A Model for Analyzing an Integrated Diamond Interchange, Freeway and Ramp Metering Control System

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Abstract

The majority of ramp-metering locations in the United States are located in the vicinity of freeway interchanges, such as signalized diamond interchanges. Currently, no analytical models are available to analyze of the operations of diamond interchange, freeway, and ramp metering in an integrated fastion. This paper is for the objective of developing such a model. Modeling methodologies were developed to consider the close interactions among the three system components: a diamond interchange, ramp meters, and freeway mainline facilities. Specific contributions of this study include the modeling of ramp platoon arrivals associated with the diamond signal timing, the impact of ramp metering queue spillback on the dimond interchange operations, and modeling of freeway operations incorporating the two-capacity phenomenon. Numerical results were presented to demonstrate the model capabilities.

Key Words: Diamond Interchange, Ramp Metering, Integration, Freeway Operations.

Introduction

The majority of freeway ramp meters in the U.S. urban areas are located in the vicinity of diamond interchanges, where two traffic signals are installed on the arterial street to control the interchanging traffic (Garber and Fontaine 1999). A significant challenge in managing traffic operations at such a location is to deal with the potential queue spillback from ramp meters as shown in Figure 1.

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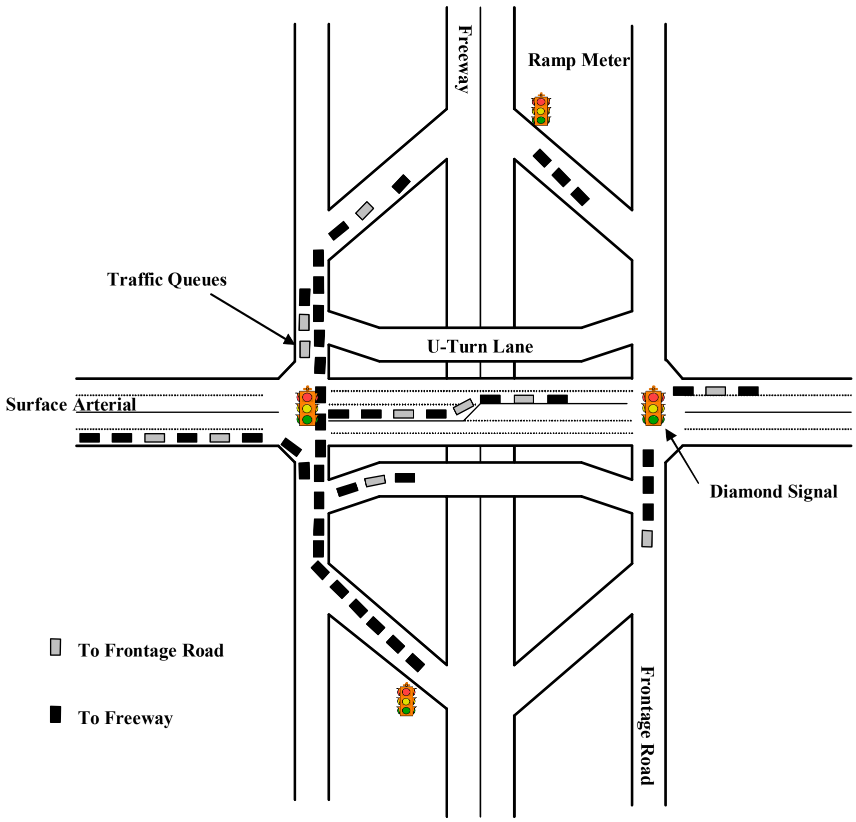


FIGURE 1 Queue spillback at a diamond interchange with ramp metering.

A significant number of studies have been conducted in the individual areas of diamond interchange operations (Messer and Berry 1975; Messer et al. 1977), ramp metering and freeway operations (Papageorgiou 1989; UC Berkeley 2002). However, limited studies could only be found in analyzing these sytem components in an integrated fasion, i.e., to consider the close interactions among each system components. For example, signalized diamond interchange creates platoon arrivals at the ramp meters, and the structures of the platoons are directly related to the diamond interchange signal timing. Depending on the spacing between the ramp meters and the diamond interchange, traffic queues may evolve and eventually spillback to the diamond interchange. Such an impact must be addressed accurately model the operations of these traffic facilities.

A major study has been conducted at the Texas Transportation Institute to address the modeling issues and operational strategies for an integrated diamond interchange – ramp metering system (IDIRMS). A computer model DRIVE was developed to analyze the system operations for an IDIRMS. The major modeling methodologies in DRIVE include modeling of ramp queue spillback, which can be found in an earlier publication (Tian et al. 2004), and the modeling of ramp metering and freeway operations, which is the main focus of this paper.

Modeling Methodologies

The Cumulative Arrival and Departure Method

The cumulative arrival and departure (CA&D) method is also referred to as the demand and supply method or the input and output method (Highway Capacity Manual 2000; Lawson et al. 1997). The method has been widely used in modeling queue and delay measures at various traffic facilities. The primary principle of the CA&D method is to derive the cumulative arrival and departure curves at a traffic facility, where the vehicle delays and queues can be estimated based on the horizontal and vertical offsets of the two curves. The CA&D method establishes the basis for developing the modeling methodologies in this study.

The Two-capacity Phenomenon

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 condition, namely the *free-flow* capacity, and the capacity value during congested flow, namely the *queue-discharge* capacity (Hall and Agyemang-Duah 1991). As shown in Figure 2 based on actual field measurements, the flow drop from the free-flow condition to the congested condition can be clearly seen. The modeling methodologies should take into consideration of the two-capacity phenomenon.

Model Description

The modeling of freeway and ramp-metering operations in this study consists of procedures for determining traffic-responsive ramp-metering rate, stochastic freeway mainline capacity, queues, and delays on both the ramps and the mainlines. The analysis is carried out on a second-by-second basis, including detailed descriptions of the arrival and departure flow profiles. All the modeling procedures described below were incorporated into a computer model called DRIVE.

Equation 1 through Equation 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 Equation 4 so that the same ramp-metering rate would result in the same metering interval.

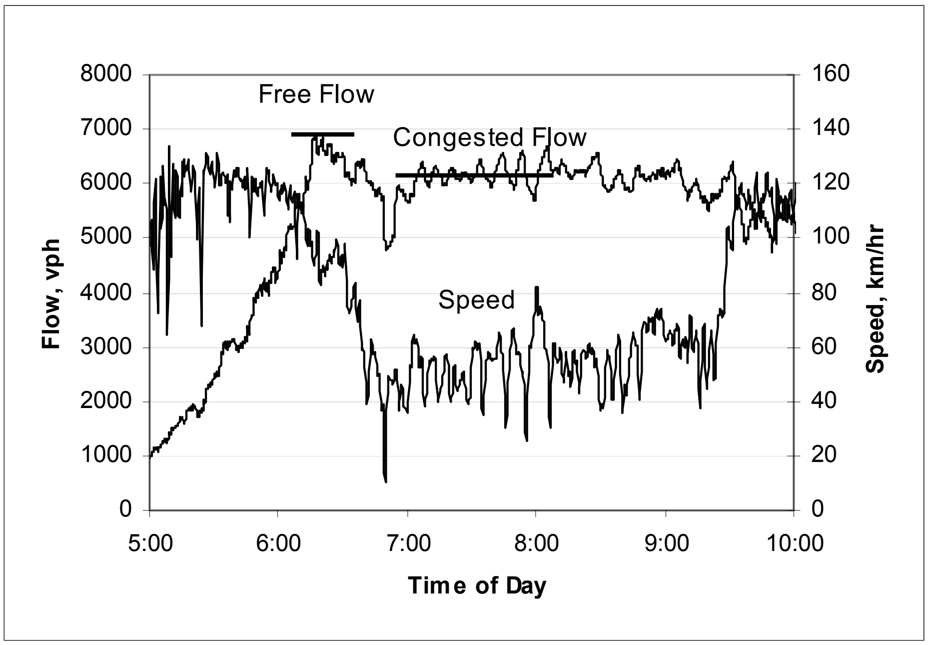


FIGURE 2 Time series flow-speed diagram.

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

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

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

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

The ramp-metering rate, $M_r(t)$, determined from Equation 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, V_T, where S_{Rr}, the ramp queue flush rate, would result.

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

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

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

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

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

Equation 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 Equation 9. The mean capacities and their standard deviations would have to be obtained either from field studies or through simulation. η in Equation 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.

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

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

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

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

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

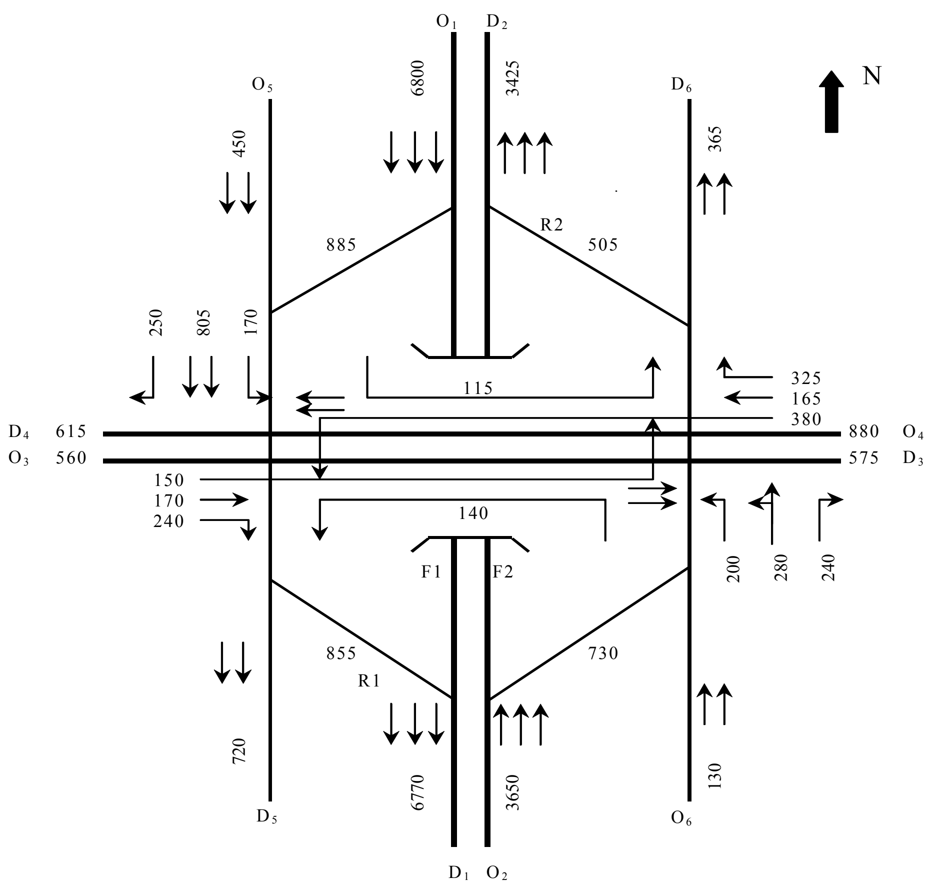
$$O_{Fr}(t) = 3600[D_{Fr}(t) - D_{Fr}(t-1)] \tag{13}$$

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

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

A Sample Case Analysis

This section illustrates the applications of DRIVE in performing analysis for a sample network. Figure 3 shows the network configuration, the link traffic volume counts during the a.m. peak period, and the estimated OD matrix. The network data are based on the Mayfield Road/SH 360 interchange located in Arlington, Texas. An excessive queue detector is located near the end of the on-ramp, and it is used for triggering the queue flush. To flush the ramp queue as a means of preventing spillback to the surface street is the policy adopted in many states.



O/D	D1	D2	D3	D4	D5	D6	Total
O1	5916	0	136	204	476	68	6800
O2	0	2920	219	183	110	219	3650
O3	207	129	168	0	34	22	560
O4	334	282	0	167	53	44	880
O5	284	41	32	45	45	5	450
O6	29	53	19	16	4	9	130
Total	6770	3425	575	615	720	365	12470

FIGURE 3 Traffic demand data for the sample case analysis.

Table 1 lists the input parameters and variables for performing the sample analysis using DRIVE. The input parameters are grouped based on the three sub-systems: diamond interchange, ramps, and mainlines. Table 2 lists some of the performance measures produced by the model for the ramp meters and freeway mainlines.

DRIVE produces a complete set of performance measures regarding different components of the IDIRMS. As an example for the sample case, the southbound ramp (R1) had 95% queue length of 22 cars, which exceeded the ramp storage space of 20 cars, therefore, ramp metering queue flush occurred 14 times (about 22% in time) during about 1-hour operation.

TABLE 1 Input parameters for sample calculations

Sub-system	Input Parameters	Directions	
Diamond Interchange	Cycle Length C = 100 sec; Phasing: 4 phase; Diamond Spacing = 300 ft; Travel Time T = 13 sec; Overlap Φ = 11 sec; Left-Turn Storage Q_{Mm} = 20 cars		
Ramps		R1 (SB)	R2 (NB)
	Ramp Storage, cars: Block Distance, cars: Metering Threshold, vph: Min. Metering Rate $M_{r,min}$, vph: Max. Metering Rate $M_{r,max}$, vph: Metering Interval a, sec:	20 50 4000 900 450 20	15 30 4000 900 450 20
Freeway Mainlines		F_1 (SB)	F_2 (NB)
	Free-Flow Capacity c_{Fr}, vph: F.F. Standard Deviation σ_{Fr}, vph: Queue-Discharge Capacity c_{Qr}, vph: Q.D. Standard Deviation σ_{Qr}, vph:	7040 110 6700 50	7040 110 6700 50

TABLE 2 Output performance measures for the sample calculations

Sub-system	Performance Measures	Values	
Ramps		R1 (SB)	R2 (NB)
	Throughput U_r, vph: Maximum Queue q_{Mr}, veh: 95% Queue, veh: 50% Queue, veh: Average Delay d_{Rr}, sec/veh: Queue Flush Rate, flush/hr: Metering Attainability, %: Ramp Queue Spillback, %: Diamond Interchange Block, %:	852 24 22 18 55.8 14 78% 2.8% 0%	508 6 5 2 10.5 0 100% 0% 0%
Freeway Mainlines		F1 (SB)	F2 (NB)
	Throughput U_{Fr}, vph Average Delay d_{Fr}, sec/veh	6714 45.3	3431 1.5

Smmary and Conclusions

This paper documents the development of an analytical model for analzing an integrated diamond interchange, ramp metering, and freeway control system. Modeling methodologies were developed to address the close interactions of the three sub-system components, including ramp platoon arrival and the two-capacity phenomenon for freeway mainline. A sample case analysis is also presented to demonstrate the capabilities of the model. The developed model is the first ever that is able to analyze such a system in an integrated manner.

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