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RESEARCH PAPER

Modeling and Implementation of an Integrated Ramp Metering-Diamond Interchange Control System

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Abstract: This paper addresses a modeling approach to analyzing an integrated system that includes freeway mainlines, ramp metering, and an upstream signalized diamond interchange. The modeling approach takes into consideration of the various components, their operational characteristics, and their interactions within the system. Strategies are also proposed for real-time operation and possible field implementation. The key element of achieving an integrated operation is to control the ramp feeding the traffic through special signal timings at the diamond interchange. Whenever a long queue is detected at the metered ramp, the signal timing should be adjusted to reduce the traffic flows entering the ramp. In this way, the ramp meter will remain in operation as long as possible, which would delay the onset of queue flush (i.e., termination of ramp meter) and minimize the possibilities of a freeway breakdown. Because a diamond interchange is usually controlled by special signal phasing and timing, the control strategies are specially focused on the special diamond signal phasing schemes. The system design and system architecture are also presented for potential deployment of the system in the field.

Key Words: ramp metering; freeway; integration; diamond interchange

0 Introduction

Freeway ramp metering has been used worldwide as an effective traffic management technique to minimize freeway congestion and improve safety. In practice, however, the efficiency of ramp metering often diminishes when limited storage spacing exists on the metered ramp. In many cases, a ramp meter is located in close vicinity of an upstream signal, such as a signalized diamond interchange in urban areas. In the United States, a particular scenario is that the ramp metering system and the surface street signal system are maintained and operated by different jurisdictions. For example, the State Departments of Transportation usually manage the ramp metering system as part of their freeway systems, while the surface street traffic signal system is usually maintained and operated by city or county jurisdictions. As a result, the ramp metering system and the surface street signal system are primarily independent each other, where the close interactions between the two systems are seldom addressed. The primary objective of this paper is to document a modeling approach to analyzing an integrated system that includes freeway mainlines, ramp metering, and an upstream traffic signal, more specifically a signalized diamond interchange.

A general policy adopted by most jurisdictions for operating ramp metering is to flush the ramp queues (e.g., suspension of ramp metering) whenever queue spillback to the surface street occurs (Tian, 2002). One of the major problems of queue flush is an increased probability of freeway breakdown, thus significantly diminishing the effectiveness of ramp metering operations (Tian *et al.*, 2005; Zhang and Levinson, 2004). In urban areas, the majority of ramp metering is located in close vicinity of surface street signals. A common type upstream signal is a signalized diamond interchange. Similar to a regular traffic signal, traffic released from the signal and feeding the ramp meter tends to be in platoons. The platoon traffic causes sudden surge of traffic queues when the meter is on, and if the distance between the ramp meter and the upstream signal is short, queue spillback to the surface street can easily result. Queue spillback not only causes many safety concerns, but also affects the operations of the surface street

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system (Tian *et al.*, 2005).

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. Several researchers developed mathematical models for an integrated freeway corridor control system (Chin, 1993; Papageorgiou, 1995; Wu and Chang, 1999). 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 (van Aerde Yagar, 1988; Yang and Yagar, 1995; Paesani *et al.,* 1997; McNally *et al.,* 2001). 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 (Paesani *et al.,* 1997; McNally *et al.,* 2001).

This paper provides a modeling approach to analyzing an integrated system, addressing the relationships among various system components. The key element of achieving integrated operation is to control traffic from entering the ramp, through special signal timings, when a long queue is detected at the metered ramp. In this way, the ramp meter will remain in operation for as long as possible, which would delay the onset of queue flush and prevent possible freeway breakdown. Because diamond interchange has its special signal timing, the control strategies were specially focused on the type of diamond signal phasing. First, description of the model is provided. The concept of integration and operations is then illustrated based on a common diamond phasing scheme. The requirements on the system implementation and the system architecture are then discussed. Finally, a concluding section is provided.

1 Model description

A model to analyze the integrated system needs to consider the close interactions among freeway mainline, ramp meter, and diamond interchange operations. A brief description of the model is given in this section. Our primary focus will be on the enhanced modeling features where the interactions among the individual components are discussed.

A significant amount of literature has been devoted to studying each individual component of the system. Extensive literature could be found on how to manage the operations of the diamond interchange signals (Messer and Berry, 1975; Messer *et al.*, 1977). Special signal phasing schemes have been developed for operating the diamond interchange signals, among which the basic three-phase and the TTI four-phase are commonly used in the field. The details of these two types of phasing schemes can be found in the cited literatures. Basically, three-phase is specially designed for use where there is enough space between the two signals to store the arterial left-turn queues, and the TTI four-phase is better suited where there is limited spacing between the two signals. These operational strategies typically ignore the constraints imposed by downstream facilities such as ramp metering. One of the major enhancements of our model is the consideration of the effect of ramp queue spillback on the diamond interchange operations. The details of this modeling feature can be found in an earlier paper by Tian *et al.* (2004). The models were addressed based on various queue spillback scenarios and how the queues were distributed among the ramp feeding movements, so that the performance measures such as queue length, stops and delay can be obtained.

Two types of ramp metering strategies are available for an isolated ramp metering namely fixed-time ramp metering and traffic-responsive ramp metering (Tian, 2002). Studies have shown that traffic-responsive ramp metering is more efficient than fixed-time ramp metering owing to its ability of adjusting metering rates based on freeway mainline conditions. The model described in this paper is based on the traffic-responsive ramp metering to achieve the maximum efficiency of the system operations.

As for freeway mainline modeling, one of the unique operational features is the so called two-capacity phenomenon, suggesting that freeway capacity has two distinctive regimes: the capacity during free flow and the capacity during congested flow measured at an active bottleneck location (Hall and Agyemang-Duah, 1991). An active bottleneck, as originally defined by Daganzo (1997) is a bottleneck that is not influenced by another bottleneck further downstream. 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 a drop in flow rate (Persaud *et al.*, 2001). Fig.1 illustrates a speed-flow plot based on actual data from a freeway site, where the higher flow rate (an indication of higher capacity) under the free-flow condition and the lower flow rate (an indication of lower capacity) under the congested condition can be clearly seen. More detailed discussions regarding the two-capacity phenomenon can be found in an earlier paper by Tian (2006). Without the existence of the two-capacity phenomena, an isolated ramp metering would not be able to achieve the objective of minimizing system delays.

The modeling of the integrated ramp metering-diamond interchange system consists of procedures for determining traffic-responsive ramp-metering rate, stochastic freeway mainline capacity, queues and delays on the ramps, the mainlines, and the diamond interchange. A microscopic simulation model is developed, which performs the analysis on a second-by-second basis. The following section describes how the ramp and freeway are modeled, while the modeling of diamond interchange can be found in another study (Tian *et al*., 2005).

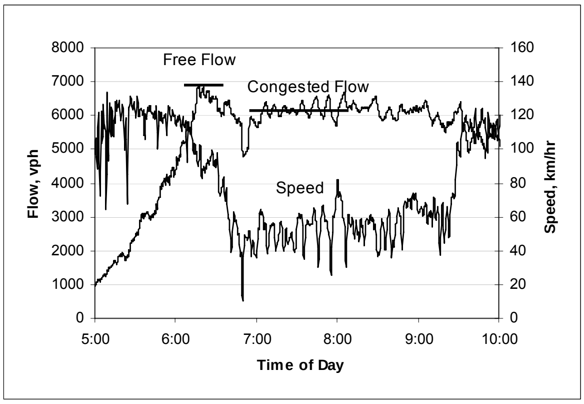


Fig. 1 Time series flow and speed plots

First, the variables in the model equations are described below:

$A_{Rr}(t)$ = cumulative vehicle arrivals at ramp r during time interval t, veh

$A_{Fr}(t)$ = cumulative vehicle arrivals in mainline freeway direction r during time interval t, veh

$c_{Fr}(t)$ = freeway mainline capacity of direction r during time interval t, vph

c_{Fr} = free-flow capacity of direction r, vph

c_{Qr} = queue-discharge capacity of direction r, vph

$D_{Rr}(t)$ = cumulative vehicle departures at ramp r during time interval t, veh

$D_{Fr}(t)$ = cumulative vehicle departures in freeway direction r during time interval t, veh

$F_r(t)$ = randomly generated freeway mainline demand of direction r at time interval t, vph

$F_r'(t)$ = capped freeway mainline arrival flow rate at the point of ramp merge location, vph

$F_r''(t)$ = average mainline arrival flow rate at time t during a ramp-metering interval, vph

$\Delta F_r(t)$ = mainline residual demand at time interval t, vph

$M_r(t)$ = ramp-metering rate at ramp r during time interval t, vph

$M_{r,min}$ = minimum metering rate for ramp r, vph

$M_{r,max}$ = maximum metering rate for ramp r, vph

$O_{Rr}(t)$ = throughput at ramp r during time interval t, vph

$O_{Fr}(t)$ = freeway mainline throughput of direction r during time interval t, vph

$q_{Fr}(t)$ = freeway mainline queue length of direction r at time interval t, veh

$q_{Rr}(t)$ = queue length at time interval t and ramp r, veh

r = index for freeway direction and metered on-ramp, r = 1,

$R_r(t)$ = traffic arrival rate at time interval t at ramp r, vph

S_{Rr} = ramp queue flush rate at ramp r, vph

TD_{Fr}= total freeway mainline delay of direction r, veh-hr

TD_{Rr} = total delay for ramp r, veh-hr

σ_{Fr} = standard deviation of free-flow capacity for mainline direction r, veh

σ_{Qr} = standard deviation of queue-discharge capacity for mainline direction r, veh

γ = flow cap factor, 1.2 (see Eq. (1))

η = breakdown factor, 1.2–1.5 (see Eq. (4))

ω = ramp-metering equivalency factor, 1/1.83

Eq. (1) through Eq. (3) derive the freeway mainline flow expected to arrive immediately upstream of the on-ramp at time interval t. The initial randomly generated demand, $F_r(t)$, is capped at a level that equals a factor γ times the free-flow capacity, c_{Fr}, representing the maximum flow rate that could get to the ramp merge point. $F_r''(t)$ is the average flow at time step t during the ramp-metering interval, a. $F_r''(t)$ will be used to determine the ramp-metering rate in Eq. (4) so that the same ramp-metering rate would result in the same metering interval.

$$F_r'(t)=\begin{cases}\gamma c_{Fr}, & F_r(t)>\gamma c_{Fr}\\ Min[F_r(t)+\Delta F_r(t-1),\gamma c_{Fr}], & Otherwise\end{cases} \tag{1}$$

$$\Delta F_r(t)=Max\left[0,\Delta F_r(t-1)+F_r(t)-F_r'(t)\right] \tag{2}$$

$$F_r''(t)=\frac{1}{a}\sum_{i=\mathrm{int}(\frac{t-1}{a})a+1}^{i+a-1}F_r'(i) \tag{3}$$

$$M_r(t)=\begin{cases}M_{r,\min}, & q_{Fr}[\mathrm{int}(\frac{t-1}{a})a]\geq\frac{c_{Fr}(\eta-1)}{3600}\\ M_{r,\min}, & F_r''(t)+\frac{1}{\omega}M_{r,\min}>c_{Fr}\\ S_{Rr}, & F_r''(t)\leq V_T\\ Min\{\omega[c_{Fr}-F_r''(t)],M_{r,\max}\}, & Otherwise\end{cases} \tag{4}$$

The ramp-metering rate, Mr(t), determined from Eq. (4) follows the basic demand-capacity principle. However, it does have a component of terminating ramp-metering operation if the mainline flow is below the metering threshold, VT, where SRr, the ramp queue flush rate, would result.

Eqs. (5) through (8) represent the cumulative arrival and departure method in discrete forms. Eq. (5) is the number of cumulative arrivals for the ramp, r. Eq. (6) is the ramp queue length at time t. Eq. (7) is the cumulative departure function at the ramp. Eq. (8) is the ramp throughput flow at time t.

$$A_{Rr}(t)=\sum_{i=1}^{t}\frac{R_r(i)}{3600} \tag{5}$$

$$q_{Rr}(t)=Max[0,q_{Rr}(t-1)+\frac{R_r(t)-M_r(t)}{3600}] \tag{6}$$

$$D_{Rr}(t)=A_{Rr}(t)-q_{Rr}(t) \tag{7}$$

$$O_{Rr}(t)=3600[D_{Rr}(t)-D_{Rr}(t-1)] \tag{8}$$

Eq. (9) determines the freeway mainline capacity at time t, which has the two-capacity nature with random variations, as given by the random variable generation function $F^{-1}()$. $F^{-1}()$ produces a random variable based on the normal distribution with the mean freeway capacity, either c_{Qr} or c_{Fr}, and the standard deviation, either σ_{Qr}, or σ_{Fr}, depending on the conditions described in Eq. (9). The mean capacities and their standard deviations would have to be obtained either from field studies or through simulation. η in Eq. (9) is called the breakdown factor (calibrated at 1.3) to reflect that the freeway will break down once the bottleneck demand is 1.3 times or higher than the free-flow capacity, c_{Fr}. Introducing η in the equation is to allow freeway to maintain at free-flow condition even with marginal queues on the freeway.

$$c_{Fr}(t) = \begin{cases} F^{-1}(RND, c_{Qr}, \sigma_{Qr}), & 3600 q_{Fr}(t-1) + F_r''(t) + O_{Rr}(t) > \eta c_{Fr} \\ F^{-1}(RND, c_{Fr}, \sigma_{Fr}), & Otherwise \end{cases} \tag{9}$$

Eq. (10) through (13) represent the modeling process using the discrete form cumulative arrival and departure method for the freeway mainline. Eq. (14) and Eq. (15) are the total delays in terms of vehicle-hours for the ramp and the mainline, respectively.

$$A_{Fr}(t) = \sum_{i=1}^{t} \frac{[F_r''(i) + O_{Rr}(i)]}{3600} \tag{10}$$

$$q_{Fr}(t) = Max[0, q_{Fr}(t-1) + \frac{F_r''(t) + O_{Rr}(t) - c_{Fr}(t)}{3600}] \tag{11}$$

$$D_{Fr}(t) = A_{Fr}(t) - q_{Fr}(t) \tag{12}$$

$$O_{Fr}(t) = 3600[D_{Fr}(t) - D_{Fr}(t-1)] \tag{13}$$

$$TD_{Rr} = \sum_{i=1}^{T} \frac{q_{Rr}(i)}{3600} \tag{14}$$

$$TD_{Fr} = \sum_{i=1}^{T} \frac{q_{Fr}(i)}{3600} \tag{15}$$

2 Strategies for integrated operation

The primary objective for integrating the operations among freeway, ramp metering and a signalized diamond interchange operations is to achieve optimal performance for the entire system, including the freeway and surface street systems. To achieve such an objective, the system resources must be managed and coordinated to reach an optimal system performance. The resources within an integrated ramp metering/diamond interchange system mainly include the queue storage spaces on the ramp, the queue storage spaces on the diamond interchange approaches, and the capacities of both freeway mainline and the diamond interchange. To achieve the optimal system performance, the freeway capacity must be maximized by preventing freeway from breakdown.

Therefore, one of the important aspects of integration is to minimize ramp queues so that ramp metering operation can be maintained for as long as possible, thus freeway breakdown or the onset of breakdown can be minimized. In the following section, the required system design and operational features are addressed. Then recommended control algorithms are described in detail.

2.1 System requirements and design

In order to achieve the objective discussed previously, 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. Therefore, additional detection, communication, and signal control devices may be necessary. The proposed system design and operations as described next could be implemented based on the existing functions and features of most advanced traffic signal controllers.

Fig.2 is a proposed system design, where the required additional detectors are shown. These 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 (standard control detectors are not shown in the figure).

There are two types of queue detectors on each external approach at 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. 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. 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 coordination, and they would serve the purpose of adjusting the phase splits to achieve balanced usage of available queue storage spaces. The queue spillback/interface detectors on the frontage roads downstream of the diamond interchange signals serve the purpose of detecting ramp queue buildups and as an interface 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.

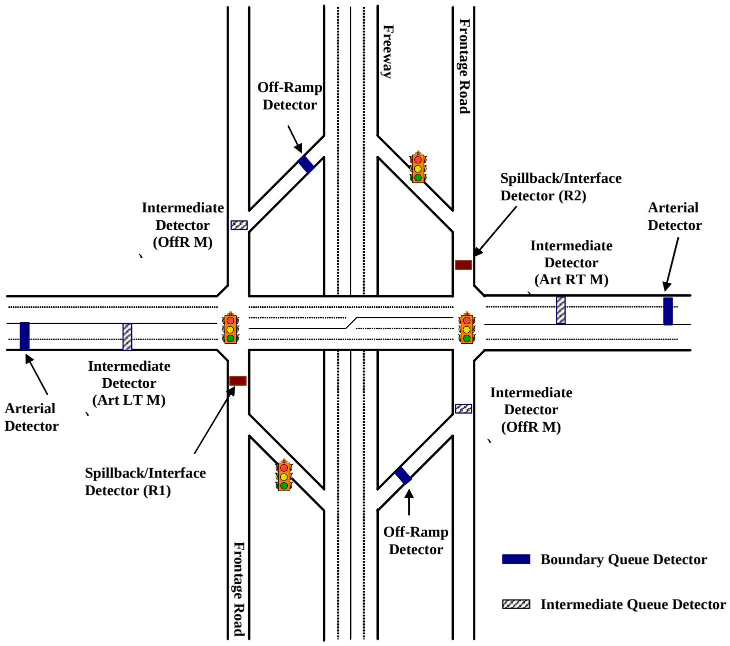


Fig. 2 Proposed detection system and detector layouts

2.2 Concept of operations

A brief description of the basic concept of the coordinated operations 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 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. 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 candidate signal phase (specific to the type of phasing and queue conditions) and holds that phase (i.e., keep the phase in green). By holding a particular phase(s), 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.

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., through movement on the frontage road approach and the left-turn movement on the internal arterial street approach), and depends on the types of phasing scheme, (i.e., basic three-phase or TTI four-phase) used at the diamond signal. After the phase hold, the green splits may be lengthened for a particular phase to facilitate clearing excessive queues that resulted from the phase hold. The control strategies should facilitate efficient 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.

In this study, integrated operational strategies were developed based on two common diamond phasing schemes: basic three-phase and TTI four-phase. The following discussions specifically address the conditions and the candidate holding phases with three-phase strategies. Fig.3 illustrates the conditions and the proposed holding phases with three-phase operations. Fig. 3(a) shows the holding phases being the internal left-turn phases (ϕ_1 and ϕ_5). By holding these phases (i.e., keep them in green), the other phases that contribute vehicle entry will be in red and no further vehicles can enter the metered ramps (except for the uncontrolled arterial right-turn and the free U-turn traffic in typical Texas diamonds). 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. Fig. 3(b) shows the holding phases being the arterial through phases (ϕ_2 and ϕ_6). Although control of vehicle entry to the ramps would also be achieved by holding these phases, the internal left-turn lanes can potentially spillback and lock up the diamond interchange. 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.

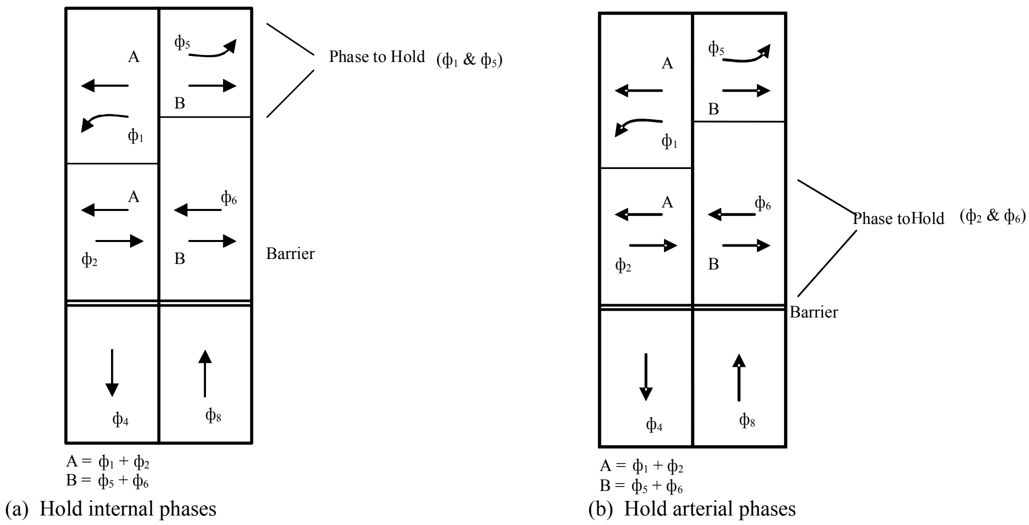


Fig. 3 Candidate phases to hold with three phases at a diamond interchange with frontage roads

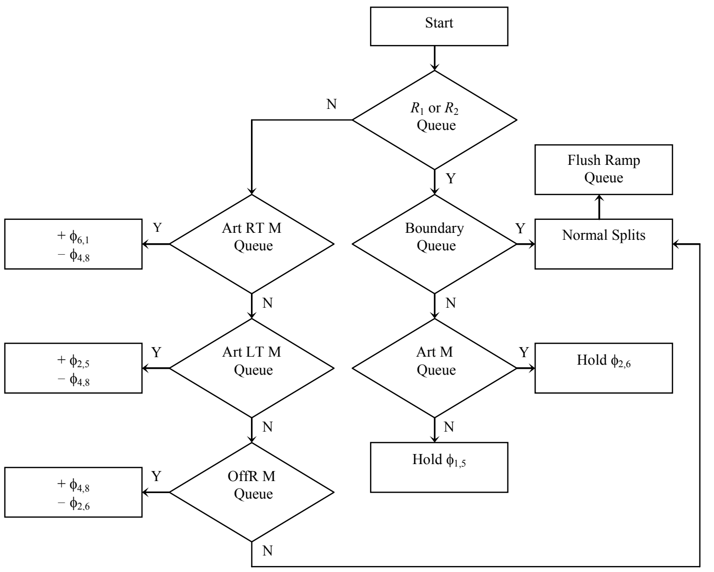
The algorithm for selecting which phase to hold under the three-phase timing scheme is shown in Fig.4. As long as no queues are detected by any of the spillback queue detectors, the diamond interchange receives the normal splits. Special signal timing will result only when a queue over one of the system detectors is detected. If the system detects that the ramp meter is not in immediate danger of becoming oversaturated (i.e., no queues are detected at the ramp R_1 or R_2 detectors), but queues are present at the intermediate queue detectors (ArtLT M, Art LT M, or OffR M), then the controller will adjust its phase splits in an attempt to provide additional capacity to those movements experiencing difficulties. For example, if a queue is detected on the intermediate queue detector on the right-side arterial approach (Art RT M), the splits for the movements coming from the right side of the diamond (ϕ_6 and ϕ_1) are increased a fixed, user-defined increment (a value of 10 % of the cycle was used in our evaluation), Likewise, if a queue is detected on the intermediate queue detector on the left-side approach (Art LT M), the splits for the movements coming from the left side of the diamond (ϕ_2 and ϕ_5) will be increased and the splits for the frontage road phases (ϕ_4 and ϕ_8) will be reduced. In both of these situations, the frontage road/freeway ramp phases (ϕ_4 and ϕ_8) are reduced by the same time increment in order to keep the same cycle length. If a queue is detected to impose interference with the operations of the off-ramp (through the OffR M), the system will increase the splits for frontage road approaches (ϕ_4 and ϕ_8) and decrease the arterial main street phases (ϕ_2 and ϕ_6). The diamond interchange will return to its normal splits if the queues no longer exist at any of the intermediate detectors. However, if the queues continue to grow until any of the boundary detectors detects a queue, the ramp-metering operation is suspended and the ramp queue is flushed.

When queues are detected on either metered ramps (i.e., the R_1 or R_2 detectors), the diamond signal would hold particular phases, either internal left-turn phases (ϕ_1 and ϕ_5) or the main-street, arterial through phases (ϕ_2 and ϕ_6), 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 will hold the main-street, arterial through phases (ϕ_2 and ϕ_6); otherwise, the controller will hold the left-turn phases (ϕ_1 and ϕ_5).

3 System architecture and data flow

The integration strategies and the control algorithm described in this paper are based on the principle of adapting existing system features for easy field implementation. For the purpose of facilitating field implementation of the system, two figures are prepared in this study, with Fig. 5 illustrating the proposed system architecture, and Fig. 6 illustrating the data flows within the control algorithm. In addition to the standard vehicle detection and signal control elements at the ramp-metering sub-system and the diamond interchange sub-system, the system requires additional vehicle detection systems, namely the boundary queue detection, intermediate queue detection, and queue spillback detection. The required detector locations are illustrated previously in Fig. 2.

The integrated control algorithm consists of three major functions: the Integration Need Assessor, the Strategy Selector, and the Strategy Implementer. The Coordination Need Assessor processes information from the various queue detectors and determines whether integrated operation is needed based on the queuing conditions. Once the queuing conditions warrant coordination, 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.



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 Fig. 3 for reference)

Fig. 4 Control logic and flow chart with three-phase operation

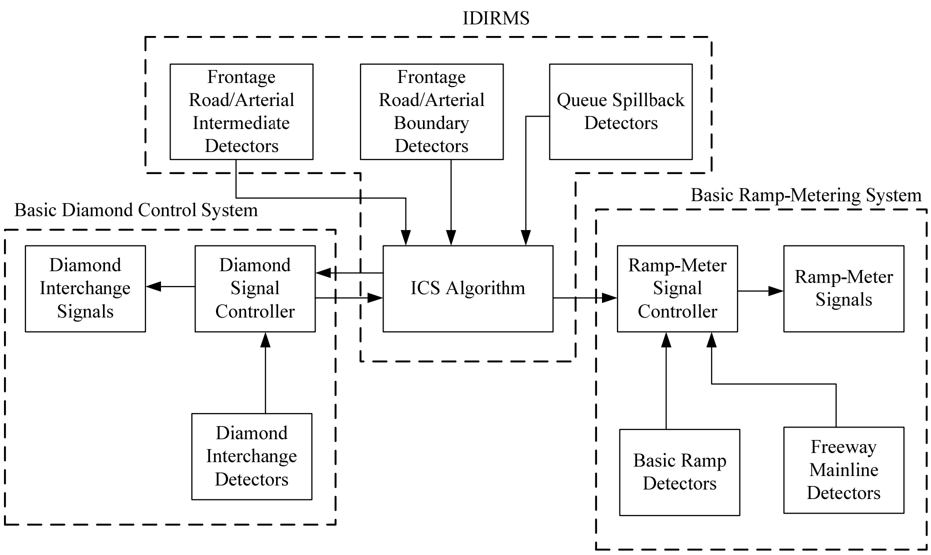


Fig. 5 Integrated system architecture

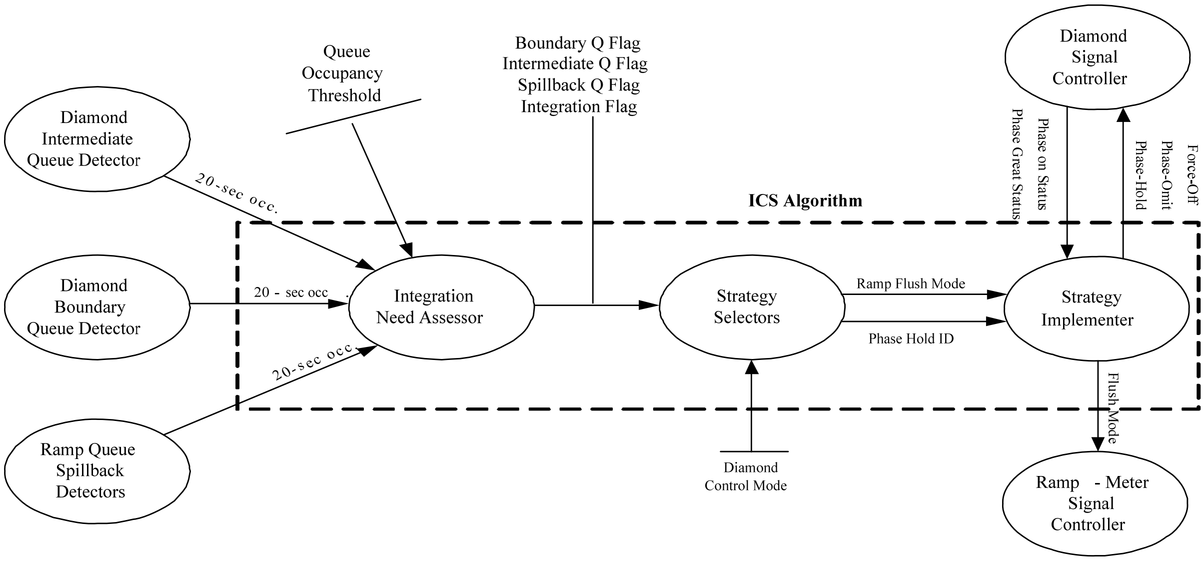


Fig. 6 Diagram of data flows of the proposed control algorithm

4 Concluding remarks

This paper documents a modeling approach to analyzing an integrated ramp metering-diamond interchange control system. In most urban areas, ramp meters are often located in close proximity of surface street traffic signals, where signalized diamond interchanges are commonly seen. Because of the unique traffic flow and geometric characteristics at diamond interchanges, the integrated control system specifically focused on the special signal timing schemes applied at diamond interchanges. The modeling approach takes into consideration of the close interactions among various system components, such as the entering and feeding traffic flows and the effect of queue spillback on the system operations. To implement the system in the field, an enhanced detection system needs to be deployed, which includes various system detectors. A control algorithm is also proposed, which relies on real-time information from the system detectors and application of the diamond signal phasing schemes. Finally, the system architecture is presented for potential field implementation of the integrated system.

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