Simulation-Based Estimates of Delays at Freeway Work Zones

by

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ABSTRACT

Work zone related traffic delay is an important cost component on freeways with maintenance activities. This study demonstrates that delays are always underestimated by using the deterministic queuing theory. Computer simulation is a valuable approach of estimating delay under variety of existing and future conditions. However, a single simulation run, which can be quiet costly in terms of both computer and analyst time, produces a delay estimate for only one traffic level under one set of conditions. A method is developed in this paper to approximate delays by integrating limited simulation data, obtained from CORSIM and the concept of deterministic queuing model, while various geometric conditions and time-varying traffic distribution are considered. A calibrated and validated simulation model that can reflect work zone traffic operations on a segment of Interstate I-80 in New Jersey is used to generate data for developing the proposed model. The comparison of delays estimated by the deterministic queuing model and the proposed model is conducted, while factors affecting the accuracy of the delay estimates are discussed.

KEY WORDS: Delays, Work Zone, Simulation, CORSIM, Queue, Estimation

I. INTRODUCTION

In recent years, work zone related congestion on streets and highways has grown to critical discussion in many areas of the United States. This congestion has many detrimental effects including lost time, higher fuel consumption and vehicle emissions, increased accident risk, and greater transportation cost. Traffic congestion occurs when the ratio of travel demand to the roadway capacity exceeds a certain level. Congestion can be either recurrent occurring at bottlenecks caused by geometric conditions such as the reduction in the number of lanes and lane width for roadway maintenance and/or reconstruction or non-recurrent caused by incidents.

The application for delay measures includes the traditional capacity improvement, alternatives analysis, operations evaluation, and a wide range of planning evaluations, such as the determination of lane closure configuration over time and space for a roadway maintenance or reconstruction project. In order to perform routine maintenance or reconstruction activities on roadways, lanes and shoulders are frequently closed. Due to physical loss of roadway space and the rubbernecking factor, the reduced capacity causes the increased traffic delays. Vehicular delay is often calculated by comparing actual travel speeds to desired travel speeds (e.g., free-flow speed). The magnitude of delay associated with a work zone mainly depends on the distribution and composition of traffic flow over the maintenance period and the corresponding work zone capacity. The estimation of work zone related traffic delays is essential for scheduling of maintenance and construction activities as well as for estimating the life-cycle cost of pavement rehabilitation, restoration, resurfacing and reconstruction works alternatives.

The concept of deterministic queuing model is widely accepted by practitioners (Abraham and Wang, 1981; Dudek and Rechard, 1982; Morales, 1986; Schonfeld and Chien, 1999) for estimating queuing delay. However, the delay was usually underestimated because the approaching and shock-wave delays were neglected (Nam and Drew, 1998; Mcshine and R. Ross, 1992). CORSIM, a well known microscopic traffic simulation model developed by Federal Highway Administration (1992), can be apply to estimate queuing delay at work zones. Despite its reliability, tedious work to prepare input files for different geometric conditions, traffic and roadway conditions may lessen its application for delay analysis purpose. Computer simulation is a valuable approach for estimating delay under variety of existing and future conditions. However, a single simulation run, which can be quite costly in terms of both computer and analyst time, produces a delay estimate for only one traffic level under one set of conditions. Therefore, it is necessary to develop a method that can accurately estimate delay with limited amount of simulation data.

In this study, total delay is defined by the sum of queuing delay occurring before the work zone, and moving delay experienced by drivers traveling through the work zone. The use of the proposed method for estimating delay is illustrated with simulation data for a freeway segment on interstate Freeway I-80 in New Jersey.

II. LITERATURE REVIEW

Two well-known methods developed for analyzing freeway queuing delay include the deterministic queuing models (Abraham and Wang, 1981; Dudek and Rechard, 1982; Morales, 1986; Schonfeld and Chien, 1999) and the shock wave models (Richards, 1956;

Wirasinghe, 1978). The deterministic queuing models have been used for estimating delays in practice for decades. It has been often depicted using a deterministic queuing diagram as shown in Figure 1. The critical input to the deterministic queuing diagram are the demand volume Q, freeway capacity C, work zone capacity C_w, and work zone maintenance duration t_1. The shaded area is the total delay to the traffic stream, and is given by the following equation:

$$Delay = \frac{t_1^2 (C - C_w)(Q - C_w)}{2(C - Q)} \qquad (1)$$

The shock wave model estimates queuing delay by assuming that the traffic flow is analogous to fluid flow, and the shock wave speed propagates linearly. In the determination of queuing delay, the shock wave speed is approximated based on traffic density, which is often difficult to be measured. Wirasinghe (1978) developed a model based on shock wave theory to determine individual and total delays upstream of an incident. The model was formulated considering traffic conditions under different densities and areas which are formed by shock waves in a time-space plot. Later, Al-Deck, Garib, and Radwan (1995) presented a method which utilized detailed incident and traffic data collected simultaneously in several traffic surveillance systems at different locations in the United States. In that study, recurrent and non-recurrent congestion can be identified, while shock wave theory was used to estimate incident congestion. The method was applied to Rt. I-880 in Alameda County, California. Satisfactory results were achieved for both single and multiple incident cases.

Memmott and Dudek (1984) developed a computer program, called Queue and User Cost Evaluation of Work Zones (QUEWZ), which can assess the work zone user cost including the user delay and vehicle operating costs. However, QUEWZ was developed based on traffic data collected from Texas highways, which would be inappropriate to be applied on highways in other States. In QUEWZ, a deterministic queuing model was applied to estimate queue delay, while approaching speed, calculated by using the equations taken from the Highway Economic Evaluation Model (1976) and hypothetical speed-volume relations, was used to estimate delay through the lane-closure section.

Schonfeld and Chien (1999) developed a mathematical model to optimize work zone lengths for two-lane (one lane per direction) highways where one lane in each direction at a time was closed for performing maintenance activities. In that study, deterministic queuing theory was applied to estimate user delay caused by the lane closure. The optimal work zone length was determined by minimizing the total cost including the agency and user delay costs. In addition to the queuing delay cost, the moving delay incurred by vehicles traversing through work zone was considered to formulate the user delay function. In a recent study conducted by Nam and Drew (1998) found that deterministic queuing models always underestimate the delays comparing with that estimated by shock wave models.

Jiang (1999) conducted a delay study for Indiana Department of Transportation, in which the work zone related delays were classified into three categories: (1) deceleration delay experienced by vehicle deceleration before entering work zones, (2) moving delay experienced by vehicles passing through work zones with lower speed, (3) acceleration delay experienced by vehicle acceleration after existing work zones, and (4) queuing delay caused by the ratio of vehicle arrival and discharge rates.

Previous studies (Nemeth and Rathi, 1995; Rouphail anf Tiwari, 1985; Rouphail, Yang, and Fazio, 1988; Pain, McGee, and Knapp 1981) that dealt with traffic operations and capacities at freeway lane closures are reviewed, which provide valuable information in designing simulation networks, determining calibration parameters and evaluating delays in this study. Nemeth and Rathi (1985) conducted a simulation study for a hypothetically created freeway network by using FREESIM and indicated the potential impact of speed reduction at freeway lane closures. They found that compliance with the reduced speed limit had no significant impact on the number of uncomfortable decelerations, but it reduced variance in speed distribution over the work zone. The results showed that the speed reduction at work zones does not create hazardous disturbance in traffic flow.

Pain, McGee, and Knapp (1981) conducted a comprehensive speed studies and found that the mean speed significantly varied with the configurations of lane closures (e.g., right lane closure, left lane closure, and a two-lane bypass), traffic control devices (e.g., cones, tubular cones, barricades, and vertical panels), and locations within work zones. Later, Rouphail and Tiwari (1985) investigated speed characteristics near freeway lane closure areas. They identified factors affecting speed through a lane closure, including (1) geometric related factors (i.e., the configurations of lane closures before and within the work zone, grade and curvatures, effective lane width and lateral clearance, sight distance and proximity to on and off ramps), (2) traffic related factors (i.e., flow rates passing through work zone areas and truck percentage in traffic stream); (3) traffic control related factors (i.e., arrow board, and canalization devices, speed zoning signs, the presence of flagmen); and (4) work zone activity related factors (i.e., location, crew size, equipment type, noise, dust level, and length of work zone). They also found that the vehicle mean speed through a work zone decreased while (1) the intensity of construction and maintenance activities increased, and (2) the construction and maintenance activities moved closer to the travel lanes.

Later Rouphail, Yang, and Fazio (1988) derived various mean values and coefficients of variation to describe the speed changes in different work zones. They found that the average speed in a work zone did not vary considerably under light traffic conditions; however, the speed recovery time took longer as traffic volumes increased.

Capacity reduction is the most critical factor that influences traffic delays. Several studies (Dudek and Richards, 1982; Rauphail and Tiwari, 1985; Krammes and Lopez, 1994; and Dixon, Hummer and Lorscheider, 1995) identified that the capacity at freeway work zone mainly depends on (1) lane closure configuration, (2) on-ramp and off-ramp proximity (3) lane narrowing, (4) physical barriers, (5) percentage of heavy vehicles in the traffic stream (6) additional warning signs (7) reduced speed limit and (8) grade. However, the detailed procedure for estimating freeway work zone capacity that can capture the influence of above variables was not developed.

Previous studies also developed different methods to identify capacities of freeway work zones. Dudek and Richards (1982) identified work zone capacity as the hourly traffic volume under congested conditions . They used traffic volume that can pass through work zones in one hour, while there are queue formed at up stream from the lane closure, as capacity. The 1994 Highway Capacity Manual provided typical capacity values of freeway work zones. As Dixon, Hummer and Lorscheider (1995) indicated that these values were obtained using the traffic data collected on the roadways in Texas, which may not represent the roadway capacity in other states because of different freeway characteristics and driving behaviors.

CORSIM (CORidor SIMulator) a microscopic simulation model developed by Federal Highway Administration (FHWA). It is viewed as one of the most comprehensive traffic simulation model, which can simulate coordinate traffic operations, including incident conditions (i.e., work zones and accidents) on surface streets and freeways. CORSIM runs on a microcomputer and simulates various traffic flows (i.e., volumes, vehicle compositions) operating on roadways with different geometric conditions (i.e., grades, radius of curvature, super-elevations on the freeway, lane additions/drops) and freeway incidents (i.e., accidents, work zones rubbernecking factor) while considering various driver types (i.e., from cautious to aggressive), vehicle types (i.e., passenger car, truck, carpool, bus) and characteristics (i.e., length, acceleration/deceleration rate). Vehicle movements follow car following, lane changing and crash avoidance models programmed in CORSIM model (Federal Highway Administration, 1992). Many researchers have employed CORSIM for freeway operational analysis, such as velocity and capacity studies (Nemeth and Rathi, 1995; Cohen and Clark 1986; Chien and Chowdhury, 1998).

III. TRAFFIC DELAYS AT FREEWAY WORK ZONES

The definition of work zone delay, including queuing and moving delays, is the difference between the average travel times under normal and roadway maintenance situations, multiplied by the demand (number of vehicles) passing through the work zone in a given time period. The magnitude of delay associated with the work zone mainly depends on the variation of traffic flow over the maintenance period and the corresponding work zone capacity. The moving delay, incurred by vehicles travelling within the work zone, increases as the average zone speed decreases. The speed reduction is mainly caused by the disturbance of work zone barriers and the variation of traffic density. In addition, motorists may suffer queuing delay when they stop-and-go in the traffic stream before entering the work zone. A queue will form once the traffic flow exceeds the work zone capacity, whose length changes dynamically because of flow variation over time.

Furthermore, if the inflow demand exceeds work zone capacity during a given time period, vehicles can not be completely discharged before the end of the time period. Thus, the queue discharging time will be extended to the next time period. If the inflow rate continuously exceeds the capacity, the queue growing rate varies with the inflow rates in different time periods. Theoretically, the total number of vehicles in a queue can be fully discharged, if the cumulative inflow rates reaches the cumulative capacity after a number of time periods. In addition, while forming the queue, the shock wave delay associated with the rates of discharging and in-coming flows is a fraction of queuing delay. However, it is difficult to be formulated mathematically. Equations derived for estimating moving and queuing delays are discussed next. All variables used to formulate the moving and queuing delays are defined in Table 1.

Moving Delay

Moving delay is incurred by motorists traveling through a work zone with reduced travel speed due to limited roadway clearance, narrowed lanes, and rubbernecking factors, etc. Moving delay can be estimated by the product of the difference between average travel times under normal and work zone conditions and the traffic passing through the work zone. Depending on the relationship among work zone capacity C_w, inflow $Q(i)$ during $t_p(i)$, duration of time period i $t_p(i)$, and queue length accumulated from the previous time period $q(i)$, the moving delay $t_M(i)$ can be formulated considering two different situations:

Situation 1: $[Q(i)+q(i)] \le C_w t_p(i)$

In this situation, the total volume, constituted by queue length $q(i)$ and entry flow $Q(i)$ during $t_p(i)$, can be discharged through the work zone in the same time period. Therefore, the moving delay can be obtained from Eq. 2.

$$t_M(i) = (\frac{L}{V_w} - \frac{L}{V_a})[Q(i)+q(i)] \quad (2)$$

where V_a, V_w and L represent free-flow speed, average speed within the work zone and work zone length, respectively. In Eq. 2, $q(i)$ can be determined by the excess traffic flow and work zone capacity accumulated from previous time periods:

$$q(i) = \sum_{j=k}^{i-1}[Q(j) - C_w t_p(j)] \quad \text{for } i > k \quad (3)$$

where k is the time period as $Q(k)$ is greater than $C_w t_p(k)$. Note that $q(i)$ is always greater than or equal to zero.

Situation 2: $[Q(i)+q(i)] > C_w t_p(i)$,

Under this situation, the term [$Q(i)+q(i)$] in Eq. 2 can be replaced by $C_w t_p(i)$ subject to the capacity constraint. Thus, the moving delay $t_M(i)$ is

$$t_M(i) = (\frac{L}{V_w} - \frac{L}{V_a}) C_w t_p(i) \quad (4)$$

Note that the average work zone speed V_w can be determined from roadway surveillance systems or empirical speed functions (e.g., BPR functions), to reflect realistic travel speed varying with the ratio change of traffic volume to roadway capacity.

Queuing Delay

In order to estimate queuing delay with CORSIM, a segment of freeway network on the east bound I-80 in New Jersey is developed. The major data, collected from a project report conducted by Parsons Brinkerhoff Inc., Garmen Associates and New Jersey Institute of Technology, include road geometry, traffic volumes, and average speeds at five different data stations, while the warning sign locations were collected from the site. The simulation model is calibrated by fine tuning parameters such as car following sensitivity factor, vehicle startup delay, and driver response leg time to reflect the realistic traffic operations. After validating the calibrated model, two typical freeway work zone configurations (e.g., three- and four-lane with one blocked lane) are simulated with various entry volumes and work zone capacities, while the corresponding queue delays can be obtained from simulation results.

<u>Work Zone Capacity</u>

CORSIM is able to simulate exact number of vehicles passing through a designated link (with lane closure- work zone). In this study, the "work zone capacity" C_w is defined as the maximum hourly flow passing through the work zone, which is approximated by gradually increasing entry flow rate until the maximum flow passing through a work zone is identified. In order to reduce the statistic variance in simulation analysis (e. g., the maximum observed flow varies with the change of random number seed), the maximum discharged flow rate (work zone capacity) is determined by averaging maximum flows obtained from 10 one-hour simulation runs with different random number seeds. From simulation results, we found that the capacities for three-, and four-lane freeways with one lane closure are 4000, and 6550 passenger car per hour (pcph), respectively.

Queuing Delay from CORSIM

As defined previously, queuing delay can be obtained from the travel time difference under normal and work zone conditions multiplied by the demand. In order to estimate queuing delays, the three work zone configurations under both conditions with various ratios of entry volume to work zone capacity (V/C_w) are simulated.

After conducting simulation analysis, we found that if the traffic volume is low (e.g. $V/C_w \leq 0.4$), the average queuing delay is relatively small and can be ignored. However, when $V/C_w > 0.4$, the average queuing delays become obvious. The average queuing delay (min/veh) is obtained by the queuing delay, observed from 10 simulation runs, divided by the corresponding entry volume. The mean and the standard deviation of queuing delays for the two cases with various V/C_w ratios are summarized in Table 2 and shown in Figures 2 and 3.

Model Development

Although computer simulation is a valuable method of estimating delay under variety of existing and future conditions, however, a single simulation run, which can be quite costly in terms of both computer and analyst time, produces a delay estimate for only one traffic level under one set of conditions. In order to avoid simulating a huge number of situations (combinatory combinations of demand flow rates, traffic composition, geometric conditions, and work zone length and duration), a method integrating the concept of deterministic queuing theory and limited amounts of simulation data is developed. The traffic flow distribution over time and work zone capacity are the major model input to approximate queuing delay. The queuing delay in each time period is calculated based on the queue length accumulated from the previous time periods. If the queue length is zero at time period i, the queuing delay $T_Q(i)$ is purely incurred by flow $Q(i)$ during $t_p(i)$, which can be obtained from Eq. 5.

$$T_Q(i) = Q(i)t_a t_p(i) \tag{5}$$

where t_a representing average queuing delay can be identified from Figures 2 and 3 for three- , and four-lane freeways, respectively.

However, if there is a queue accumulating from the previous time periods ($q(i) > 0$), the queuing delay is determined based not only on flow $Q(i)$ during $t_p(i)$, work zone capacity C_w but also the duration to discharge $q(i)$. Two situations are considered while approximating the queuing delay, which are discussed below.

Situation 1 : $Q(i) + q(i) > C_w t_p(i)$

Assuming that vehicles in a queue entering a work zone are based on first come first serve basis, and the queuing delay experienced by vehicles from downstream to upstream increases linearly. The total queuing delay incurred by $Q(i)$, as shown in Figure 4, entering during $t_p(i)$ can be formulated as follows

$$T_Q(i) = [\frac{t_F(i) + t_L(i)}{2}]Q(i) \quad (6)$$

where $t_F(i)$ and $t_L(i)$ represent the queuing delays experienced by the first and the last vehicles in $Q(i)$, respectively. In addition, $t_F(i)$ is equal to the discharging time of the queue length $q(i)$ accumulated from the previous time period ($i-1$), which can be obtained from Eq. 7.

$$t_F(i) = \frac{q(i)}{C_w} \quad (7)$$

In order to find $t_L(i)$ in Eq. 6, the average queuing delay t_a corresponding to a V/C_w ratio (where $V = Q(i)/t_p(i)$) can be identified from the curves shown in either Figure 2 or 4. Since, the queuing delay increases linearly with the demand as assumed in deterministic models $t_L(i)$ can be derived as

$$t_L(i) = 2t_a t_p(i) \quad (8)$$

Based on the values of $t_F(i)$ and $t_L(i)$ obtained from Eqs. 7 and 8, the total queuing delay $T_Q(i)$ can be determined from Eq. 6.

Situation 2: $Q(i) + q(i) \le C_w t_p(i)$

Under this situation, number of vehicles will be discharged by the end of the time period is $[Q(i) + q(i)]$. Thus, only a fraction of approaching flow in time period i will be delayed by $q(i)$, and the duration t to discharge the queue is equal to queue length $q(i)$ divided by the difference of work zone capacity C_w and the entering flow rate $Q(i)/t_p(i)$.

$$t = \frac{q(i)}{[C_w - Q(i)/t_p(i)]} \tag{9}$$

Thus, the number of vehicles $p_a(i)$, a portion of $Q\ (i)$, affected by discharging $q(i)$ is

$$p_a(i) = \frac{tQ(i)}{t_p(i)} \tag{10}$$

The queuing delay experienced by $p_a(i)$ can be estimated by Eq. 6, in which $t_L(i)$ can be estimated by Eq. 11.

$$t_L(i) = 2t_a t \tag{11}$$

Again, t_a can be identified from either Figure 2 or 3, while assuming that $V/C_w = 1$. On the other hand, the queuing delay incurred by the rest of vehicles (i.e., $\frac{Q(i)[t_p(i)-t]}{t_p(i)}$) can be estimated by Eq. 5 where $t_p(i)$ is replaced by $[t_p(i)-t]$, while the ratio of V/C_w is $= \frac{Q(i)}{t_p(i)C_w}$.

IV. AN EXAMPLE

The use of the developed method to estimate queuing delays is illustrated with simulation data for a construction site on interstate Freeway I-80 in New Jersey.

In order to estimate work zone delay, a hypothetical construction site is assumed on a four-lane segment of east bound Interstate I-80. It is also assumed that the roadway maintenance work require to close one lane with 0.5 mile long and devoting the remaining three lanes to traffic. Given that the work zone capacity is 6238 vph (equivalent to 6550 pcph), while the average vehicle approaching speed and work zone speed are 70 and 50 mph, respectively. The maintenance activities will last 16 hours (from 6:00 am to 11:00 pm), during which the traffic flow distribution is shown in Table 3 and Figure 5. The truck volume is assumed to be 10% of the traffic flow.

<u>Estimation of Moving Delay</u>

The estimated moving delays over a 16-hour maintenance period have illustrated in Table 4, where columns 1 through 4 are user specified input information, including index of time period and its corresponding duration, work zone capacity and flow rate. The output information contains queue length, moving delay by time period, and total moving delay. For example, the queue length in column 5 is computed by using Eq. 2, while $[Q(i)t_p(i)+q(i)]$ in column 6 can also be obtained. By comparing columns 6 and 3, the moving delay in each time period shown in column 7 can be determined by either Eq. 2 or 4. The total moving delay obtained by the sum of moving delays in all time periods is shown in column 8.

<u>Estimation of Queuing Delay</u>

The estimated queuing delays are summarized in Table 5. Where column 1 and 2 are user specified input information, including the index of time period and demand at each time period. The accumulated queue length is determined by Eq. 3 and shown in column 3. V/C_w ratio corresponding to each period is presented in column 4. The queuing delays for all time periods without queue accumulated from previous time periods are approximated by using Eq. 4 after determining the corresponding average queuing delay from simulated results shown in Figure 3 and shown in column 5. For the time periods with queue accumulated from previous time periods, Eq. 5 is applied for approximating queuing delay with corresponding $t_F(i)$ and $t_L(i)$ obtained from Eqs. 7 and 8. The results of $t_F(i)$, $t_L(i)$ and t_a are presented in columns 5, 6, and 7, while queuing delays incurred by incoming flow $Q(i)$ during $t_p(i)$ are presented in column 8. Finally sum of the delays of all time periods is presented in Column 9.

Comparison of Estimated Queuing Delays

In order to verify the accuracy of estimated queuing delay by applying the proposed model, the same network with given traffic demand distribution is simulated by CORSIM. The resulting queuing delays estimated by the proposed model, CORSIM (average of ten runs), and deterministic queuing model are 361150 veh-min, 349099 veh-min (with 7911 veh-min standard deviation), and 216868 veh-min, respectively. It shows that the queue delay estimated by the proposed method is very close (e.g. 3.5% difference) to that observed from the real world simulation, if simulation results can reflect real world traffic operation. However, the deterministic queuing model significantly underestimates the queuing delays.

V. CONLUSIONS

In this study a simulation based model is developed for estimating freeway work zone delay. Comparisons of delays estimated by the deterministic model, the proposed model and the CORSIM model are calculated, while results show that the proposed model performed very well for estimating delay in an example discussed in this study. In addition, we found that the deterministic queuing model underestimated the overall delays. Extensive calibration and validation of CORSIM may be required in the future after obtaining traffic operational data under work zone conditions and then the estimated delay curve derived from CORSIM can be approximately adjusted. The credibility of the proposed simulation-based model fully depends on the accuracy of the delay curve derived from CORSIM.

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Table 1: Notation

Variable		Description
V	=	Hourly volume (vph);
C	=	Normal roadway capacity (vph);
i	=	Time period (hr);
$T_Q(i)$	=	Total queuing delay at time period i (veh-min);
t_a	=	Average queuing delay for a given hourly entry flow and work zone capacity (veh-min);
$Q(i)$	=	Flow rate at time period i (vph);
C_w	=	Work zone capacity (vph);
$q(i)$	=	Queue length accumulated from time period $i-1$ (veh);
$t_F(i)$	=	Queuing delay experienced by first vehicle of $Q(i)$ before entering the work zone (min);
$t_L(i)$	=	Queuing delay experienced by last vehicle of $Q(i)$ before entering the work zone (min);
t	=	Time required to completely discharge the queue (hr);
$t_M(i)$	=	Moving delay at time period i (min);
V_w	=	Average work zone speed (mph);
V_a	=	Average approaching speed (mph);
L	=	Work zone length (miles);
$t_q(i)$	=	Duration of time period (hr);

Table 2: Queuing Delay vs. V/C Ratio with Various Cases

V/C_w Ratio	Average Delay (min./veh.)	
	Case 1	Case 2
0.5	0.039 (0.019)*	0.056 (0.011)
0.6	0.080 (0.028)	0.115 (0.016)
0.7	0.140 (0.026)	0.246 (0.032)
0.8	0.250 (0.040)	0.556 (0.046)
0.9	0.872 (0.100)	1.175 (0.060)
1	2.841 (0.157)	2.722 (0.164)
1.1	6.015 (0.246)	5.754 (0.103)
1.2	9.686 (0.226)	9.272 (0.271)
1.3	13.637 (0.495)	13.148 (0.242)
1.4	17.865 (0.532)	16.974 (0.131)
1.5	21.958 (0.463)	
1.6	25.877 (0.506)	
1.7	30.254 (0.551)	

*Average delay (Standard Deviation)

Table 3: Traffic Flow Over Time

Time Period	Duration (hr)	Demand Flow Rate	
		(vph)	(pcph)
1	7 – 8	4762	5000
2	8-9	5714	6000
3	9-10	6667	7000
4	10-11	6667	7000
5	11-12	5714	6000
6	12-13	4762	5000
7	13-14	4762	5000
8	14-15	3809	4000
9	15-16	4762	5000
10	16-17	5714	6000
11	17-18	6667	7000
12	18-19	6667	7000
13	19-20	6190	6500
14	20-21	4762	5000
15	21-22	3809	4000
16	22-23	3809	4000

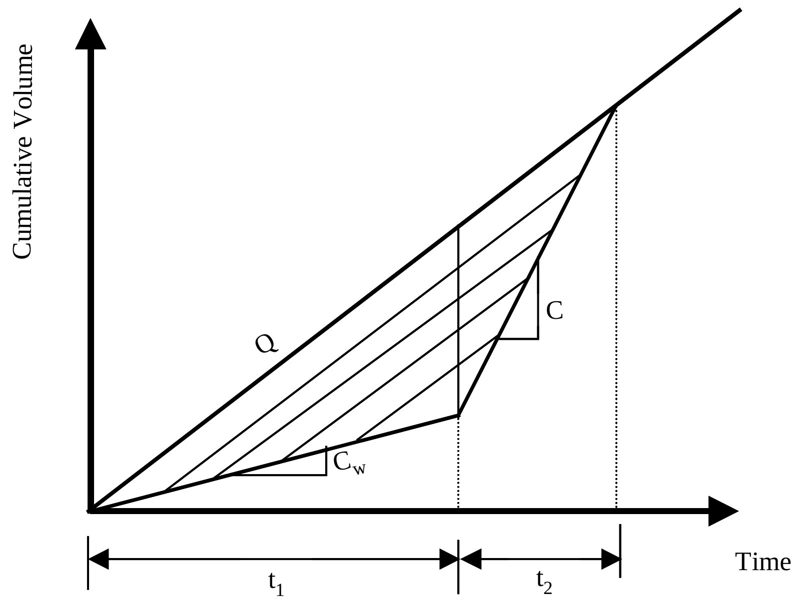
Note: Demand flow rate from vph to pcph is converted based on HCS [21] methodology

Table 4: Estimation of Moving Delay

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
i **Time Period**	$t_p(i)$ **(hrs)**	C_w **(vph)**	$Q(i)$ **(vph)**	$q(i)$ (veh)	$Q(i)+q(i)$	$t_M(i)$ (veh-hr)	$\sum_{i=1}^{16} t_M(i)$ (veh-hr)
1	7-8	6238	4762	0	4762	13.61	
2	8-9	6238	5714	0	5714	16.33	
3	9-10	6238	6667	0	6667	17.82	
4	10-11	6238	6667	429	7096	17.82	
5	11-12	6238	5714	858	6572	17.82	243.53
6	12-13	6238	4762	334	5096	14.56	
7	13-14	6238	4762	0	4762	13.61	
8	14-15	6238	3809	0	3809	10.88	
9	15-16	6238	4762	0	4762	13.61	
10	16-17	6238	5714	0	5714	16.33	
11	17-18	6238	6667	0	6667	17.82	
12	18-19	6238	6667	429	7096	17.82	
13	19-20	6238	6190	858	7048	17.82	
14	20-21	6238	4762	810	5572	15.92	
15	21-22	6238	3809	0	3809	10.88	
16	22-23	6238	3809	0	3809	10.88	

Table 5: Estimation of Queuing Delay ($C_w = 6550\ pcph$)

(1) i Time Period	(2) $Q(i)$ (pcph)	(3) $q(i)$ (pc)	(4) $\frac{V}{C_w}$	(5) $t_F(i)$ (min)	(6) $t_L(i)$ (min)	(7) t_a (min/pc)	(8) $T_Q(i)$ (pch)	(9) $\sum_{i=1}^{16} T_Q(i)$ (pch)
1	5000	0	0.76	-	-	.44	2212.06	361150
2	6000	0	0.92	-	-	1.42	8537.96	
3	7000	0	1.07	-	-	4.81	33635.39	
4	7000	450	1.14	4.12	14.14	7.07	63916.73	
5	6000	900	1.05	8.24	8.68	4.34	50785.73	
6	1129	350	1.00	3.21	1.23	2.72	2503.85	
6	3871	0	0.76	-	-	.334	1292.91	
7	5000	0	0.76	-	-	.44	2212.06	
8	4000	0	0.61	0	0	.13	516.00	
9	5000	0	0.76	0	0	.44	2212.06	
10	6000	0	0.92	0	0	1.42	8537.96	
11	7000	0	1.07	0	0	4.81	33635.39	
12	7000	450	1.14	4.12	14.14	7.07	63916.73	
13	6500	900	1.13	8.24	13.60	6.8	71002.63	
14	2750	850	1.00	7.79	2.99	2.72	14767.63	
14	2250	0	0.76	-	-	.194	436.50	
15	4000	0	0.61	-	-	.13	516.00	
16	4000	0	0.61	-	-	.13	516.00	



Q: Demand Flow Rate (vph)
C: Roadway Capacity (vph)
C_w: Work Zone Capacity (vph)
t_1: Lane Closure Duration (vhp)
t_2: Duration for Discharging the Queue (h)
▨ Queuing Delay (veh-hr)

Figure 1: Delay Estimated by Deterministic Queuing Model

Figure 2: Average Delay vs. V/C Ratio
(Three-lane Freeway with One Blocked Lane without Trucks)

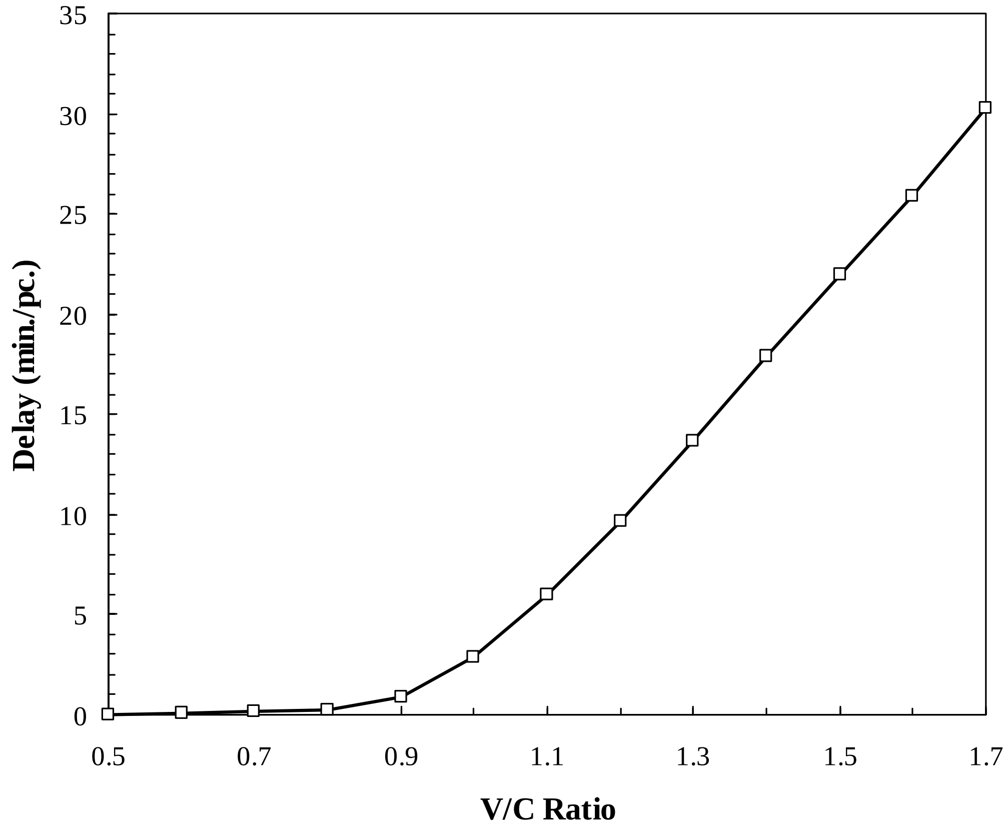


Figure 3: Average Delay vs. V/C Ratio
(Four-lane Freeway with One Blocked Lane without Trucks)

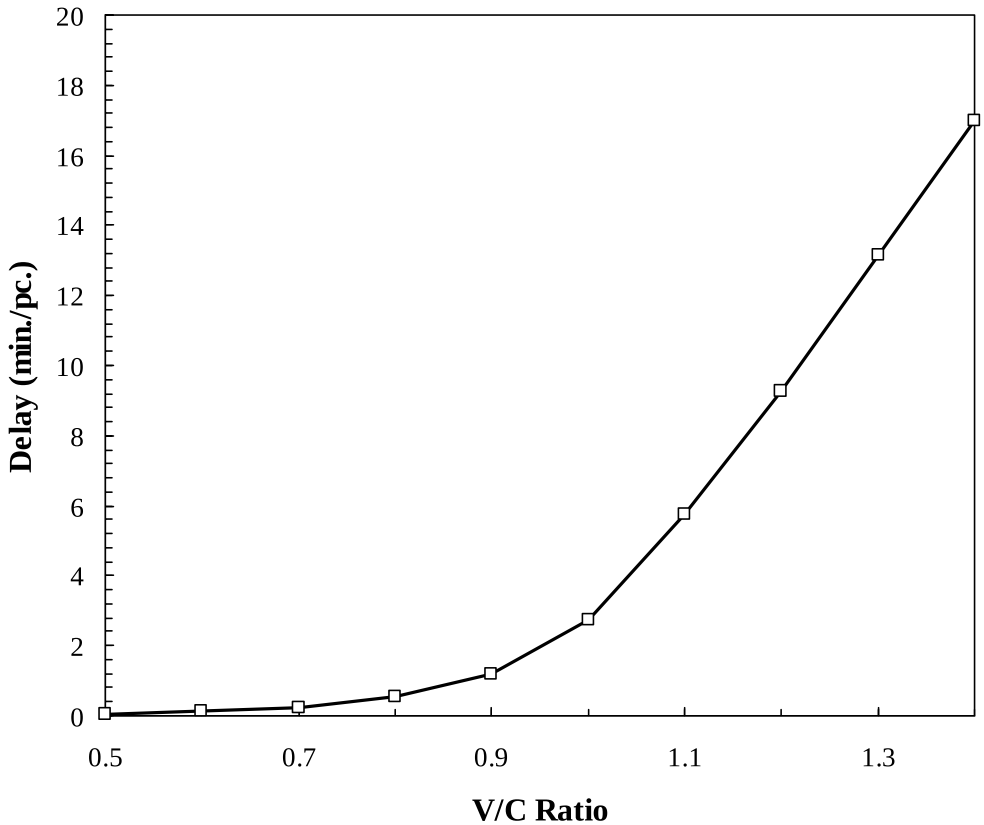
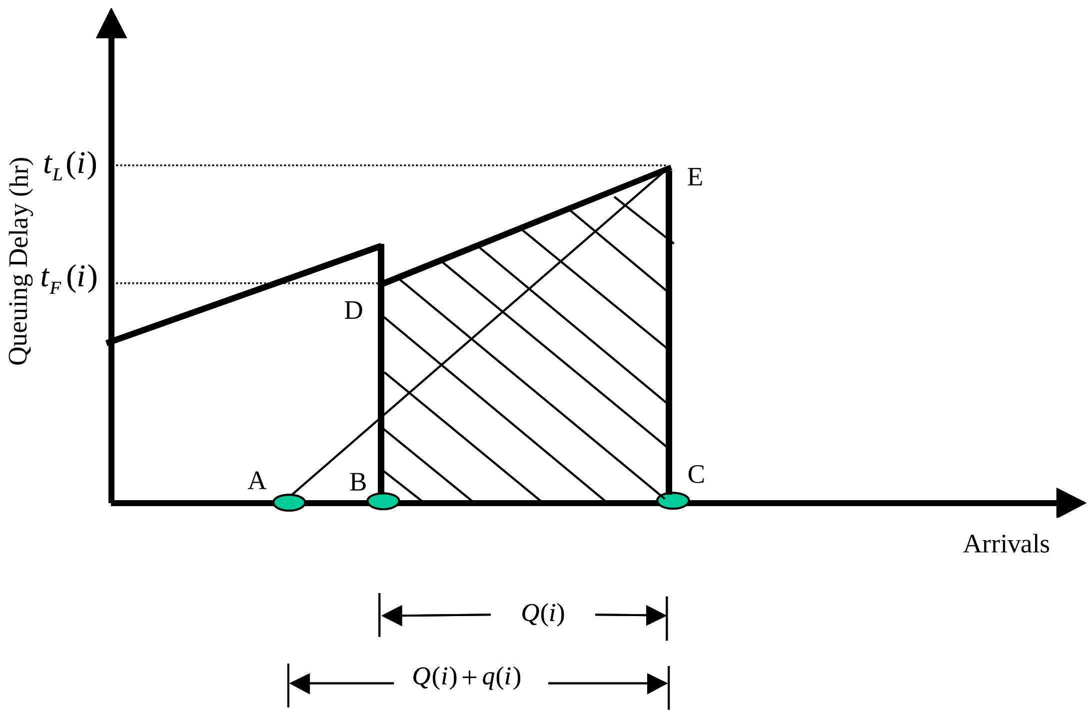


Figure 4: Queuing Delay of Vehicles in $[q(i)+Q(i)]$



A =the first vehicle of $q(i)$

B =the first vehicle of $Q(i)$

A =the last vehicle of $Q(i)$

Figure 5: Traffic Flow Rate Over Time