determine the feasibility of operating a dual-lane flow signal at the study site (Gessner Street/Katy Freeway eastbound on-ramp). These evaluation criteria included:

- the ability to design and construct a dual-lane flow signal on a frontage road/freeway slip-ramp configuration that adheres to TxDOT's engineering and safety requirements and economic considerations;
- the ability to meter a wide range of on-ramp demand volumes (i.e., 0 to 1,800 vehicles per hour) and manage various arrival patterns; and
- the ability to contain queues within the on-ramp queue storage reservoir without spillback occurring on the adjacent frontage road or upstream on-ramp and signalized interchange termini, or on both.

The conceptual Gessner Street/Katy Freeway eastbound on-ramp dual-lane flow signal design was examined both qualitatively and quantitatively with respect to the three established evaluation criteria. This evaluation included the analysis of the geometric design and construction evaluation, a comparative analysis of single-lane and dual-lane flow signals, and a microscopic simulation analysis. The microscopic simulation analysis was used to compare the existing and proposed flow signal configurations, and to demonstrate the traffic control and operational flexibility of the dual-lane flow signal design strategy. Based on these analyses and evaluations, the design and operation of a dual-lane flow signal on a frontage road/freeway slip-ramp was deemed feasible.

CONCLUSIONS

Analysis of the geometric, traffic control, and operational element investigated as part of this research revealed that a dual-lane flow signal configuration can be feasibly designed and operated on a typical frontage road/freeway slip-ramp in Texas. In addition, the dual-lane flow signal design strategy can improve the operations and safety provided by the single-lane flow signal design used today, as discussed below:

- The dual-lane flow signal design strategy offers the following benefits as compared to traditional single-lane flow signal design strategy: the ability to meter up to approximately 1,800 vehicles per hour compared to the 900 vehicles per hour limitation associated with single-lane configurations; the ability to store 100 to 130 percent more vehicles in the same distance; the opportunity to provide preferential lane assignments for carpools, vanpools, and transit; the flexibility to accommodate various on-ramp demand volumes and arrival patterns; and the reduction in flow signal violations by motorists;
- The proposed dual-lane flow signal design strategy developed is both practical and economically feasible to design and construct on urban freeways that have at least 12 meters of lateral distance between the outside freeway and inside frontage road travel lanes; and
- The proposed dual-lane flow signal traffic control strategy is compatible under fixed-time, local traffic responsive, and system control techniques.

RECOMMENDATIONS

The following recommendations are offered based on the survey and analyses conducted as part of this research effort:

- Based on the operational success of dual-lane flow signals on traditional diamond- and parclo-type interchanges in other states and the analyses conducted as part of this research, the proposed conceptual dual-lane flow signal design (see Figure 7), as illustrated for the Gessner Street/Katy Freeway eastbound on-ramp (see Figure 8), is recommended to be developed into a field demonstration project to further evaluate the geometric, traffic control, and operational issues associated with operating a dual-lane flow signal configuration on frontage road/freeway slip-ramps; and
- Prior to the deployment of the proposed dual-lane flow signal demonstration project, the current RMC-300 controller specifications need to be modified to provide the additional traffic control features recommended for two-lane metering described herein.

FUTURE RESEARCH

Based on this research's survey and analyses, it is recommended that future research be conducted in the following areas related to the geometric, traffic control, and operational design elements of dual-lane flow signals located on frontage road/freeway slip-ramps:

- The placement of the secondary queue detector within the queue storage reservoir should be evaluated to determine the best location for queue responsiveness within the traffic control strategy proposed in this report. In addition, the time duration of actuation/unactuation and the required queue occupancy to adjust the metering rate should be examined through simulation and field experimentation;
- Primary queue detector placement and occupancy detection parameters should be examined through both simulation and field experimentation to determine the design and traffic control elements necessary to prevent queue spillbacks onto the frontage road and upstream in the off-ramp merge area and signalized interchange terminal;
- On-ramp discharge rates between successive metering levels should be explored relative to both isolated and system control and the queue responsiveness of metered on-ramp locations;

- Following the development and installation of the demonstration project, the operations of the dual-lane flow signal configuration should be recorded and compared to the operations occurring under the existing single-lane configuration. Particular attention should be paid to the queue containment and traffic control capabilities; and
- Further research should be conducted to establish application guidelines for single-lane and multiple-lane flow signals.

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15. Rotich, W. Oregon Department of Transportation, Portland, Oregon. Questionnaire conducted May 1997.

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APPENDIX A:

DUAL-LANE RAMP METER SURVEY AND MAILING LIST

SURVEY OF DUAL-LANE RAMP METERING

This survey is being used to evaluate the feasibility of the design and operation of dual-lane ramp meters in the state of Texas. Your help in answering these questions is greatly appreciated by the Texas Transportation Institute.

- Please fill out the applicable sections of the survey and mail/fax it back (see end of survey for mail/fax information), or answer via e-mail by requesting an electronic copy of the survey at *mbutorac@ttiadmin.tamu.edu*. Please return the surveys prior to May 5, 1997.
- Any questions regarding the survey may be directed to Marc Butorac either by telephone at (409) 845-9881 or by e-mail at *mbutorac@ttiadmin.tamu.edu*.

Survey Questions:

1. Your name:

2. Contact name (if different):

   Agency:

   Address:

   Phone: E-Mail:

3. Approximately how many ramp meters are currently operational in your agency?

   Total number of ramp meters:

   Freeways which maintain operational ramp meters (list facilities):

4. If you operate dual- or multi-lane meters, please fill out the table below regarding the ramp meter configuration types:

Type of Multi-Lane Meter	Yes	No	# of Meters
Single-Lane + HOV Bypass			
Dual-Lane with Mixed Traffic			
Dual-Lane + HOV Bypass (parallel lanes)			
Dual-Lane + HOV Bypass (separated HOV lane)			
Three-Lane with Mixed Traffic			
Other:			

HOV: High Occupancy Vehicle

5. How are your multi-lane ramp meters operated (e.g., time staggered, space staggered, simultaneously, or random) in relationship to a vehicle's presence and the displayed green time?

6. What is your minimum and maximum dual-lane metering rates (vph) and corresponding green, yellow (if used), and red display times?

Metering Rate	Vehicles/Hour	Green	Yellow Time	Red Time
Minimum				
Maximum				

How many vehicles do you release per green displayed?

7. What is your desired and minimum pavement width and clear distances to the nearest obstruction on a dual-lane ramp?

8. What type of ramp meter control (e.g., fixed-time, traffic responsive, integrated system, or other) do you use?

What ramp meter software package do you use?

9. What is your dual-lane ramp meter initialization or start-up process (warning device, time, sequence of events)?

10. What is your termination sequence (shut-off procedure) for dual-lane ramp meters?

11. What is your excessive queue policy for dual-lane ramps?

12. What is your signal head mounting practice (pole or mast arm mounted)?

What is your standard signal display (three or two heads)?

What is your standard signing configuration at the ramp meter signal? Please illustrate the signing location and message below.

13. What type of loop detectors do you employ, and how are they related to the function of the ramp meter controller?

Type of Detector	Yes	No	Function
Mainline Detector			
Merge Detector			
Passage Detector			
Demand or Presence Detector			
1st Upstream Queue Detector			
2nd Upstream Queue Detector			
Other:			

14. What other geometric design, control, or operational issues do you think are important under a dual-lane ramp meter configuration?

Geometric Design:

Control:

Operation:

15. Would you like a copy of the final report?

If you are able to provide any literature, design standards, standard detail drawings, or specification regarding the geometric design, control, and/or operation of your dual-lane ramp metering systems, it would be greatly appreciated. Thank you for your time!

<u>Survey Submittal Process</u>:

Please mail, fax, or e-mail your survey responses to:

MAIL: Marc A. Butorac
Transportation Systems Division
Texas Transportation Institute
TTI/CE Building, Room 304B
Texas A&M University System
College Station, TX 77843-3135

FAX: (409) 845-6481

E-MAIL: mbutorac@ttiadmin.tamu.edu

PHONE: (409) 845-9881

MAILING LIST

State	Contact Person	Address	Survey Returned?
Arizona	Jerry Pfeifer	Arizona DOT 2302 West Durango Street Phoenix, AZ 85009 (602) 255-7809	Yes
California	Laurie Guiness	Caltrans - Traffic Operations Program 1120 N Street Sacramento, CA 95814 (916) 654-6112	Yes
Colorado	Gordon Hickman	Colorado DOT 2000 South Holly Street Denver, CO 80222 (303) 757-9939	Yes
Florida	R.W. Brindley	Kimley-Horn & Associates, Inc. 14750 NW 77th Court, Suite 100 Miami Lakes, FL 33016 (305) 827-0588	Yes
Georgia	Joe Stapleton	Georgia DOT #2 Capitol Square S.W. Atlanta, GA 30334-1002 (404) 635-8005	Yes
Illinois	A. P. Cioffi	Illinois DOT 445 West Harrison Oak Park, IL 60304 (708) 524-2145	Yes
Michigan	Raymond Klucens	Michigan DOT 1050 6th Street Detroit, MI 48226 (313) 256-9800	Yes

State	Contact Person	Address	Survey Returned?
Minnesota	Glen Carlsen	Minnesota DOT 1101 4th Avenue South Minneapolis, MN 55404 (612) 341-7500	Yes
New York	Tom Werner	New York State DOT 1220 Washington Avenue Albany, NY 12232 (518) 457-1780	Yes
Ohio	Len Kutney	City of Columbus 109 N. Front Street Columbus, OH 43215 (614) 645-7792	Yes
Oregon	Dorothy Upton	Oregon DOT 123 NW Flanders Street Portland, Oregon 97209 (503) 731-8205	Yes
Virginia	Jimmy Chu	Virginia DOT 1426 Columbia Pike Arlington, VA 22203 (703) 383-2600	Yes
Washington	Kristen Benson	Washington State DOT 15700 Dayton Avenue North P.O. Box 330310 Seattle, WA 98133 (206) 440-4466	Yes
Wisconsin	Amanda Zacharias	Wisconsin DOT 633 West Wisconsin Avenue, Suite 1200 Milwaukee, WI 53203 (414) 227-2141	Yes
Quebec	Sandra Sultana	Quebec Ministry of Transport 255 Cremazie Est, Local RC.1 Montreal, Quebec, Canada H2M 1L5 (514) 873-5245	Yes

APPENDIX B:

MAY 1997 QUEUE AND DEMAND VOLUME DATA FOR THE GESSNER STREET/KATY FREEWAY SINGLE-LANE FLOW SIGNAL

	Tuesday (5/6/1997)			Wednesday (5/14/1997)			Thursday (5/8/1997)		
Time	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	2								
	7								
	14								
630	9	15	8			0			0
	3								
	3								
	5								
631	5	19	4			0			0
	3			7					
	0			7					
	1			7					
632	0	6	1	15	13	9			0
	2			17					
	9			14					
	12			13					
633	7	21	7.5	5	13	12.25			0
	6			8			5		
	3			20			7		
	5			22			7		
634	14	11	7	19	15	17.25	5	17	6
	14			16			4		
	10			12			2		
	8			7			2		
635	7	15	9.75	17	16	13	8	12	4
	4			14			11		
	13			12			12		
	15			8			10		
636	15	16	11.75	7	16	10.25	12	14	11.25
	11			6			11		
	7			8			9		
	3			13			13		
637	5	15	6.5	12	15	9.75	15	16	12
	9			9			10		
	7			8			9		
	8			3			7		
638	5	14	7.25	1	11	5.25	7	12	8.25
	4			5			9		
	3			5			11		
	8			4			12		
639	11	5	6.5	1	12	3.75	7	17	9.75
	8			0			4		
	6			0			2		
	5			8			8		
640	4	12	5.75	13	17	5.25	8	16	5.5
	8			11			5		
	15			9			4		
	12			7			1		
641	8	13	10.75	6	12	8.25	1	9	2.75
	9			12			7		
	8			14			15		
	7			18			12		
642	11	20	8.75	14	15	14.5	10	17	11
	9			12			6		
	7			10			2		
	5			9			3		
643	4	5	6.25	13	14	11	9	13	5
	2			14			9		
	4			10			10		
	3			7			12		
644	0	10	2.25	5	12	9	6	14	9.25

Time	Tuesday (5/6/1997) Queue (15-second)	Tuesday (5/6/1997) Volume (1-minute)	Tuesday (5/6/1997) Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Wednesday (5/14/1997) Volume (1-minute)	Wednesday (5/14/1997) Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Thursday (5/8/1997) Volume (1-minute)	Thursday (5/8/1997) Ave. Queue (1-minute)
	2			3			7		
	1			7			10		
	2			8			7		
645	5	14	2.5	6	18	6	4	9	7
	9			7			1		
	5			4			0		
	4			3			4		
646	3	17	5.25	5	12	4.75	7	13	3
	0			7			6		
	3			5			4		
	5			4			3		
647	9	18	4.25	2	10	4.5	3	10	4
	10			0			1		
	6			0			2		
	4			4			8		
648	2	9	5.5	3	12	1.75	5	15	4
	8			0			4		
	5			1			3		
	3			0			5		
649	1	13	4.25	2	10	0.75	4	15	4
	0			7			6		
	0			5			8		
	3			3			9		
650	1	12	1	2	13	4.25	7	16	7.5
	2			6			5		
	1			5			3		
	3			5			6		
651	0	10	1.5	4	14	5	9	14	5.75
	0			0			14		
	2			0			10		
	6			1			8		
652	5	11	3.25	1	6	0.5	6	12	9.5
	4			2			7		
	3			3			8		
	4			6			7		
653	5	23	4	7	16	4.5	5	14	6.75
	7			5			4		
	6			2			2		
	4			2			3		
654	3	6	5	4	14	3.25	3	10	3
	0			7			0		
	4			3			0		
	10			1			0		
655	5	12	4.75	1	8	3	1	6	0.25
	3			0			1		
	0			6			4		
	1			11			2		
656	2	9	1.5	9	16	6.5	0	11	1.75
	7			6			0		
	4			4			2		
	3			2			1		
657	7	15	5.25	1	12	3.25	6	14	2.25
	0			3			10		
	1			0			7		
	8			0			7		
658	14	21	5.75	0	3	0.75	3	11	6.75
	11			0			1		
	9			1			1		
	7			4			7		
659	4	7	7.75	6	14	2.75	6	15	3.75

	Tuesday (5/6/1997)			Wednesday (5/14/1997)			Thursday (5/8/1997)		
Time	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	9			2			5		
	7			1			3		
	8			1			1		
700	5	11	7.25	1	8	1.25	1	9	2.5
	2			3			6		
	1			4			11		
	3			6			10		
701	2	10	2	5	17	4.5	5	15	8
	1			4			2		
	1			2			0		
	0			0			1		
702	0	3	0.5	4	11	2.5	1	6	1
	1			8			1		
	1			9			0		
	2			7			1		
703	1	11	1.25	5	14	7.25	0	5	0.5
	1			6			4		
	2			9			6		
	2			10			12		
704	1	14	1.5	8	15	8.25	9	16	7.75
	4			9			6		
	3			8			5		
	0			6			6		
705	1	8	2	7	14	7.5	5	15	5.5
	0			3			4		
	2			5			1		
	12			4			2		
706	9	21	5.75	5	12	4.25	1	8	2
	10			3			0		
	7			6			3		
	4			8			7		
707	10	12	7.75	3	16	5	11	14	5.25
	10			6			11		
	7			4			7		
	5			3			4		
708	3	18	6.25	1	10	3.5	4	12	6.5
	2			3			9		
	0			6			13		
	1			13			12		
709	4	9	1.75	12	15	8.5	9	16	10.75
	5			8			5		
	2			9			4		
	0			12			6		
710	0	8	1.75	10	13	9.75	6	12	5.25
	2			12			4		
	6			10			1		
	3			9			0		
711	2	13	3.25	5	9	9	0	4	1.25
	0			4			1		
	1			8			3		
	0			10			5		
712	5	14	1.5	8	13	7.5	8	16	4.25
	5			5			8		
	5			3			5		
	3			1			3		
713	0	7	3.25	4	11	3.25	9	15	6.25
	0			5			8		
	8			5			4		
	10			1			3		
714	10	19	7	2	9	3.25	5	13	5

Time	Tuesday (5/6/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	9			1			4		
	7			5			9		
	3			7			11		
715	2	11	5.25	9	12	5.5	15	17	9.75
	8			6			14		
	13			5			9		
	12			6			7		
716	10	13	10.75	6	13	5.75	7	12	9.25
	8			8			11		
	8			14			12		
	16			15			9		
717	16	21	12	12	14	12.25	8	14	10
	15			8			9		
	14			8			6		
	9			8			3		
718	8	9	11.5	9	15	8.25	5	15	5.75
	7			9			11		
	16			9			10		
	16			7			9		
719	13	16	13	6	11	7.75	7	14	9.25
	12			8			4		
	10			10			6		
	15			9			10		
720	16	15	13.25	10	15	9.25	9	14	7.25
	19			9			6		
	14			5			4		
	10			2			1		
721	15	10	14.5	8	13	6	2	8	3.25
	15			8			8		
	19			8			11		
	17			6			8		
722	17	17	17	5	10	6.75	6	15	8.25
	17			5			3		
	22			8			8		
	21			10			14		
723	21	18	20.25	12	17	8.75	17	12	10.5
	18			19			16		
	18			9			16		
	15			9			10		
724	15	20	16.5	9	14	11.5	7	14	12.25
	13			18			10		
	14			22			16		
	20			20			17		
725	20	11	16.75	17	15	19.25	16	12	14.75
	15			17			12		
	11			12			9		
	11			10			14		
726	8	12	11.25	22	14	15.25	17	15	13
	11			23			20		
	12			19			16		
	14			19			13		
727	12	12	12.25	18	14	19.75	11	14	15
	12			9			10		
	12			9			14		
	10			16			13		
728	15	15	12.25	11	19	11.25	14	13	12.75
	15			10			11		
	11			5			9		
	9			2			10		
729	7	7	10.5	2	17	4.75	19	12	12.25

Time	Tuesday (5/6/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	4			8			19		
	3			10			15		
	11			11			12		
730	12	15	7.5	10	17	9.75	10	14	14
	12			10			8		
	12			13			11		
	8			16			18		
731	7	8	9.75	18	13	14.25	14	14	12.75
	15			15			12		
	15			13			10		
	11			10			11		
732	11	13	13	9	14	11.75	13	12	11.5
	10			14			19		
	14			14			25		
	16			12			15		
733	16	14	14	11	14	12.75	5	12	16
	15			10			0		
	10			9			0		
	10			9			0		
734	9	9	11	14	13	10.5	0	23	0
	22			11			0		
	20			12			1		
	16			11			1		
735	14	13	18	11	15	11.25	3	15	1.25
	19			14			10		
	19			13			10		
	20			11			10		
736	20	17	19.5	9	14	11.75	6	18	9
	16			6			4		
	16			7			2		
	19			9			5		
737	19	16	17.5	11	15	8.25	8	15	4.75
	20			11			11		
	18			9			10		
	13			10			9		
738	8	8	14.75	7	11	9.25	9	14	9.75
	8			7			9		
	15			8			12		
	15			11			15		
739	18	9	14	14	13	10	14	15	12.5
	16			12			11		
	16			10			12		
	12			9			7		
740	15	15	14.75	8	13	9.75	8	12	9.5
	18			10			15		
	15			11			13		
	15			11			11		
741	12	10	15	11	14	10.75	10	14	12.25
	8			8			9		
	11			8			11		
	15			10			13		
742	18	10	13	11	15	9.25	14	15	11.75
	17			16			12		
	16			14			12		
	15			12			10		
743	15	20	15.75	11	13	13.25	10	14	11
	21			13			9		
	19			22			16		
	14			20			17		
744	14	18	17	15	15	17.5	17	13	14.75

Time	Tuesday (5/6/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	11			13			14		
	11			14			10		
	13			16			9		
745	15	22	12.5	21	15	16	13	15	11.5
	14			19			10		
	16			17			16		
	15			14			17		
746	12	20	14.25	12	16	15.5	17	13	15
	18			9			20		
	18			12			21		
	17			12			18		
747	14	7	16.75	10	10	10.75	16	14	18.75
	12			8			12		
	10			6			10		
	8			3			8		
748	15	12	11.25	1	10	4.5	14	11	11
	13			7			13		
	10			12			10		
	8			8			11		
749	6	8	9.25	5	15	8	11	11	11.25
	4			2			8		
	4			4			9		
	12			6			16		
750	17	13	9.25	5	13	4.25	14	14	11.75
	12			6			10		
	11			4			9		
	8			3			9		
751	8	11	9.75	4	14	4.25	8	14	9
	15			7			8		
	15			5			9		
	16			3			6		
752	14	12	15	4	13	4.75	5	10	7
	12			1			4		
	12			0			5		
	12			2			8		
753	14	12	12.5	4	14	1.75	8	13	6.25
	11			7			3		
	8			8			0		
	7			7			3		
754	9	11	8.75	5	13	6.75	2	7	2
	9			3			6		
	5			5			9		
	7			6			4		
755	4	10	6.25	4	13	4.5	3	13	5.5
	7			3			0		
	5			1			1		
	12			4			5		
756	14	25	9.5	7	15	3.75	7	15	3.25
	11			5			8		
	8			1			5		
	6			0			5		
757	3	8	7	0	4	1.5	3	10	5.25
	11			0			4		
	16			1			4		
	16			0			8		
758	11	14	13.5	3	8	1	7	17	5.75
	11			0			7		
	13			0			4		
	10			3			4		
759	8	8	10.5	7	14	2.5	8	14	5.75

Time	Tuesday (5/6/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	7			3			7		
	6			2			6		
	3			1			7		
800	1	4	4.25	1	6	1.75	7	12	6.75
	1			0			5		
	5			0			5		
	6			4			8		
801	2	12	3.5	5	12	2.25	7	13	6.25
	0			2			4		
	2			1			3		
	1			1			1		
802	1	5	1	1	12	1.25	4	10	3
	3			3			6		
	6			5			5		
	6			2			2		
803	6	14	5.25	0	11	2.5	0	9	3.25
	1			0			1		
	1			1			3		
	4			2			5		
804	6	16	3	0	7	0.75	11	17	5
	5			6			9		
	3			5			8		
	2			2			6		
805	2	9	3	2	12	3.75	5	12	7
	1			2			6		
	4			5			9		
	2			5			7		
806	2	13	2.25	3	16	3.75	4	12	6.5
	1			1			2		
	3			0			0		
	5			1			0		
807	2	13	2.75	5	12	1.75	4	10	1.5
	2			6			6		
	1			3			7		
	0			3			4		
808	1	11	1	2	9	3.5	3	12	5
	12			0			4		
	11			4			4		
	9			1			6		
809	5	11	9.25	4	14	2.25	4	15	4.5
	2			3			1		
	0			2			2		
	1			0			4		
810	0	9	0.75	1	8	1.5	4	15	2.75
	7			1			4		
	3			1			1		
	3			1			0		
811	0	18	3.25	2	13	1.25	4	12	2.25
	0			2			2		
	1			3			5		
	2			7			6		
812	2	13	1.25	7	18	4.75	2	10	3.75
	3			4			1		
	0			3			1		
	0			2			0		
813	3	8	1.5	0	10	2.25	1	6	0.75
	1			2			3		
	1			5			0		
	0			2			1		
814	0	5	0.5	1	16	2.5	0	6	1

	Tuesday (5/6/1997)			Wednesday (5/14/1997)			Thursday (5/8/1997)		
Time	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	2			2			0		
	0			1			0		
	0			6			3		
815	0	8	0.5	9	17	4.5	6	15	2.25
	1			7			5		
	0			9			3		
	0			7			2		
816	0	7	0.25	8	14	7.75	3	10	3.25
	3			6			0		
	3			10			6		
	2			8			8		
817	2	12	2.5	9	14	8.25	7	15	5.25
	5			6			5		
	1			6			6		
	0			7			6		
818	9	10	3.75	10	14	7.25	10	16	6.75
	10			10			10		
	10			8			7		
	8			7			4		
819	6	16	8.5	6	12	7.75	3	9	6
	9			3			1		
	10			2			7		
	10			4			6		
820	10	10	9.75	1	11	2.5	7	17	5.25
	7			1			6		
	7			1			4		
	7			0			3		
821	6	11	6.75	0	8	0.5	2	12	3.75
	8			1			4		
	6			2			3		
	5			1			4		
822	9	6	7	1	9	1.25	5	15	4
	4			0			5		
	1			0			6		
	0			3			6		
823	0	12	1.25	3	10	1.5	6	15	5.75
	0			3			4		
	0			3			1		
	0			0			6		
824	0	7	0	0	9	1.5	6	11	4.25
	0			3			7		
	3			6			9		
	4			7			8		
825	2	10	2.25	8	18	6	7	12	7.75
	0			5			7		
	0			3			6		
	2			2			8		
826	2	10	1	3	9	3.25	11	15	8
	1			0			8		
	0			1			5		
	0			0			10		
827	0	8	0.25	1	8	0.5	8	15	7.75
	0			0			9		
	5			2			11		
	2			2			12		
828	0	10	1.75	1	13	1.25	15	13	11.75
	1			2			12		
	0			1			11		
	1			1			9		
829	0	7	0.5	1	9	1.25	10	17	10.5

	Tuesday (5/6/1997)			Wednesday (5/14/1997)			Thursday (5/8/1997)		
Time	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	2			0			9		
	2			1			11		
	3			0			9		
830	1	14	2	2	4	0.75	11	14	10
	0			0			9		
	4			2			12		
	6			4			10		
831	5	15	3.75	1	11	1.75	15	13	11.5
	5			0			12		
	2			1			10		
	0			0			10		
832	2	10	2.25	2	10	0.75	10	14	10.5
	3			0			16		
	0			3			18		
	1			0			14		
833	0	10	1	0	8	0.75	12	11	15
	0			1			12		
	1			1			9		
	3			1			13		
834	2	10	1.5	1	7	1	15	13	12.25
	2			1			12		
	1			3			8		
	3			1			6		
835	7	13	3.25	0	10	1.25	3	9	7.25
	8			1			1		
	6			0			0		
	2			0			0		
836	2	10	4.5	3	9	1	3	9	1
	0			2			0		
	4			1			0		
	2			0			4		
837	7	5	3.25	1	12	1	6	13	2.5
	4			4			5		
	2			3			2		
	0			6			4		
838	0	14	1.5	7	9	5	5	12	4
	2			5			3		
	2			5			3		
	6			10			4		
839	7	15	4.25	9	9	7.25	5	13	3.75
	3			7			3		
	0			3			3		
	0			3			1		
840	4	16	1.75	0	7	3.25	0	10	1.75
	5			2			1		
	4			1			1		
	3			0			2		
841	2	7	3.5	0	8	0.75	0	7	1
	1			1			0		
	1			0			2		
	2			0			3		
842	3	10	1.75	0	2	0.25	1	10	1.5
	4			1			0		
	10			0			5		
	11			3			6		
843	9	13	8.5	2	11	1.5	1	12	3
	6			3			1		
	5			4			2		
	4			5			7		
844	1	10	4	1	11	3.25	3	12	3.25

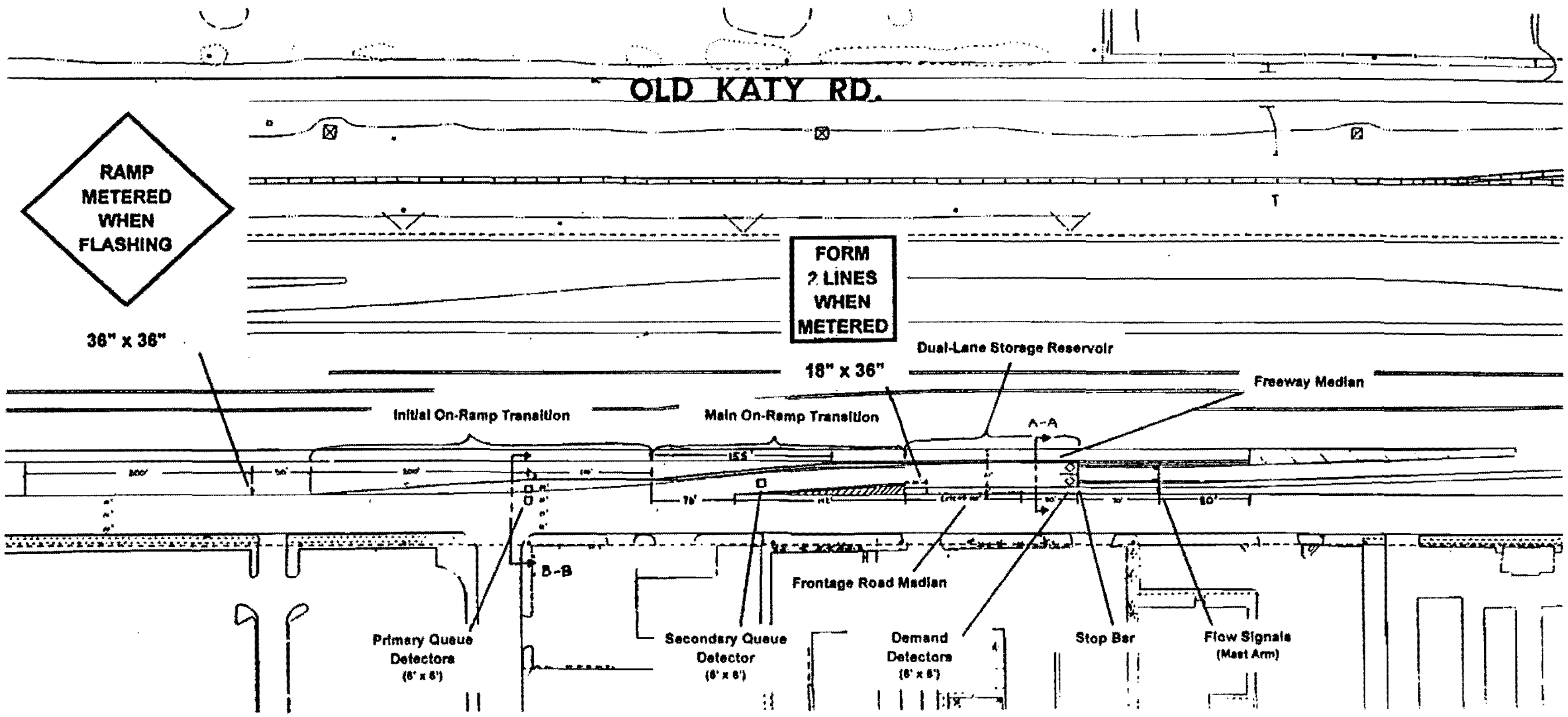
Time	Tuesday (5/6/1997) Queue (15-second)	Tuesday (5/6/1997) Volume (1-minute)	Tuesday (5/6/1997) Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Wednesday (5/14/1997) Volume (1-minute)	Wednesday (5/14/1997) Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Thursday (5/8/1997) Volume (1-minute)	Thursday (5/8/1997) Ave. Queue (1-minute)
	0			1			3		
	1			0			1		
	1			2			4		
845	1	8	0.75	5	11	2	3	11	2.75
	2			2			3		
	0			2			5		
	1			0			6		
846	0	4	0.75	1	8	1.25	5	17	4.75
	2			2			9		
	1			4			14		
	0			3			11		
847	3	4	1.5	3	17	3	13	12	11.75
	2			4			16		
	0			5			14		
	2			3			13		
848	1	17	1.25	2	11	3.5	20	14	15.75
	2			0			16		
	1			0			16		
	1			1			16		
849	1	12	1.25	0	13	0.25	6	18	13.5
	1			3			0		
	1			3			0		
	3			1			0		
850	3	12	2	1	11	2	0	19	0
	5			0			0		
	4			1			0		
	4			0			0		
851	6	19	4.75	1	10	0.5	0	8	0
	7			6			0		
	5			4			1		
	9			0			2		
852	10	8	7.75	2	14	3	1	6	1
	7			4			0		
	7			0			0		
	6			3			1		
853	6	20	6.5	7	16	3.5	4	12	1.25
	8			6			5		
	9			10			1		
	7			13			2		
854	7	10	7.75	12	15	10.25	0	5	2
	9			14			4		
	12			15			5		
	11			13			4		
855	9	11	10.25	13	14	13.75	7	20	5
	8			17			8		
	3			14			6		
	10			11			9		
856	8	14	7.25	7	13	12.25	8	13	7.75
	5			1			6		
	3			0			3		
	3			0			5		
857	1	8	3	1	21	0.5	4	13	4.5
	5			2			7		
	1			6			13		
	4			6			12		
858	5	10	3.75	6	19	5	13	18	11.25
	5			5			9		
	4			4			12		
	2			1			9		
859	5	21	4	1	9	2.75	8	10	9.5

Time	Tuesday (5/6/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Wednesday (5/14/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Thursday (5/8/1997) Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	5			3			8		
	4			3			6		
	3			0			5		
900	4	3	4	0	10	1.5	2	12	5.25
	1			1			3		
	3			5			5		
	2			5			9		
901	0	2	1.5	7	19	4.5	6	16	5.75
	2			6			4		
	1			3			4		
	0			2			4		
902	3	5	1.5	4	12	3.75	6	10	4.5
	4			4			5		
	6			6			4		
	4			3			1		
903	8	3	5.5	4	15	4.25	2	8	3
	8			5			1		
	7			6			3		
	5			5			2		
904	3	3	5.75	3	13	4.75	0	8	1.5
	3			3			3		
	2			2			6		
	0			4			7		
905	0	4	1.25	7	15	4	5	16	5.25
	0			7			4		
	0			8			2		
	2			10			2		
906	2	6	1	8	13	8.25	6	15	3.5
	0			8			7		
	3			7			6		
	1			5			4		
907	3	7	1.75	3	11	5.75	7	13	6
	10			2			5		
	7			8			9		
	7			6			9		
908	7	18	7.75	4	17	5	10	13	8.25
	6			2			8		
	8			0			10		
	9			0			12		
909	9	12	8	1	8	0.75	12	13	10.5
	9			0			11		
	9			1			10		
	10			2			11		
910	14	11	10.5	5	17	2	8	14	10
	15			4			8		
	16			4			4		
	13			1			7		
911	13	15	14.25	4	13	3.25	9	12	7
	18			6			9		
	15			11			5		
	17			7			5		
912	18	12	17	6	11	7.5	8	13	6.75
	18			5			6		
	20			5			7		
	20			9			8		
913	20	18	19.5	8	14	6.75	7	14	7
	15			10			7		
	17			10			7		
	23			9			6		
914	23	14	19.5	12	13	10.25	5	14	6.25

	Tuesday (5/6/1997)			Wednesday (5/14/1997)			Thursday (5/8/1997)		
Time	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)	Queue (15-second)	Volume (1-minute)	Ave. Queue (1-minute)
	23			14			4		
	20			11			4		
	19			10			3		
915	20	14	20.5	13	16	12	1	9	3
	19			9			7		
	19			12			10		
	18			13			7		
916	17	15	18.25	10	13	11	6	18	7.5
	24			8			6		
	24			11			8		
	20			14			7		
917	20	26	22	12	14	11.25	4	13	6.25
	16			12			7		
	16			11			6		
	19			7			5		
918	19	17	17.5	10	14	10	14	15	8
	20			7			12		
	18			5			12		
	13			4			12		
919	8	8	14.75	1	11	4.25	16	14	13
	8			3			15		
	6			5			14		
	3			3			11		
920	1	5	4.5	4	13	3.75	9	14	12.25
	3			2			8		
	1			2			13		
	5			1			10		
921	4	5	3.25	0	8	1.25	8	12	9.75
	1			1			8		
	0			0			7		
	3			4			6		
922	4	18	2	6	13	2.75	7	17	7
	4			4			8		
	1			3			8		
	0			3			7		
923	2	10	1.75	2	10	3	7	11	7.5
	6			4			9		
	5			7			9		
	1			7			11		
924	0	10	3	3	11	5.25	8	12	9.25
	2			3			6		
	1			2			9		
	4			6			13		
925	7	13	3.5	4	14	3.75	10	14	9.5
	7			3			9		
	4			0			7		
	6			2			7		
926	3	16	5	4	15	2.25	9	17	8
	0			7			11		
	2			4			10		
	5			1			8		
927	10	9	4.25	2	12	3.5	7	15	9
	14			8			8		
	10			12			6		
	8			9			3		
928	7	11	9.75	8	10	9.25	1	9	4.5
	5			8			1		
	9			9			0		
	7			10			6		
929	3	12	6	10	15	9.25	6	16	3.25

APPENDIX C:

PROPOSED GESSNER STREET/KATY FREEWAY DUAL-LANE FLOW SIGNAL DEMONSTRATION PROJECT CONCEPTUAL DESIGN


OLD KATY RD.
RAMP METERED WHEN FLASHING
36" x 36"
FORM 2 LINES WHEN METERED
18" x 36"
Dual-Lane Storage Reservoir
Freeway Median
Initial On-Ramp Transition
Main On-Ramp Transition
A-A
B-B
Primary Queue Detectors (6' x 6')
Secondary Queue Detector (6' x 6')
Frontage Road Median
Demand Detectors (6' x 6')
Stop Bar
Flow Signals (Mast Arm)