
Zong Tian and Kevin Balke

Diamond interchanges and their associated ramps are where the surface street arterial system and the freeway system interface. Historically, these two elements of the system have been operated with little or no coordination between the two. One drawback of operating the ramp-metering system and the diamond interchange system in isolation is that traffic from the ramp, particularly if it is metered, can spill back into the diamond interchange, causing both congestion and safety concerns at the diamond interchange. While flushing the ramp queues by temporarily suspending ramp metering has been the primary strategy for preventing queue spillback, it can result in freeway system breakdown, which would affect the entire system’s efficiency.

The aim of this research was to develop operational strategies for managing an integrated diamond interchange ramp-metering system (IDIRMS), and to develop a general framework for implementing such an integrated system. Integrated control strategies (ICS) were developed based on the two commonly used diamond interchange phasing schemes, basic three-phase and TTI four-phase. The ICS were evaluated using VISSIM microscopic simulation under three general traffic demand scenarios: low, medium, and high, as characterized by the volume-to-capacity ratios at the metered ramps. Preliminary system design and detailed functional diagrams were developed to guide traffic engineers for field implementation of the system.

The results of the evaluation indicated that the integrated operations through an adaptive signal control system were most effective under the medium traffic demand scenario by preventing or delaying the onset of ramp-metering queue flush, thereby minimizing freeway breakdown and system delays. The integrated system would require enhanced detection and communication systems, but the system could be designed and implemented based on existing features equipped with most advanced traffic signal controllers.

Diamond Interchange, Ramp Metering, Integration, IDIRMS, ICS, Simulation
DEVELOPMENT AND EVALUATION OF A FRAMEWORK FOR SELECTING OPERATIONAL STRATEGIES FOR AN INTEGRATED DIAMOND INTERCHANGE - RAMP METERING CONTROL SYSTEM

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ABSTRACT

Diamond interchanges and their associated ramps are where the surface street arterial system and the freeway system interface. Historically, these two elements of the system have been operated with little or no coordination between the two. One drawback of operating the ramp-metering system and the diamond interchange system in isolation is that traffic from the ramp, particularly if it is metered, can spill back into the diamond interchange, causing both congestion and safety concerns at the diamond interchange. While flushing the ramp queues by temporarily suspending ramp metering has been the primary strategy for preventing queue spillback, it can result in freeway system breakdown, which would affect the entire system’s efficiency.

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The results of the evaluation indicated that the integrated operations through an adaptive signal control system were most effective under the medium traffic demand scenario by preventing or delaying the onset of ramp-metering queue flush, thereby minimizing freeway breakdown and system delays. The integrated system would require enhanced detection and communication systems, but the system could be designed and implemented based on existing features equipped with most advanced traffic signal controllers.
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EXECUTIVE SUMMARY

Freeway interchanges establish interconnections between freeway systems and surface street arterials and provide the backbone of highway transportation networks. One of the most commonly used interchange types is the diamond interchange, where two traffic signals are installed on the arterial street to control the interchanging traffic. Diamond interchanges are often characterized by complex traffic flow patterns, especially high turning movements and limited spacing between the signals, which make managing their operations difficult. As a result, diamond interchange locations are often sources of operational bottlenecks for both surface street arterials and freeways.

One operational issue existing today is that the diamond interchange and ramp metering are primarily treated as independent elements, primarily due to jurisdictional responsibilities where the surface street arterial is managed by city or county agencies while the freeway and ramp-metering system is managed by the state Department of Transportation. The lack of system integration or coordination between the diamond signals and ramp metering often creates major operational concerns, among which queue spillback from the metered ramp is the most obvious. Suggested strategies to control queue spillback generally involve some queue override policies to flush the ramp queues by either increasing the metering rate or terminating metering operations. However, such an operation may lead to freeway breakdown, a phenomenon indicated by a sudden drop in speed and perhaps in flow. Freeway breakdown results in longer vehicle delays and affects the efficiencies of the entire system.

The goal of this research is to explore whether providing integrated operations between a diamond interchange and ramp meters could eliminate the deficiencies of the current independent system operations, and whether a framework and guidelines could be developed to facilitate design and implementation of the system. Some of the specific objectives of this research include (a) identifying viable operational strategies for providing the integrated operations between a diamond interchange signal and ramp metering; (b) conducting proof-of-concept evaluations in a simulation environment; and (c) establishing a framework to guide traffic engineers for potential field implementation of the integrated system.

In this research, integrated control strategies (ICS) were developed with a focus on dealing with recurring congestion from daily traffic operations. ICS were developed based on the two commonly used diamond interchange phasing schemes: basic three-phase and TTI four-phase. In order to achieve integrated operations, the diamond interchange signal must be able to sense any ramp queue buildup and respond with adequate signal control, which would require the diamond signals having some adaptive control features. To achieve the required control and operations, an enhanced detection system was proposed, which includes a set of boundary detectors, intermediate detectors, and spillback/interface detectors. These detectors are in addition to the basic detection systems for normal diamond interchange operation and ramp metering operation.

The boundary queue detectors and intermediate queue detectors need to be placed on the external approaches of the diamond interchange. The boundary queue detectors set limits of allowable queue spillback at a particular location. Queues that spillback beyond these boundaries should be avoided because interference with other traffic facilities, such as the adjacent traffic
signals in the arterial or the freeway mainlines, might occur. The intermediate queue detectors sense the potential queue buildup that results from the special signal operations during ICS’s implementation, and they would serve the purpose of adjusting the phase splits to achieve balanced usage of available queue storage spaces. Two queue spillback/interface detectors are placed on the frontage roads downstream of the diamond interchange signals, serving the purpose of detecting ramp queue buildups and as an interface between the ramp metering system and the diamond interchange system.

A brief description of the basic concept of operations of ICS is as follows. The diamond interchange signal would remain in normal operation as long as none of the boundary queue detectors (i.e., arterial detectors, off-ramp detectors) and none of the spillback/interface detectors detects traffic queues. However, some minor adjustments on the phase splits (e.g., up to 10% of the cycle length) could be made based on the queue conditions at the intermediate queue detectors. Whenever a ramp queue is detected by any of the queue spillback detectors, the diamond signal would transition to a candidate signal phase (specific to the type of phasing and queue conditions) and holds that phase so that further vehicle entry to the ramp is controlled and queue spillback to the diamond interchange signal would be prevented. The diamond signal returns to normal operation once the ramp queue is dissipated. Ramp metering would remain in normal operation until one or more boundary detectors detect vehicle queues, which is the ultimate condition when ramp metering has to be suspended to release the excessive demands in order to avoid further interference with arterial or freeway operations.

Evaluations of the effectiveness of ICS were conducted using the VISSIM simulation model under three generally defined traffic demand scenarios: low, medium, and high. One critical element of ICS is to have the ramp metering to operate with traffic-responsive instead of fixed metering. Traffic-responsive ramp-metering algorithms, such as ALINEA, can actively respond to freeway congestion; thus, they are more effective in preventing freeway breakdown and achieving significant delay savings for the freeway traffic. Fixed metering, although it may still be effective in improving freeway operations under certain circumstances, is less effective in preventing freeway breakdown.

Based on the proposed advanced detection system and the ICS concept of operations, a framework was developed to guide the traffic engineers for potential implementation of the system in the field. The system architecture and detailed functional diagrams were developed to describe the main features and data flows of the control algorithm.

ICS proved to be effective only within a certain traffic demand level, e.g., the medium level as defined in this study. Under the low demand scenario, where both the freeway mainlines and the ramps have sufficient capacities, implementing ICS would not result in significant difference in the system performances. On the other hand, when the traffic demands are high for both the freeway mainlines and the ramps, ICS would only provide marginal benefits for the freeway mainline operations by delaying the onset of ramp queue flush and freeway breakdown. Once the traffic queues on the surface street exceed boundary limits and ramp queue flush starts, the delay savings on the freeway traffic will be significantly diminished. The non-freeway traffic would experience excessive delays and queues, which would normally outweigh the delay savings of the freeway traffic. ICS proved to be most effective under the generally defined medium demand scenario, where temporary phase hold would not result in overflow of the queue.
storage spaces and freeway breakdown can be effectively prevented or delayed. Although non-freeway traffic would still generally experience increased delays, the delay savings on the freeway traffic would normally outweigh the delays imposed to the non-freeway traffic. ICS associated with the three-phase and four-phase schemes yielded similar system performance measures although individual surface street traffic movements may experience different levels of delay.

Finally, the system architecture for the integrated system indicates that the system can be developed based on existing features and functions equipped with most advanced traffic signal controllers, although additional detection and communication equipments are necessary for achieving the desired control and operations. Nevertheless, field implementation and testing of the proposed ICS are necessary steps to evaluate their viability and effectiveness in managing the system operations in real time. More sophisticated control algorithms could be developed with the advance of detection, communication, and information technologies where more accurate traffic flow and system information could be obtained in real time.
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CHAPTER I
INTRODUCTION

BACKGROUND

Freeway interchanges establish interconnections between freeway systems and surface street arterials and provide the backbone of highway transportation networks. One of the most commonly used interchange types is the tight urban diamond interchange (TUDI), where two traffic signals are installed on the arterial street to control the interchanging traffic (1, 2). Diamond interchanges are often characterized by complex traffic flow patterns, especially high turning movements and limited spacing between the signals, which make managing their operations difficult. To complicate matters, the majority of freeway ramp meters are located in the vicinity of freeway interchanges such as diamond interchanges. As a result, diamond interchange locations are often sources of operational bottlenecks for both surface street arterials and freeways.

One operational issue existing today is that the diamond interchange and ramp metering are primarily treated as independent elements, primarily due to jurisdictional responsibilities where the surface street arterial is managed by city or county agencies while the freeway and ramp-metering system is managed by the state department of transportation. Traffic engineers and planners typically do not consider the interactions between these two elements, nor do they consider the potential benefits that can be derived from coordinating their operations. The lack of system integration or coordination between the diamond signals and ramp metering often creates major operational concerns, among which queue spillback from the metered ramp is the most obvious. This situation is illustrated in Figure 1.

During typical rush hours, high traffic demands on the freeway often require restricted entry of traffic from the metered ramp, thus resulting in long queues on the ramp. The fact that the traffic released from the upstream diamond signal arrives in platoons also exacerbates the queue spillback effect, where limited storage spacing on the ramp cannot accommodate the short-term surge of large platoon arrivals. Unless the signal controller at the upstream diamond interchange has some way to sense the queue buildup, traffic would continue to flow to the ramp, until the queue spills back to the surface street (e.g., frontage road or the diamond signal location). Such queue spillback occurrences would interfere with the surface street operation and cause serious safety concerns.

Suggested strategies to control queue spillback generally involve some queue override policies to flush the ramp queues by either increasing the metering rate or terminating metering operations (3). However, such an operation may lead to freeway breakdown, a phenomenon indicated by a sudden drop in speed and perhaps in flow. Freeway breakdown results in longer vehicle delays and affects the efficiencies of the entire system. Therefore, it is of significance to explore whether providing integrated operations between a diamond interchange and ramp meters could eliminate the deficiencies of the current independent system operations, and if integration of the
system operations is desired, a framework and guidelines should be developed to facilitate design and implementation of the system.

![Diagram of a diamond interchange with ramp metering]

**Figure 1** Queue spillback at a diamond interchange with ramp metering.

**PROBLEM STATEMENT**

Current operations at a diamond interchange and ramp meters lack system coordination between the two components. The lack of system coordination is reflected by the fact that little consideration is currently given to diamond operational strategies that minimize or eliminate ramp queue spillback when ramp metering is in operation. Existing diamond interchange strategies focus on serving traffic demands monitored by various traffic sensors on the diamond interchange approaches. Appropriate signal phasing and timing are then developed to best serve the traffic demands (4, 5). However, existing diamond operations completely ignore the constraints imposed by the downstream ramp meter. Excessive and non-controlled release of traffic from the diamond often results in queue spillback at the ramp meter (6).
Queue spillback resulting from the lack of coordination between the ramp meter and diamond interchange creates serious operational concerns on the diamond interchange and the surface street arterial. Although queue override policies currently being used at ramp meters can eliminate queue spillback, frequent queue flushes can lead to freeway breakdown and diminish the main purpose of ramp metering. Therefore, a need exists to address the diamond interchange, ramp-metering, and freeway components in an integrated and coordinated manner to eliminate the deficiencies of the current operations. Integrated control strategies (ICS) need to be developed to minimize queue spillback occurrences at the ramp meter while maintaining efficient operations for the system. A framework needs to be established for system design and implementation if integration of the operations between diamond interchange and ramp metering is desired.

RESEARCH OBJECTIVES

The goals of this research are (a) to develop and evaluate strategies for integrating the operations between diamond interchange and ramp-metering, and (b) to develop a framework for design and implementation of such integration systems. Specific objectives of this research include the following:

- Identify viable ICS for managing the operations of an integrated diamond interchange – ramp metering system (IDIRMS). ICS should be developed based on a set of established system operating objectives and priorities. The ICS should take into account the close interactions between the diamond interchange signals and the ramp-metering signal.

- Conduct proof-of-concept evaluations, in a simulation environment, on the applicability and effectiveness of the ICS under various traffic flow conditions.

- Establish a framework for potential field implementation of the ICS at an IDIRMS, including detailed description of the system architecture, data flows, and system functions.

ORGANIZATION OF THE REPORT

This report includes a total of five chapters, including this introductory chapter. Chapter II includes a literature review of state-of-the-art technologies in modeling the operations of a diamond interchange, freeway, and ramp metering. Chapter III documents the development of ICS and the evaluations of the applicability and effectiveness of the ICS using the VISSIM simulation model. Chapter IV documents the framework developed in this research for implementing ICS, which includes the system architecture, detailed functional diagrams and data flows for the control algorithm. Finally, Chapter V provides a summary and major conclusions resulting from this research.
CHAPTER II
STATE OF THE ART

This chapter provides a state-of-the-art literature review on the operations of diamond interchange, freeway and ramp metering. The two most common signal phasing schemes are discussed for controlling diamond interchange operations. The ALINEA local traffic-responsive ramp-metering algorithm is introduced. The two-capacity phenomenon of freeway operations and its related studies are noted. Research on integrated operations between diamond interchange and ramp metering is provided.

DIAMOND INTERCHANGE OPERATIONS

At a diamond interchange, the two traffic signals are typically controlled by a single signal controller. Figure 2 shows the standard signal phase design, which includes the standard eight phases (except for $\phi_3$ and $\phi_7$), as most signal controllers possess. Each signal phase controls a particular traffic movement. The two internal through movements are controlled using overlap phases, A and B. For example, overlap phase A controls the internal through movement, which receives green whenever $\phi_1$ or $\phi_2$ is green. A diamond interchange also applies unique signal phasing schemes to control its operations, defining the changing sequence of the signal phases and their associated traffic movements.

The two most commonly used diamond phasing schemes are basic three-phase and TTI four-phase (7), as shown in Figure 3 and Figure 4. The two phasing schemes will be simply referred to as three-phase and four-phase in the remaining chapters of the dissertation. Some signal controllers such as those manufactured by Naztec, Inc., (8) and Eagle Traffic Control Systems, Inc., (9) have built-in functions and specifications to operate these two types of signal phasing schemes.
Figure 2  Diamond interchange standard phase design.

Figure 3  Three-phase and traffic progression diagram.
Figure 4  Four-phase and traffic progression diagram.

Three-phase uses a lag-lag phasing sequence, i.e., the arterial left-turn movement lags the through movement on both sides of the interchange and emphasizes progression for the arterial through traffic. The frontage road/ramp phases ($\phi_4$ and $\phi_8$) start and end at the same time, followed by the arterial through ($\phi_2$ and $\phi_6$) and the internal left-turn movement phases ($\phi_1$ and $\phi_5$). Three-phase operation maintains progression for the arterial through traffic, i.e., the arterial traffic going through the interchange would not stop. The arterial left-turn traffic will be stopped but can normally be cleared by the end of the cycle given sufficient green time for $\phi_1$ and $\phi_5$. Some of the frontage road traffic may be stopped depending on the spacing of the interchange and the frontage road phase duration. For example, the frontage road traffic would have to stop when the phase time ($\phi_4$ or $\phi_8$) is longer than the travel time, $TT_{1,2}$ or $TT_{2,1}$ (see Figure 3). With the increase of spacing and travel time, the proportion of frontage road traffic to be stopped will be reduced. Therefore, three-phase is appropriate when the frontage roads have balanced traffic demands and there are longer spacing and storage spaces for the internal left-turn vehicles.

Four-phase uses a lead-lead phasing sequence, i.e., the left-turn movements lead the through movements on both sides of the interchange, and it is aimed at minimizing internal queues. Note that the term “overlap” used in describing the four-phase scheme (see Figure 4) has a different meaning than in Figure 2. Overlap in the four-phase scheme is a dummy phase used for the purpose of efficiency while still guaranteeing traffic progression. This phasing scheme is suitable for diamond interchanges that are closely spaced. If timed appropriately, the queues in the internal interchange can be completely eliminated with U-turn lanes. There are some conditions, however, when traffic might stop. For example, the arterial through movement will not stop only if $\phi_5$
is at least the length of $\phi_2$. The frontage road phase ($\phi_4$) traffic will not stop only if $\phi_6$ is at least $2\Phi$ long.

**FREEWAY OPERATIONS AND RAMP METERING**

Currently, there are more than 20 metropolitan areas in the United States where ramp metering has been implemented (3, 10). Other countries that have also implemented ramp metering include Great Britain, Canada, Denmark, France, Germany, Japan, the Netherlands, New Zealand, and Sweden (3, 11).

Ramp metering offers several operational features for improving freeway traffic flow, safety, and air quality by regulating the flows onto the freeway system. A ramp signal is installed on an entrance ramp, which operates in a green-yellow-red cycle or only on a green-red cycle. A metering cycle typically includes a fixed green interval, which would allow one vehicle entry per cycle. By varying the red interval, different metering cycles would result and the amount of traffic entering the freeway would be controlled.

**Types of Ramp Metering**

Figure 5 shows a typical ramp-metering design used in the United States. Major elements of a ramp-metering system include mainline and ramp detectors, a ramp-metering signal, and advanced warning devices. The primary (also called excessive or advance) queue detector is used as a means of implementing queue flush policies. Ramp metering operation is suspended and the ramp queue is flushed whenever the primary queue detector detects a queue, as specified by an occupancy threshold level. In actual field operations, there is usually a transition period after queue flush before resuming normal metering operations. During the transition period, the ramp meter would be essentially still in the queue-flush mode.

![Figure 5 Design elements for a ramp-metering system.](image-url)
There are basically four types of ramp-metering operations based on the level of complexity of the control algorithm: fixed time, local traffic responsive, coordinated freeway ramp metering, and integrated freeway/surface street system. Fixed-time metering is the simplest form and operates at a constant metering cycle. Fixed-time metering mainly serves to break up the platoons of entering vehicles into single vehicle entries, which would provide smooth freeway merge and reduce the accidents related to merging conflicts. This strategy is mostly used where traffic conditions are predictable.

The major drawback of fixed-time metering is that the operations cannot react to temporary traffic fluctuations on the freeway mainline. When freeway mainline flow is low and does not warrant ramp-metering operations, ramp traffic may incur unnecessary queues and delays.

Local traffic-responsive ramp metering can automatically adjust the ramp-metering rate based on current traffic conditions in the vicinity of the ramp. Local traffic-responsive ramp metering requires detector installation on the freeway mainline. Controller electronics and software algorithms can select an appropriate metering rate based on occupancy or flow data from the ramp and mainline detectors; therefore, traffic-responsive ramp-metering systems can generally deliver better results than fixed-time metering.

The most well-known traffic-responsive ramp-metering algorithm is probably the ALINEA algorithm proposed by Papageorgiou et al. (12). The algorithm was developed based on the feedback concept of automatic control. A number of studies have also led to various modified ALINEA algorithms (13, 14). While ALINEA has been widely used in European countries, its applications in the United States is somewhat limited (11, 15, 16). The original ALINEA algorithm is described in Equation 1 to determine \( M_r(t) \), the ramp-metering rate for the time interval \( t \):

\[
M_r(t) = M_r (t - 1) + K_R [\pi_m - \pi(t)]
\]

The ALINEA algorithm described in Equation 1 can smoothly react to traffic flow changes in the freeway mainline under both free-flow and congested conditions. The occupancy is directly related to traffic conditions. When the measured occupancy, \( \pi(t) \), is less than the target occupancy, \( \pi_m \), a positive value results for the second term on the right-side equation. As a result, the metering rate will be increased to allow more vehicles to enter the freeway. Similarly, the metering rate will be reduced when the measured occupancy exceeds the target occupancy value. The ALINEA algorithm also has the advantage of easy field implementation and calibration because only the two parameters, \( K_R \) and \( \pi_m \), need to be calibrated.

The coordinated freeway ramp-metering system seeks to optimize a multiple-ramp section of freeway, often with the control of a bottleneck as the ultimate goal (17, 18). Typically a centralized computer supervises numerous ramps and implements control features which can override local metering instructions. This centralized configuration allows the metering rate at any ramp to be influenced by conditions at other locations within the network. In addition to recurring congestion, system-wide
ramp metering can also manage freeway incidents, with more restrictive metering upstream and less restrictive metering downstream of the incident. Such a metering system usually places higher priorities on managing freeway operations with little consideration of the surface street traffic.

The integrated freeway/surface street ramp-metering system is the highest-level ramp-metering system and has drawn significant interest in studying this subject area (6, 19, 20, 21, 22, 23, 24). Such a system attempts to maintain optimal operations for the entire corridor, which includes the freeway ramp-metering system and the adjacent surface street arterial system. Due to the fact that freeway ramp metering directly affects surface street operations, the close interaction between the ramp-metering signal and the surface street arterial signal (normally interchange signal) must be taken into consideration. As a result, the hardware requirements for this mode of operation are the most complex, requiring detectors upstream and downstream of the ramp, as well as a communication medium and central computer linked to the ramp signals and surface-street signals.

In our study, the IDIRMS is better classified as a hybrid between the integrated freeway/surface street system and the local traffic-responsive system. Only a single ramp-metering location (one meter per direction) is considered, but the close interaction between the ramp-metering signal and the surface street diamond interchange signal needs to be addressed.

**The Two-Capacity Phenomenon on Freeway Operations**

Unlike other traffic facilities, freeways have a unique operational feature described as the two-capacity phenomenon, suggesting that freeway capacity has two distinctive regimes: the capacity value during free flow and the capacity value during congested flow measured at an active bottleneck location (25, 26). An active bottleneck, as originally defined by Daganzo (27) is a bottleneck that is not influenced by another bottleneck further downstream. The two capacities are defined as the free-flow capacity, $c_F$, and the queue-discharge capacity, $c_Q$. The transition from the free-flow condition to the congested condition is often referred to as freeway breakdown, characterized by a sudden speed drop, an increase in density, and perhaps a drop in flow rate (28).

Figure 6 and Figure 7 illustrate the breakdown scenario and the two-capacity phenomenon, which are based on field detector data collected by the Ministry of Transportation of Ontario, Canada, upstream of an active freeway merge bottleneck near the Cawthra Rd./Queen Elizabeth Way interchange (29). Figure 6 is a plot of occupancy versus flow. Two distinctive regions, the free-flow region and the congested region, can be clearly seen. A disconnection between the two regions can also be observed. Lower flow rates can be noticed under the congested region than the highest flows that can be achieved under the free-flow region. Figure 7 is a time series plot of the flow and speed. At about 6:20 a.m., the freeway experienced a sudden drop in speed, indicating the start of breakdown. A lower flow rate under breakdown can be clearly seen. While much higher flows can be achieved with 20-second aggregation, the capacity flow is often measured at a much longer time interval, for example, a 15-
minute period as defined in the HCM.

Figure 6 Occupancy-flow diagram.

Figure 7 Time series flow-speed diagram.
A significant number of publications have been devoted to studying the two-capacity phenomenon. While the majority of the studies have confirmed the two-capacity phenomenon, there has been disagreement on the level of capacity reduction once breakdown occurs. Hall and Agyemang-Duah (25) emphasize the importance of how the flows should be measured. Firstly, the bottleneck location where flow is measured has to be free from downstream congestion, i.e., any queuing and flow drop should be solely caused by the freeway merge itself, not the congestion from another downstream bottleneck. Secondly, the flow measurement location should not be upstream of the merge because it would not reflect the true capacity due to part of the capacity being consumed by the ramp traffic. Thirdly, the time interval for flow measurement is also critical. Although much higher flows could be achievable within a shorter time period, the flow rate for determining the capacity should be measured over a prolonged period, such as at least 15 minutes as defined in the HCM for capacity flow. Another important point that Hall and Agyemang-Duah made was that the measurement of pre-breakdown flow should be restricted to the period when demand is close to capacity.

Complying with the above conditions, Hall and Agyemang-Duah selected a freeway merge site in Toronto, Canada, and concluded that the two-capacity phenomenon does exist and the capacity drop after breakdown is about six percent based on the study site. The literature that supports the two-capacity phenomenon includes studies by Cassidy and Bertini (30), Persaud et al. (28, 31), Lorenz and Elefteriadou (32), and Zhang and Levinson (33). These studies report that the range of capacity drops between two percent and 16 percent once breakdown occurs. There are also many unpublished documents based on field observations to support the two-capacity phenomenon (34, 35, 36).

Review of existing literature indicates that freeway breakdown is probabilistic in nature, i.e., freeway breakdown could occur at different flow levels (28, 31, 32, 37). Random variations exist for the flows under both free-flow and queue-discharge-flow conditions. Generally, the variations in the queue-discharge flows are smaller than those before breakdown.

**Ramp Metering and the Two-Capacity Phenomenon**

One of the major purposes of ramp metering is to maintain the freeway in the free-flow region by controlling vehicle entry to the freeway so that freeway demand does not exceed its bottleneck capacity. In fact, it is the two-capacity phenomenon that determines the significance of ramp-metering applications. If no two-capacity phenomenon exists and freeway capacity is a single value, ramp metering itself would not achieve any reduction on overall system delay.

Consider the case when the total freeway demand without ramp metering (i.e., mainline demand, \(V_F\), plus ramp demand, \(R\)) is greater than the freeway capacity, but the total demand with ramp metering (i.e., mainline demand, \(V_F\), plus ramp metering rate, \(M\)) is less than the freeway capacity. When ramp metering is in operation, the freeway would actually have a throughput of \(V_F + M\), which is lower than the
throughput of $c_F$ when metering is not present. With ramp metering in operation, the freeway capacity may be under-utilized, thus resulting in higher overall delays for the entire system. The excessive delays would be primarily imposed on the ramp traffic. A numerical example is given below to illustrate this point.

Figure 8 illustrates a 1-hour traffic demand profile at the freeway mainline and the ramp. A single regime capacity of 6500 vehicles per hour (vph) is assumed for the freeway bottleneck location, and a fixed ramp-metering rate of 1200 vph is also assumed. The illustrated traffic demand profile indicates that during the initial ten minutes of the analysis period, the freeway mainline demand of 5000 vph plus the ramp demand of 2000 vph exceed the freeway bottleneck capacity of 6500 vph. Without ramp metering, the throughput at the freeway bottleneck would equal its capacity of 6500 vph. Assuming that the ramp traffic and the mainline traffic have the same priority to be serviced, the delay would then occur to both the mainline traffic and the ramp traffic. However, with ramp metering in operation, the total demand at the freeway bottleneck would be the mainline demand 5000 vph plus the ramp-metering rate 1200 vph, which is less than the freeway bottleneck capacity 6500 vph, resulting in under-utilization of the freeway capacity. In this case, delay would occur only to the ramp traffic.

![Figure 8 Freeway and ramp traffic demand profile.](image)

The detailed queue and delay calculations are shown in Table 1 for both a two-capacity regime scenario and a single-capacity regime scenario. Calculation of the delays is based on the basic principle of the cumulative arrival and departure method (38, 39) as described in the following equations in discrete form:
\[ \frac{\Delta A}{\Delta t} = V(t) \]  
\[ \frac{\Delta D}{\Delta t} = O(t) = \begin{cases} 
    c, & \text{if } A(t) > D(t) \\
    V(t), & \text{otherwise} 
\end{cases} \]  
\[ q(t) = A(t) - D(t) \]  
\[ TD = \sum_t q(t)\Delta t \]

where

- \( A(t) \) = cumulative number of vehicle arrivals at time \( t \), veh
- \( c \) = capacity of the facility, vph
- \( D(t) \) = cumulative number of vehicle departures at time \( t \), veh
- \( O(t) \) = throughput flow rate of the facility at time \( t \), vph
- \( q(t) \) = queue length at time \( t \), veh
- \( V(t) \) = traffic demand at time \( t \), veh
- \( TD \) = total vehicle delays during the analysis period \( T \), veh-sec or veh-min or veh-hr depending on the unit of \( t \)

For the calculations in Table 1, the free-flow capacity, \( c_F \), was assumed 6600 vph, and the queue-discharge capacity, \( c_Q \), was assumed 6000 vph. For each 5-min interval (\( t = 5 \) min), the freeway demand, \( V(t) \) and the ramp traffic demand, \( R(t) \) are given, while the freeway and ramp queues, and the freeway and ramp delays are calculated.
Table 1 Delays with/without ramp metering and with different capacity scenarios

<table>
<thead>
<tr>
<th>t (min)</th>
<th>No Metering</th>
<th>With Metering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_f(t)$</td>
<td>$R(t)$</td>
</tr>
<tr>
<td>0~5</td>
<td>5000</td>
<td>2000</td>
</tr>
<tr>
<td>5~10</td>
<td>5000</td>
<td>2000</td>
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<td>10~15</td>
<td>8000</td>
<td>2200</td>
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<td>20~25</td>
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<td>35~40</td>
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<td>600</td>
</tr>
<tr>
<td>55~60</td>
<td>4000</td>
<td>600</td>
</tr>
<tr>
<td>Total Delay</td>
<td>315.3 veh-hr²</td>
<td></td>
</tr>
<tr>
<td></td>
<td>168.1 veh-hr³</td>
<td></td>
</tr>
</tbody>
</table>

**Note:**
1. For the two-regime capacity scenario, the freeway capacity, $c(t)$ is equal to $c_f$ if $q_f(t-1) = 0$ and $V_f(t) + O_R(t) \leq c_f$; otherwise, $c(t)$ is equal to $c_Q$. For the case of No Metering, $O_R(t) = R(t)$.
2. Results with the two-regime capacity: $c_f = 6600$ vph, $c_Q = 6000$ vph.
3. Results with the single-regime capacity: $c_f = c_Q = 6500$ vph.

As shown in Table 1 that the freeway had a lower capacity (6000 vph) at the beginning of the analysis period without ramp metering, indicating the case of a breakdown. With ramp metering, however, the freeway was able to maintain at a free-flow condition, thus had a higher capacity (6600 vph) at the beginning of the analysis period. Ramp metering was able to reduce the system delays (from 315.3 veh-hr to 288.9 veh-hr) when the two-capacity regime existed. Similar calculations were carried out assuming a single-regime capacity of 6500 vph. In this case, ramp metering actually increased the system delays (from 168.1 veh-hr to 197.9 veh-hr).
INTEGRATED OPERATIONS

The concept of integrated operations between the surface street signal system and freeway ramp control system dates back to the early 1970s in the context of corridor control (6). Several researchers developed mathematical models for an integrated freeway corridor control system (40, 41, 42). Field implementation and testing have also been conducted in recent years and sought to improve the freeway corridor as a whole, consisting of both the freeway ramp-metering system and the parallel arterial streets (21, 22, 23, 43, 44). However, the majority of the studies on integrated systems often emphasize too broad a range of the network, while not many detailed investigations have been carried out regarding the close interactions between ramp metering and the nearby upstream signalized intersection, such as a diamond interchange. Ignoring the basic integration elements between ramp metering and upstream signals has lead to unsuccessful field operations (21, 22).

A limited number of literature sources were found to be related to this research subject. Gordon (45) studied the effect of the ramp-metering sampling interval on ramp queues. One of the conclusions of his study is that queue spillback can be significantly reduced by using a shorter sampling interval, i.e., a more responsive metering operation. His study mainly focused on the ramp metering itself without addressing how the upstream signal timing might affect the ramp queues.

Chaudhary and Messer (46) studied the ramp-metering queues given a fixed ramp-metering rate and stochastic traffic demand at an upstream diamond interchange. Their study was based on simplified assumptions of the diamond interchange timing and traffic flow, and an empirical equation was developed for estimating the ramp queue length. For example, one of the simplifications was to consider only one side of the diamond interchange, and all the traffic departed from the signal was assumed to arrive at the ramp, which is not the case with the frontage road system.

Han and Reiss (47) studied the relationship between a simple two-phase upstream signal and a ramp meter. They concluded that using a varied ramp-metering rate would be more effective in eliminating the short-term queue spillback that resulted from signal-controlled vehicle arrivals.

Two studies found in the literature are more closely related to this research topic. One was conducted by Head and Mirchandani (48) to specifically look at the coordination between ramp-metering and diamond interchange operations. Their study sought to develop a real-time adaptive control system that would achieve the coordination between ramp metering and a diamond interchange’s operation. Their study focused more on the adaptive feature of the diamond interchange by developing detection and prediction algorithms. Consideration of ramp metering was limited to a fixed ramp-metering rate.

Venglar and Urbanik (49) proposed a system architecture aimed at developing an adaptive control system for a diamond interchange, incorporating various technologies including video detection, a traffic simulator, fiber-optic lane assignment signing, and communication equipment. The system was intended to integrate various
transportation modes and respond to various transportation needs. However, ramp metering was not a component of the system.
CHAPTER III
DEVELOPMENT AND EVALUATION OF INTEGRATED CONTROL STRATEGIES (ICS)

The processes of developing and evaluating ICS for an IDIRMS are documented in this chapter. ICS for an IDIRMS were developed focusing on the strategies dealing with recurring freeway congestion. The primary system operational objective is to maintain ramp metering in operation as a means of preventing freeway breakdown, which would require minimizing ramp queues and spillback occurrences. The ICS were implemented and evaluated using the VISSIM microscopic simulation model. The VISSIM simulation model was used to capture the details and dynamics of the operations. Microscopic simulation models such as VISSIM also provide users with the capability of developing signal control logics that resemble actual signal controller operations. Evaluations of the effectiveness of ICS were conducted based on three generally defined demand scenarios as characterized by the ramp conditions.

THE SYSTEM'S OPERATING OBJECTIVES

One of the key elements for a successful development and implementation of ICS is to achieve better management of the available resources in IDIRMS under various traffic flow conditions. The key to a successful operational strategy relies on identifying all the critical elements and determining which elements can be managed and controlled. Operational strategies should address a broader range of impacts on the entire transportation system.

The resources within an IDIRMS include three major facilities: the freeway mainlines, the ramp meters, and the diamond interchange. The properties of each facility that needs to be managed include the capacities, throughput flows, and queue storage spaces. In general, we have little or no control of the freeway mainline demands. However, we can manage the freeway mainlines to maintain free-flow conditions without breakdown using ramp metering so that the freeway would produce the maximum throughput flows. Both field operations and previous analyses indicate that ramp queue flush is one of the major causes of freeway breakdown. Flushing the ramp queue results in a sudden increase in freeway demands due to platoon vehicles entering the freeway, which increases the likelihood of freeway breakdown. Therefore, an effective approach to prevent freeway breakdown is to maintain ramp metering in operation without queue flush. However, ramp metering implies restricted ramp entry, thus increasing the likelihood of ramp queue spillback into the diamond interchange signal.

Strategies to prevent queue spillback to the diamond interchange are then used to manage the demand and store the excessive queues outside the interchange, either on the arterial street approaches or on the frontage road approaches. However, the most advantageous queue storage locations must be determined based on the analyses of potential impacts and operational trade-offs. Storing the queues on the arterial street
approaches seems to be a preferred alternative because excessive queues on the frontage road approach may present a more severe threat to the traffic system operations than storing queues on the arterial street. Queue spillback to the frontage road approach and perhaps extension to the freeway mainline may interfere with mainline operations, which would result in reduced freeway throughput \((50, 51)\). Excessive queues on the frontage road approach would also cause blockage to the left-turn and right-turn movements. On the other hand, queues on the arterial approaches must also be limited because excessive queues on the arterial approaches may interfere with other signalized intersections along the arterial.

Because the available queue storage spaces on both the frontage road and the arterial locations have limits, the objective of the ICS is therefore to maximize the usage of these available queue storage spaces. When the last resort (i.e., all storage spaces) is used up, the excessive queues and demands may eventually need to be released by means of terminating the ramp-metering operation. If ramp queue flush is then considered as a failure event, the ICS should delay its occurrence, but it may not be able to completely avoid it.

From the point of view of achieving system optimal operation and considering the operational trade-offs:

1. maximize freeway mainline operations at free-flow conditions and minimize freeway breakdown;
2. minimize ramp queue flushes and maximize normal ramp-metering operation;
3. minimize ramp queue spillback into the diamond interchange signals;
4. control vehicle entries to the ramp meters through proactive signal control at the diamond interchange; and
5. store excessive demands and queues in the most advantageous locations so that all the queue storage spaces can be efficiently used without interfering with freeway mainline and adjacent arterial signal operations.

**DEVELOPMENT OF ICS**

ICS were developed to achieve the operating objectives noted above. The ICS developed in this study focused on the conditions of recurring congestion.

Recurring congestion refers to the situation where traffic demand exceeds capacity on a regular basis. Recurring congestion can be classified into short-term and long-term congestion, which are all subjectively defined. Short-term congestion may refer to the situation where over-saturation lasts only for a short period of time (e.g., a period of 15 minutes or a few signal cycles at the diamond). Long-term recurring congestion may refer to a situation where over-saturation may last for a prolonged
period (e.g., at least 30 minutes or more). Both short-term and long-term congestion are encountered in daily operation and, therefore, are addressed in this research.

Under conditions of short-term congestion, queue spillback to the diamond interchange may or may not occur depending on how long the congestion period is and whether there are enough queue storage spaces between the ramp meter and the diamond interchange. Under long-term congestion, traffic demands exceed the ramp-metering capacity for a prolonged period, and queue spillback to the diamond interchange signal will most likely occur.

In either case, proactive control at the diamond interchange must be executed in order to prevent queue spillback occurrences. Such a proactive control could be achieved through adjustment of the diamond interchange signal timing. For example, in order to prevent queue spillback to the diamond interchange, the traffic movements feeding the ramp may be restricted entry to the downstream frontage road and the ramp. Such a control measure could not be accomplished by some minor adjustments to the signal cycle length and splits. Special signal timing may be necessary to achieve restricted vehicle entry such as using all-red extensions or holding a particular signal phase. All-red extension implies displaying extended red signal indications as a means of stopping traffic going through the interchange. Such an operation, although it may serve the purpose of restricting vehicle flows, may not be a practical application. The ICS developed in this research are based on the principle of holding a particular signal phase to achieve the objective of restricted vehicle entry.

**ICS Under Recurring Congestion**

Strategies of spillback control through proactive diamond signal timing are used to achieve smoothed ramp demand, as shown in Figure 9. Figure 9a shows the ramp demand profile when proactive control was not applied to the traffic from the diamond interchange, while Figure 9b shows the profile after proactive control was applied. In these cases, the ramp meter had a fixed metering capacity of 900 vph. As can be seen, even when the average ramp demand is less than the metering capacity, the stochastic traffic flow variation resulted in several cycles where the demand exceeded the metering capacity, which could potentially result in queue spillback. With proactive diamond signal control, the ramp demand never exceeded its metering capacity during the entire analysis period, while the same ramp-metering throughput was maintained. Of course, the figures here illustrate the best scenario that could be achieved. In reality, to achieve such perfect demand control would require accurate demand detection and quick signal operation response, which has been a challenging task facing traffic engineers and researchers.
Basic System Requirements for Adaptive Control

To prevent ramp queue spillback, the diamond interchange signal must be able to sense any ramp queue buildup and respond with adequate signal control. Therefore, the diamond signal system must have adaptive control features, which would require additional detection, communication, and signal control devices. Such a system can be
developed based on the existing functions and features of most traffic signal controllers currently used in Texas.

Figure 10 is a proposed detection design, where additional detectors need to be installed in addition to the detectors used for a standard diamond interchange control system and a traffic-responsive ramp-metering system. The additional detectors on the arterial street approaches and the freeway off-ramps serve the purpose of detecting excessive vehicle queues so that the system can respond to the traffic queues and prevent further spillback that would interfere with freeway mainline and adjacent signalized intersections.

There are two types of queue detectors on each external approach to the diamond interchange: the boundary queue detectors and the intermediate queue detectors. The boundary queue detectors set limits of allowable queue spillback at a particular location. Further queue spillback beyond these boundaries should be avoided since interference with other traffic facilities might occur, such as the adjacent traffic signals in the arterial or the freeway mainlines. Selecting these boundary detector locations should be based on analyses of site-specific characteristics. The intermediate queue detectors sense the potential queue buildup that results from the special signal operations during ICS applications, and they would serve the purpose of adjusting the phase splits to achieve balanced use of available queue storage spaces. The queue spillback/interface detectors on the frontage roads downstream of the diamond interchange signals are for the purpose of detecting ramp queue buildups and serve as interfaces between the ramp metering system and the diamond interchange system. Traffic flow data such as occupancy and volume could be measured using the queue spillback/interface detectors, serving as the outputs from the diamond interchange and the inputs for the ramp metering.

A brief description of the basic principles of ICS is presented next. The diamond interchange signal would remain in normal operation if none of the boundary queue detectors (i.e., arterial detectors, off-ramp detectors, and spillback detectors) detects traffic queues. However, minor phase splits may be adjusted based on the queue conditions at the intermediate queue detectors. The existence of a traffic queue is typically determined based on a specified occupancy level from the detectors. The occupancy of a queue detector is usually sampled over specified time intervals (e.g., 20 seconds). A traffic queue is defined when the sampled occupancy exceeds a predefined threshold value (e.g., 60 percent). Whenever a ramp queue is detected by the queue spillback detector, the diamond signal quickly transitions to a particular signal phase to hold so that further vehicle entry to the ramp is controlled and queue spillback to the diamond interchange signal would be prevented. The diamond signal goes back to normal operation once the ramp queue is dissipated.
The location of the queue spillback detector should be some distance away from the diamond signal to avoid queue spillback occurring during the transition period between normal diamond signal operations and the special integrated control operations. The signal phase(s) to hold should be the one(s) that would restrict further release of vehicles from those traffic movements feeding the ramp (e.g., the through movement on the frontage road approach and the left-turn movement on the internal arterial street approach). The green splits after the phase hold may be designed to facilitate clearing excessive queues that resulted from the phase hold. The control strategies should be designed to result in the maximum usage of the available queue storage spaces on the external diamond interchange approaches. Ramp metering would remain in operation until all the queue storage spaces are filled up.

It should be pointed out that ICS do not consider switching between phasing schemes during the operations because it is uncommon to use two types of phasing schemes at the same diamond interchange location during different time periods of the day. One particular case to prevent phasing scheme switching is related to the special

Figure 10 Enhanced detection system and detector layouts.
lane configuration for the internal movements. For example, a shared left/through lane may be used for the internal movements with the four-phase scheme. With the three-phase scheme, however, the left-turn lanes need to be exclusive lanes. Unless a dynamic lane assignment strategy is implemented, switching between three-phase and four-phase schemes may not be a viable option. The following discussions specifically address the conditions and the possible holding phases with three-phase and four-phase strategies.

**Strategies with Three-Phase**

Figure 11 through Figure 13 illustrate the conditions and the proposed holding phases with three-phase operations. Figure 11 shows the holding phases being the internal left-turn phases (ϕ1 and ϕ5). By holding these phases, no further vehicle entries to the metered ramps would result (except for the uncontrolled arterial right-turn and U-turn traffic). Holding the internal left-turn phases would provide equal treatment to the two metered ramps; therefore, it would be suitable when the two ramps have similar traffic conditions. The disadvantage of holding the internal phases is that the arterial through traffic would be stopped and unnecessary delays to the traffic would occur.

\[
A = \phi_1 + \phi_2 \\
B = \phi_5 + \phi_6
\]

**Figure 11** Hold internal phases with three-phase.
Figure 12  Hold arterial phases with three-phase.

Figure 13  Hold frontage road phase with three-phase and conditional service.

Figure 12 shows the holding phases being the arterial through phases (φ2 and φ6). Although control of vehicle entry to the ramps would also be achieved by holding these phases, it has the potential of queue spillover within the internal left-turn lanes,
which may cause lockup of the diamond interchange. However, the advantage of holding the arterial through phases is to allow arterial through traffic going through the interchange so that unnecessary delays to these vehicles can be avoided.

Figure 13 shows the holding phases being the frontage road phases with the diamond interchange operating with a special feature called conditional service. With conditional service, an additional arterial left-turn phase (φ1 as shown in the figure) can be serviced while one of the frontage road phases is being serviced (φ8 as shown in the illustrated case). The use of conditional service would result in unequal treatment to the two ramp meters. As shown in this case, holding the frontage road phase (φ8) would restrict vehicle entries to the left-side ramp meter (R1).

The control algorithm for the diamond interchange signal that incorporates the above phase-holding strategies under the three-phase scheme is shown in Figure 14. The signal control logic illustrated in Figure 14 is described as follows. When there are no queues detected by the spillback queue detectors, the signal phases either receive the normal splits or the adjusted splits, depending on the intermediate queue detector information. For example, if the intermediate queue detector on the right-side arterial approach detects a queue, the phase splits for φ6 and φ1 need to be increased, while the phase splits for φ4 and φ8 need to be reduced. If none of the intermediate queue detectors detect a queue, the diamond signal will have the normal splits. The phases would also receive normal splits whenever the boundary queue detectors detect a queue, when the ramp-metering operations are suspended. When queues are detected on either metered ramps, the diamond signal would hold particular phases, either φ1 and φ5 or φ2 and φ6, depending on the intermediate queue conditions on the arterial street. For example, if queues are detected by the intermediate queue detectors on the arterial approaches, the diamond controller would hold φ2 and φ6. Otherwise, the controller would hold φ1 and φ5.

**Strategies with Four-Phase**

Figure 15 and Figure 16 show the conditions and the proposed holding phases when the diamond signals operate with four-phase. These figures illustrate the holding phases, either the right-side frontage road phase (φ8) or the arterial through phase (φ2) to control vehicle entry to the left-side ramp (R1). Similarly, φ4 and φ6 are the holding phases if vehicle entry to the right-side ramp (R2) needs to be controlled. The strategies illustrated in Figure 15 and Figure 16 would only achieve controlling vehicle entry to one of the ramps at a time. Under special circumstances, the holding phases can be the internal left-turn phases (φ1 and φ5) if vehicle entry to both ramps needs to be controlled. This is achieved through the use of dummy phases for the internal movements to cross the controller barriers under four-phase operation. For example, the Eagle EPAC300 controller defines a dummy φ9 for the left-side internal movement phase, which is on the same side of the barrier as the arterial phase (φ2) and the frontage road phase (φ4).
Note:  R – On-Ramp; OffR – Off-Ramp; Art – Arterial; RT – Right Side; LT – Left Side; M – Intermediate
+ φ – Increase Phase Split; - φ – Reduce Phase Split (See Figure 3 for reference)

Figure 14  ICS logic and flow chart with three-phase operation.
Similarly, the control algorithm incorporating these phase-holding strategies under four-phase operation is depicted in Figure 17.
Figure 17  ICS logic and flow chart with four-phase operation.

ICS’s Ramp-Metering Component

Figure 18 illustrates the component concerning the ramp-metering operations in ICS. Under the integrated operations, ramp-metering queue flush would occur only when a traffic queue exceeds one of the boundary detector locations.
Other Considerations for IDIRMS Components

The IDIRMS and its operations addressed in this research are considered first steps to explore a truly high level intelligent IDIRMS. Besides the vehicle detection system depicted in Figure 10, the IDIRMS would require additional communication and traveler information systems. Dynamic message signs and advanced warning signs might be essential equipment for conveying necessary information to roadway users. Under integrated operation, the surface street vehicles will likely experience longer queues and delays due to implementation of phase holding in ICS. They would also
likely experience unusual signal timing due to phase holding. Drivers should be informed of such timing changes to minimize their confusion and frustration. Examples of dynamic warning signs may include “Do not block intersection,” “Signal in special transition,” etc. The communication system should enable uninterrupted data exchange between the surface street signal system (diamond interchange signal), and the freeway and ramp-metering system. NTCIP-compliant (52) devices for field implementation are then critical to ensure data exchangeability between the two systems. With the advance of detection, communication, and information technologies, more accurate traffic flow data could be obtained and applied in real time to improve system performance, which would require development of more sophisticated control algorithms.

EVALUATION OF ICS

The ICS discussed earlier in this chapter for ramp queue spillback control under recurring congestion were evaluated using the VISSIM simulation model under three generally defined traffic demand scenarios as characterized by the ramp conditions: low, medium, and high. These general traffic demand scenarios are qualitatively described in

Table 2. Table 3 provides quantitative description of the traffic scenarios in terms of the v/c ratios and the percentage of cycles that demand exceeding metering capacity. It should be noted that over-capacity during a particular cycle does not necessarily result in queue spilling back to the diamond interchange, because the queue storage space between the ramp meter and the diamond interchange provides buffers to temporarily hold the vehicle queues. Detailed traffic volumes for the three demand scenarios are included in Appendix A.

Table 2 Qualitative description of the traffic demand scenarios for ICS evaluation

<table>
<thead>
<tr>
<th>Demand Scenarios</th>
<th>Traffic Conditions</th>
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<tbody>
<tr>
<td></td>
<td>( R1 ) (Peak Direction)</td>
</tr>
<tr>
<td>Case I: Low</td>
<td>Demand is less than capacity but does experiences short-term over-capacity (e.g., several cycles).</td>
</tr>
<tr>
<td>Case II: Medium</td>
<td>Demand is slightly over the ramp’s capacity and experiences relatively longer periods of over-capacity.</td>
</tr>
<tr>
<td>Case III: High</td>
<td>Demand exceeds capacity by a significant margin and the ramp experiences over-capacity during most of the analysis period.</td>
</tr>
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Table 3  Quantitative description of the traffic demand scenarios

<table>
<thead>
<tr>
<th>Demand Scenarios</th>
<th>Ramp Conditions</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v/c Ratio</td>
<td>% Cycles Demand Exceeding Capacity</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R1</td>
<td>R2</td>
<td>R1</td>
</tr>
<tr>
<td>Case I: Low</td>
<td>0.88</td>
<td>0.54</td>
<td>20</td>
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<tr>
<td>Case II: Medium</td>
<td>1.00</td>
<td>0.60</td>
<td>65</td>
</tr>
<tr>
<td>Case III: High</td>
<td>1.06</td>
<td>A: 0.63</td>
<td>90</td>
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<tr>
<td></td>
<td>B: 1.03</td>
<td></td>
<td>B: 80</td>
</tr>
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</table>

The system operations were evaluated using VISSIM under the traffic demand scenarios described above in Table 2 and Table 3. Table 4 describes the experimental design matrix, including a total of 16 traffic scenarios and simulation cases. Two sub-cases were included in the high demand scenario, with case III-B reflecting a more highly over-saturated condition for R2 than that in case III-A.

Table 4  Naming scheme of traffic scenarios and experimental runs

<table>
<thead>
<tr>
<th>Traffic Demands</th>
<th>Three-Phase</th>
<th>Four-Phase</th>
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<tbody>
<tr>
<td></td>
<td>Without ICS</td>
<td>With ICS</td>
</tr>
<tr>
<td>Low</td>
<td>3PNL</td>
<td>3PYL</td>
</tr>
<tr>
<td>Medium</td>
<td>3PNM</td>
<td>3PYM</td>
</tr>
<tr>
<td>High – A</td>
<td>3PNHA</td>
<td>3PYHA</td>
</tr>
<tr>
<td>High – B</td>
<td>3PNHB</td>
<td>3PYHB</td>
</tr>
</tbody>
</table>

Note: xP-Diamond phasing; N-Without ICS; Y-With ICS; L-Low demand; M-Medium demand; HA-High demand, case A; HB-High demand, case B.

In conducting the VISSIM simulation run, each simulation run lasted 12,000 seconds; however, the system performance measures were only reported between 600 seconds and 12,000 seconds in simulation. The initial 600 seconds were considered a system warm-up time. At 10,600 seconds into simulation, no further vehicle entry to the network was coded; therefore, the time after 10,600 was to clear the remaining traffic in
the network. Ten multiple simulation runs were conducted using different random seeds with each traffic demand scenario. Three major performance measures were used for the evaluation, including vehicle delays, the percent time that the ramp meter was in queue flush mode, and the ramp-meter queue flush rate defined by the number of queue flushes per hour.

Ramp queue flush is perhaps one of the primary causes of freeway breakdown as evidenced by the results shown in Figure 19 through Figure 21; therefore, the performance measures related to queue flush may be good indicators for evaluating the effectiveness of ICS.
Figure 19  Relationship between freeway breakdown and queue flush: low demand.
Figure 20  Relationship between freeway breakdown and queue flush: medium demand.
Figure 21 illustrates the relationship between freeway mainline delays and ramp-meter queue flush based on the VISSIM simulations for the three traffic demand scenarios. The curve for queue flush is represented in the form of cumulative queue flush time, where the horizontal segment indicates the period when the ramp meter was in normal operation without queue flush. Each figure includes two scenarios:

(a) With ICS

(b) Without ICS

**Figure 21** Relation between freeway breakdown and queue flush: high demand.

Figure 19 through Figure 21 illustrate the relationship between freeway mainline delays and ramp-meter queue flush based on the VISSIM simulations for the three traffic demand scenarios. The curve for queue flush is represented in the form of cumulative queue flush time, where the horizontal segment indicates the period when the ramp meter was in normal operation without queue flush. Each figure includes two scenarios:

(a) With ICS

(b) Without ICS

**Figure 21** Relationship between freeway breakdown and queue flush: high demand.
parts: (a) the delay profiles without ICS and (b) the profiles with ICS. The two cases in (a) and (b) were based on identical random seeds; therefore, they had identical traffic demand profiles in both cases.

As can be seen, the freeway mainline breakdown as indicated by the significant increase in the delays directly corresponds to the queue flush operation. In each of the traffic demand scenarios, the onset of queue flush, the total queue flush time, and the number of queue flushes (represented by the number of horizontal segments in the cumulative queue flush curve) were all improved with ICS. For example, ICS did not result in any queue flush under the low demand scenario. Under the medium demand and high demand scenarios, the onset of queue flush was delayed by a significant margin; therefore, the onset of freeway breakdown was also delayed. Another interesting observation is that the freeway delay was capped at approximately 120 sec/veh once breakdown occurred and persisted, suggesting that keeping ramp metering in operation may no longer be effective in reducing freeway delays.

Figure 22 through Figure 27 present the performance measure results by traffic demand scenarios. Figure 22 illustrates the percent queue flush time for the peak direction ramp (ramp1) under different traffic demand scenarios, and Figure 23 illustrates the ramp-metering queue flush rate for the peak direction ramp (ramp 1) under different traffic demand scenarios. In general, ICS significantly improved the ramp performance, as indicated by the lower queue flush time and the number of queue flushes. With the increasing demand level, both queue flush and queue flush rate increased. The most significant improvements could be seen under the medium demand scenario.

Figure 24 and Figure 25 illustrate similar ramp performance measures for the off-peak direction (ramp 2). Significant impact on ramp 2 performance only emerged under the case of High-B (both ramp 1 and ramp 2 became over-saturated). As can be seen, worse performance measures were obtained with ICS, as explained early in this chapter. Both the queue flush time and the queue flush rate increased with ICS.
Figure 22  Percent queue flush time by demand levels and control strategies: ramp 1.

Figure 23  Queue flush rates by demand levels and control strategies: ramp 1.
Figure 24  Percent flush time by demand levels and control strategies: ramp 2.

Figure 25  Queue flush rates by demand levels and control strategies: ramp 2.

Figure 26 illustrates the delay results for the peak-direction (northbound) freeway mainline. In general, ICS resulted in delay savings for the freeway mainline
traffic. The most significant delay savings can be seen for the medium demand and High-A demand scenarios. These delay savings were due to a significant reduction in ramp queue flush where freeway breakdowns were minimized. Under the low demand scenario, the delay savings with ICS was not significant. This is because ramp queue flush was minimal under the low demand scenario, and freeway breakdown hardly occurred even without ICS. For the High-B scenario, more frequent queue flush occurred due to over-saturation at ramp 2. As a result, the freeway mainline experienced increased delays compared to the High-A scenario.

![Figure 26](image)

**Figure 26** Peak-direction freeway mainline delays by demand levels and control strategies.

Figure 27 illustrates the system-wide delay measures by traffic demand scenarios. The system-wide delay is the weighted average of all the traffic in the system, including both freeway mainline traffic and the surface street traffic. As can be seen, ICS only resulted in lower system delays under the medium demand scenario although the differences are not significant. Under both the High-A and High-B scenarios, the system delays were actually increased with ICS, especially for the High-B scenario. The increase in system delays reflected the situations where the surface street traffic experienced significant delay increases due to ICS. The delay increases for the surface traffic outweighed the delay savings in the freeway mainline. Under the low demand scenario, the system-wide delays are basically the same with and without ICS.
In summary, ICS proved to be effective only within a certain traffic demand level, e.g., the medium level as defined in this study. Under the low demand scenario, where both the freeway mainlines and the ramps have sufficient capacities, implementing ICS would not result in significant difference in the system performances. On the other hand, when the traffic demands are high for both the freeway mainlines and the ramps, ICS would only provide marginal benefits for the freeway mainline operations by delaying the onset of ramp queue flush and freeway breakdown. Once the traffic queues on the surface street exceed boundary limits and ramp queue flush starts, the delay savings on the freeway traffic will be significantly diminished. The non-freeway traffic would experience excessive delays and queues, which would normally outweigh the delay savings of the freeway traffic. ICS proved to be most effective under the generally defined medium demand scenario, where temporary phase hold would not result in overflow of the queue storage spaces and freeway breakdown can be effectively prevented or delayed. Although non-freeway traffic would still generally experience increased delays, the delay savings on the freeway traffic would normally outweigh the delay increases on the non-freeway traffic.

ICS associated with three-phase and four-phase schemes yielded similar system performance measures although individual surface street traffic movements may experience different delay levels.
CHAPTER IV
A FRAMEWORK FOR IMPLEMENTING ICS

In chapter III, the proposed ICS were documented and the additional detection system components for implementing ICS and its algorithm were tested in a simulation environment. This section documents the development of a framework for potential field implementation of ICS in an IDIRMS. The ICS algorithm and architecture are described. Detailed functional diagrams for the algorithm are also provided.

Figure 28 illustrates the proposed system architecture for an IDIRMS with the ICS algorithm. Figure 29 illustrates the data flow within the ICS algorithm. In addition to the standard vehicle detection and signal control elements at the ramp-metering subsystem and the diamond interchange sub-system, IDIRMS with ICS requires additional vehicle detection systems, namely the boundary queue detection, intermediate queue detection, and queue spillback detection. The required detector locations were illustrated previously in Figure 10.

The ICS algorithm consists of three major functions: the Integration Need Assessor, the Strategy Selector, and the Strategy Implementer. The Integration Need Assessor processes information from the various queue detectors and determines whether ICS is needed based on the queuing conditions. Once the queuing conditions warrant ICS, the Strategy Selector will determine what strategy [i.e., the candidate phase(s) to hold] should be implemented based on the conditions of the queues and the diamond control mode (i.e., phasing schemes). The Strategy Implementer will facilitate the transition from normal signal operation to integrated control or vice versa based on the current signal status and queuing conditions. The detailed functional descriptions of the ICS algorithm are provided in Figures 30 through 34.
Figure 28  IDIRMS architecture.
Functional diagrams provide detailed descriptions of the systems engineering process in functional terms, which are considered critical elements for implementing the proposed ICS in IDIRMS. Functional diagrams include the process of translating top-
level system requirements into specific qualitative and quantitative design requirements. Figure 30 shows the top-level function diagram for the proposed ICS algorithm, and the lower-level function diagrams are depicted in Figure 31 through Figure 34.

The first function (Function 1.0) is to simply get and process the detector information. More specifically, the 20-second occupancy data are retrieved from the various detectors, including the ramp queue spillback detector, the intermediate queue detector, and the boundary queue detector. These detector occupancy values are compared with the predefined queue occupancy threshold (e.g., 60 percent) to determine whether a traffic queue exists at a particular detector location. Any occupancy exceeding the threshold value is considered to have the presence of a traffic queue. The reason for using occupancy instead of detector presence is that a traffic queue might be a moving queue such as in the case of ramp metering. Presence is also not a good indicator of traffic queues if the gaps between vehicles leave the detector unoccupied.

The second function (Function 2.0) is to determine whether integration control is needed. This is assessed based on the conditions of the traffic queues. To warrant the integration control, two conditions must be satisfied: (a) no queues exceed any boundary queue locations and (b) at least one ramp has detected a queue by the queue spillback detector. When the queuing conditions do not warrant integration control, the traffic signal and the ramp-metering signal remain in normal operations.
Figure 30 Top level function diagram of proposed ICS algorithm.
Figure 31 Diagram of functions for getting and processing detector information.
Figure 32 Diagram of functions for determining need for integration control.
The third function (Function 3.0) is to determine what integration strategy should be implemented, i.e., which phase(s) need(s) to hold to control vehicles from further entering the ramp(s). Selection of the holding phase(s) is based on the queuing conditions at the intermediate queue detector locations and the diamond control mode. Details of the control logic have been depicted in the flow charts shown in Figure 14 and Figure 17.

The fourth function (Function 4.0) is to implement the control strategy, which involves the processes of signal transition between normal operation and integrated control as well as issuing appropriate commands to the diamond signal and the ramp-metering signal. Once the candidate phase(s) to hold has(have) been determined, the algorithm needs to retrieve the phase status from the diamond signal controller. The phase status should include parameters such as the minimum green times of each phase, the current phase, and the next phase. A force-off call or phase omit call may then be issued to terminate the current phase if it is not the candidate phase for holding, and either omit the following phases or allow minimum green times until transition to the holding phase(s) occurs. During the phase-holding period, the queuing conditions on the relevant queue detector locations are continuously monitored. When the conditions no longer satisfy the requirements for integrated operation, the phase holding will be terminated, and the diamond signal will return to normal operation. The ramp-metering signal will turn to queue flush mode if traffic queues are detected by any of the queue spillback detectors and traffic queues are detected by any of the boundary queue detectors.
Figure 33 Diagram of functions for determining integration control strategy.
Top Level

1.0 Get System Detector Input
2.0 Determine If Integration Control Is Needed
3.0 Determine Integration Control Strategy
4.0 Implement Integration Strategy
5.0 Return to Normal Operations
6.0 Normal Operations

Second Level

A Determine If Both Ramps Have Queue Spillback
3.7 G

Determine If Right-Side Ramp Has Queue Spillback
3.8 G

Determine If Left-Side Arterial Exists Intermediate Queue
3.10 G

Determine If Right-Side Arterial Exists Intermediate Queue
3.9 G

Determine Phase to Hold (ϕ4)
3.12 G

Implement Integration Control Strategy
REF.
4.0

Determine Phase to Hold (ϕ6)
3.13 G

Determine Phase to Hold (ϕ2)
3.14 G

Determine Phase to Hold (ϕ8)
3.15 G

Figure 33 (Continued)
Figure 34 Diagram of functions for implementing integration strategy.
CHAPTER V
SUMMARY AND CONCLUSIONS

SUMMARY OF MAJOR TASKS PERFORMED

This research aimed at developing integrated control strategies and a framework for implementing the system for better managing the integrated operations between a diamond interchange system and a ramp-metering system. The research focused on the type of diamond interchange with U-turn lanes and one-way frontage roads typically seen in urban areas in the state of Texas and some other states. The signal phasing schemes included the two most commonly used phasing schemes: basic three-phase and TTI four-phase.

ICS were developed for achieving the integrated operations, and a proof-of-concept evaluation was conducted using VISSIM under three generally defined traffic demand scenarios: low, medium, and high, as characterized by the volume-to-capacity ratios at the ramps. Finally, a framework for implementing the ICS was developed, where detailed data flow and functional diagrams were provided. Major findings and conclusions reached in this research are documented next.

MAJOR FINDINGS AND CONCLUSIONS

Various ICS were developed in this research for the purpose of achieving better system performance measures. The ICS addressed in this research were considered as first steps to further explore a truly intelligent IDIRMS. Evaluations of ICS were carried out using VISSIM with one particular interchange location and with three generally defined traffic demand scenarios. Major findings and conclusions are summarized below:

- ICS proved to be effective only within a specified traffic demand level, e.g., the medium level as defined in this study. Under the low demand scenario where both the freeway mainlines and the ramps have sufficient capacities, implementing ICS would not result in a significant difference in the system performances. On the other hand, when the traffic demands are high for both the freeway mainlines and the ramps, ICS would only provide marginal benefits for the freeway mainline operations by delaying the onset of ramp queue flush and freeway breakdown. Once the traffic queues on the surface street exceed boundary limits and ramp queue flush starts, the delay savings on the freeway traffic will be significantly diminished. The non-freeway traffic would experience excessive delays and queues, which would normally outweigh the delay savings to the freeway traffic.

- One critical element for achieving the expected effectiveness with ICS is to have the ramp meter operate with traffic-responsive instead of fixed metering. Traffic-responsive ramp-metering algorithms, such as ALINEA, can actively respond to freeway congestion; thus, they are more effective in preventing freeway breakdown and achieving significant delay savings for the freeway traffic. Fixed metering,
although it may still be effective in improving freeway operations under certain circumstances, is less effective in preventing freeway breakdown.

- ICS associated with three-phase and four-phase schemes yielded similar system performance measures although individual surface street traffic movements may experience different delay levels.

- The proposed system architecture for an IDIRMS with ICS indicated that the system can be developed based on the existing controller features and functions although additional detection and communication equipment will be necessary.

**FUTURE RESEARCH**

Several research areas identified for further research are summarized below:

- The preliminary findings of system operational features drawn from the one case analysis should be further validated based on more case studies, requiring a broader range of network configuration and traffic flow scenarios.

- Field implementation and testing of the proposed ICS are necessary steps to evaluate their viability and effectiveness in managing the operations of an IDIRMS in real time. More sophisticated control algorithms could be developed with the advance of detection, communication, and information technologies where more accurate traffic flow and system status data could be obtained in real time.
REFERENCES


## APPENDIX A
### TRAFFIC DEMAND SCENARIOS

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<tr>
<th>O/D</th>
<th>D1</th>
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<td>610</td>
<td>370</td>
<td>14000</td>
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**Figure A-1** Low demand scenario.
Figure A-2  Medium demand scenario.
<table>
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Figure A-3  High demand scenario.