Journal of Advanced Transportation, Vol. 36 No. 2, pp. 131-156
www.advanced-transport.com

Simulation-Based Estimates of Delays at Freeway Work Zones

Steven I-Jy Chien
Dimitrios G. Goulias
Shmuel Yahalom
Shoaib M. Chowdhury

Work zone related traffic delay is an important cost component on freeways with maintenance activities. This study demonstrates that delays may be underestimated by using the deterministic queuing theory. Computer simulation is a valuable approach of estimating delay under a 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. A method is developed in this paper to approximate delays by integrating limited simulation data, obtained from CORSIM and the concept of deterministic queuing theory, 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.

Introduction

In recent years, estimation of work zone related congestion on streets and highways has discussed widely in the United States. This congestion

Steven I-Jy Chien is in the Department of Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, New Jersey, USA
Dimitrios G. Goulias is in the Department of Civil and Environmental Engineering, University of Maryland, College Park, Maryland, USA
Shmuel Yahalom is at State University of New York – Maritime College, Throggs Neck, New York, USA
Shoaib M. Chowdhury is at Parsons Brinckerhoff & Douglas, Inc., New York, New York, USA
Received: April 2002; Accepted: May 2002

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 recurrent caused by geometric and traffic conditions, such as the reduction in the number of lanes and lane width for roadway maintenance, 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 determined 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 maintenance and construction activities as well as for estimating the life-cycle cost of pavement rehabilitation, restoration, resurfacing and reconstruction work alternatives.

The concept of deterministic queuing theory has been widely accepted by practitioners (Abraham and Wang, 1981; Dudek and Richards, 1982; Morales, 1986; Schonfeld and Chien, 1999) for estimating queuing delay. However, the delay may be underestimated because the approaching and shock wave delays were neglected (Nam and Drew, 1998; McShane and Ross, 1992).

Computer simulation is a valuable approach for estimating delay under a variety of existing and future conditions. Despite the reliability of simulation models, tedious work to prepare input files and calibrate and validate simulation results may lessen their application for the purpose of delay analysis. Thus, a single simulation run might be quite costly in terms of both computer and analyst time to produce a reliable delay estimate for only one traffic level under one set of conditions. It is desirable to develop an efficient method that can quickly produce accurate delay estimates based on the relationship between delay and demand/capacity ratio. This relationship can be derived from limited simulation results and will be discussed in this paper.

During 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.

Literature Review

Two well-known methods developed for analyzing freeway queuing delay include the deterministic queuing models (Abraham and Wang, 1981; Dudek and Richards, 1982; Morales, 1986; Schonfeld and Chien, 1999) and the shock wave models (Richards, 1956; Wirasinghe, 1978). The deterministic queuing theory used for estimating delays has been in practice for decades. It has often been depicted using a deterministic queuing diagram as shown in Figure 1. The critical input to the deterministic queuing diagram is the demand volume Q, freeway capacity C, work zone capacity C_w, and work zone maintenance duration t_l. The shaded area is the total delay to the traffic stream, and is given by the following equation:

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

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 measure. 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 that 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.

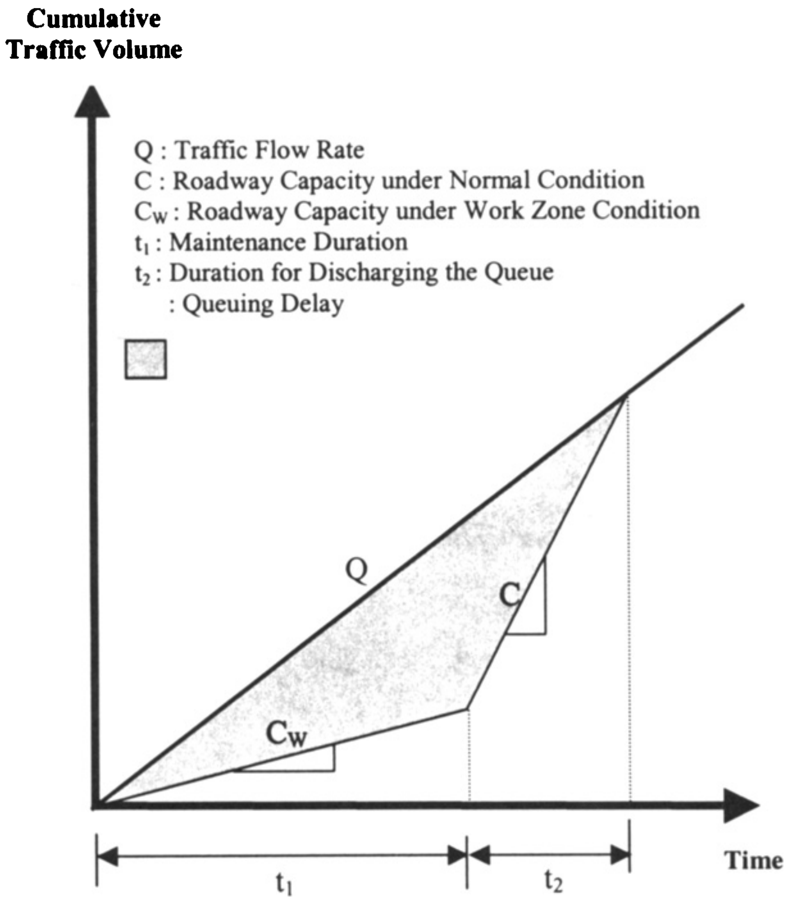


Fig. 1. Delay Estimated by Deterministic Queuing Model

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 may be inappropriate to apply on highways in other states because of different driving behavior. In QUEWZ, a deterministic queuing model was applied to estimate queue delay, while approaching speed, calculated with equations 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. A recent study conducted by Nam and Drew (1998) found that deterministic queuing models always underestimate the delays compared 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 and Tiwari, 1985; Rouphail, Yang, and Fazio, 1988; Pain, McGee, and Knapp 1981) that dealt with traffic operations and capacities at freeway lane closures 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 disturbances in traffic flow.

Pain, McGee, and Knapp (1981) conducted a comprehensive speed study 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 zones 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 has not been 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. Capacity was defined as the traffic volume that can pass through work zones in one hour, while there are queues formed upstream from the lane closure. The 1994 Highway Capacity Manual provided typical capacity values of freeway work zones. As Dixon, Hummer and Lorscheider (1995) indicated, 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) is a microscopic simulation model developed by Federal Highway Administration (FHWA) and is viewed as one of the most comprehensive traffic simulation models. CORSIM runs on a microcomputer and simulates traffic operations on various types of roadways (e.g., freeways, arterials, and streets) with different geometric conditions (i.e., grades, radius of curvatures, super-elevations, and lane additions/drops) and traffic conditions (e.g., passenger cars, carpools, trucks, and buses). It can emulate traffic operations under incident conditions (i.e., work zones and accidents) on surface streets and freeways. 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).

According to previous studies (Rathi and Venigalla, 1992; Bloomberg and Dale, 2000; Tian, Urbanik, Engelbrecht, and Balke, 2002) in comparing results generated by different simulation models (e.g., CORSIM, SimTraffic, and VISSIM), CORSIM yielded the lowest variations in performance measures when the traffic demand approached capacity. Thus, CORSIM is employed in this study for estimating delay.

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 traveling within the work zone increases as the average zone speed decreases. The disturbance of work zone barriers and the variation of traffic density mainly cause the speed reduction. 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 period, vehicles cannot be completely discharged before the end of the period. Thus, the queue discharging time will be extended to the next period. If the inflow rate continuously exceeds the capacity, the queue-growing rate varies with the inflow rates in different periods. Theoretically, the total number of vehicles in a queue can be fully discharged if the cumulative inflow rate reaches the cumulative capacity after a number of 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, the shock wave delay is difficult to formulate mathematically. Equations derived for estimating work zone related delays, including moving and queuing delays, are discussed next, while all variables used to formulate the delays are summarized in Table 1.

Table 1. Notation

The following symbols are used in this paper:

Variable		**Description**
C	=	Normal roadway capacity (vph);
C_w	=	Work zone capacity (vph);
i	=	Index of time period;
L	=	Work zone length (miles);
N	=	Required simulation runs (sample size)
$q(i)$	=	Queue length accumulated from period $i-1$ (veh);
$Q(i)$	=	Flow rate during period i (vph);
t	=	Time required to completely discharge the queue (h);
t_a	=	Average queuing delay for a given hourly entry flow and work zone capacity (min/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);
$t_M(i)$	=	Moving delay in period i (min);
$t_p(i)$	=	Duration of period i (h);
$T_Q(i)$	=	Total queuing delay in period i (veh-min);
V	=	Hourly volume (vph);
V_a	=	Average approaching speed (mph);
V_w	=	Average work zone speed (mph);

Table 1 continued

Variable		Description
$Z_{\alpha/2}$	=	The threshold value for a 100(1-α)% confidential interval (with a 95% confidential interval, $Z_{\alpha/2}$ =1.96)
σ	=	standard deviation based on 10 simulation runs
ε	=	The allowed error

Moving Delay

Moving delay is incurred by motorists traveling through a work zone with reduced travel speed due to limited roadway clearance, narrowed lanes, 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 period i $t_p(i)$, and queue length accumulated from the previous 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 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 periods:

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

where k is the 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

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

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 eastbound I-80 in New Jersey is developed. The major data, collected from a project report conducted by Parsons Brinckerhoff 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 (e.g., car following sensitivity factor called CFSF, vehicle start-up delay, and driver response lag times, etc.) to reflect the realistic traffic operations. The calibrated values of parameters are:

CFSF = (60, 60, 70, 70, 80, 80, 90, 90, 100, 100) hundredths of second;
Vehicle start-up delay = 1.1 seconds;

Driver acceleration response lag time = 2 seconds;
Driver deceleration response lag time = 2 seconds; and
Time to complete a lane change = 2.5 seconds;

The calibrated parameters help CORSIM to generate creditable results (e.g., average speeds, traffic counts) that are very close to the real-world data (e.g. ± 4% difference deviated from the mean speeds and traffic counts collected from NJDOT). This implies that the calibrated CORSIM model can properly emulate traffic operations on the Interstate I-80.

After validating the calibrated model, two typical freeway work zone configurations (e.g., three-lane and four-lane per direction 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.

Unlike deterministic models, simulation models are driven by sample of random variables from probability distributions. The simulation results generated based on these random variables may have large variance. As a result, these estimates could differ greatly among different runs of the model. In general, simulating longer period or increasing the number of simulation runs can reduce the variation. Based on the theory of probability and statistics, Eq. 5 can be used to determine the number of simulation runs (observations) for estimating the true performance measures.

$$N = \left(\frac{Z_{\alpha/2}\sigma}{\varepsilon}\right)^2 \tag{5}$$

where

N = required simulation runs (sample size);

$Z_{\alpha/2}$ = the threshold value for a 100(1-α) confidential interval (with a 95% confidential interval, $Z_{\alpha/2}$ =1.96);

σ = standard deviation based on 10 simulation runs from this study; and

ε = the allowed error.

After simulating various degree of congestion (e.g., V/C = 0.4, 0.8, 1, and 1.2), we found that 25 one-hour simulation runs for an experiment will be necessary to produce accurate estimates.

Work Zone Capacity

CORSIM is able to simulate the speeds and the number of vehicles passing through a designated link with a 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 statistical 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 25 one-hour simulation runs with different random number seeds. From simulation results, we found that the capacities for three-lane and four-lane freeways with one lane closure are 4000 and 6550 passenger cars 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 two 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 25 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, while the delay curves are plotted in Figures 2 and 3.

Model Development

Computer simulation is a valuable method of estimating delay under a 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), an delay estimation method that integrates the concept of deterministic queuing

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

V/C 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 delays (Standard Deviation)

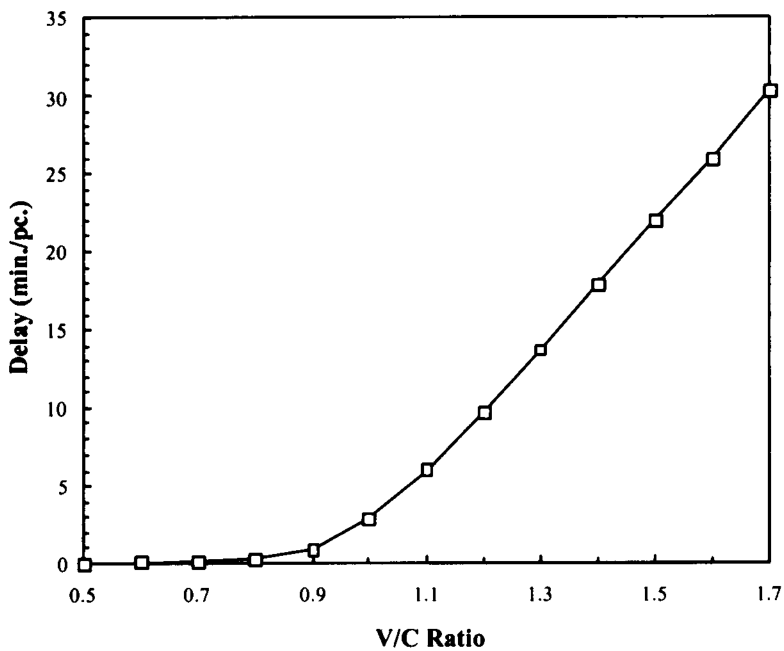


Fig. 2. Average Delay vs. V/C Ratio
(Three-lane Freeway with One Blocked Lane Without Trucks)

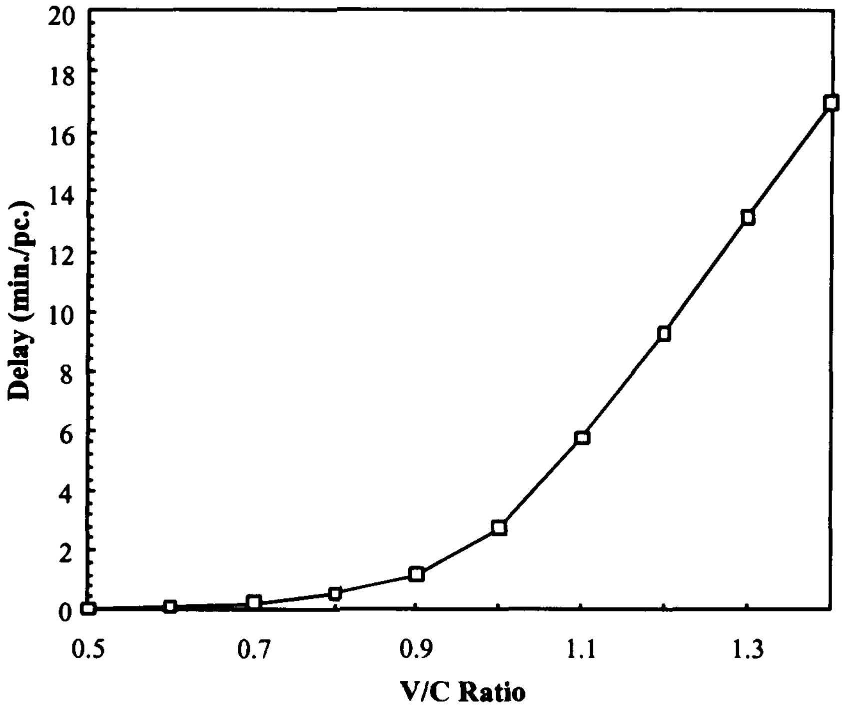


Fig. 3. Average Delay vs V/C Ratio
(Four-lane Freeway with One Blocked Lane without Trucks)

In order to develop the queuing delay estimation model, an assumption that the queuing delay will be linearly increased over time is made. The queuing delay in each period is calculated based on the queue length accumulated from previous periods. If the queue length is zero at 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. 6

$$T_Q(i) = Q(i)t_a t_p(i) \tag{6}$$

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

However, if there is a queue accumulated from the previous periods ($q(i) > 0$), the queuing delay is determined based not only on flow

$Q(i)$ during $t_p(i)$ and 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.

Table 3: Traffic Flow over Time

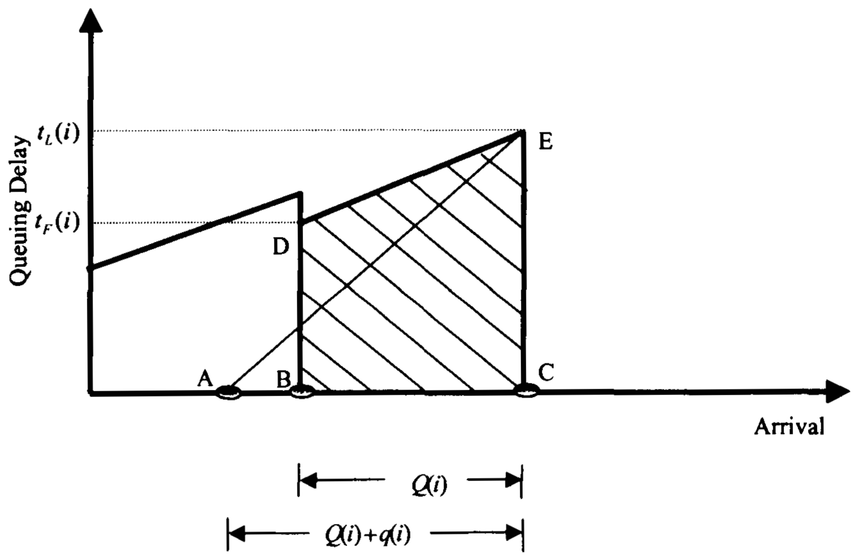
Period Index	**Duration** (h)	**Demand Flow Rate**	
		(vph)	(pcph)
1	7 – 8	4762	5000
2	8-9	5714	6000
3	9-10	6667	7000
4	10-11	6667	7000
5	11-12	5714	6000
6	12-13	4762	5000
7	13-14	4762	5000
8	14-15	3809	4000
9	15-16	4762	5000
10	16-17	5714	6000
11	17-18	6667	7000
12	18-19	6667	7000
13	19-20	6190	6500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

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

Assume 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 $Q(i)$ (See Figure 4) entering during $t_p(i)$ can be formulated as follows:

$$T_Q(i) = [\frac{t_F(i) + t_L(i)}{2}]Q(i) \tag{7}$$



A =the first vehicle $q(i)$
B =the first vehicle $Q(i)$
A =the last vehicle $Q(i)$

Fig. 4. Queuing Delay of Vehicles in [*q(i)* + *Q(i)*]

where $t_F(i)$ and $t_L(i)$ represent the queuing delays experienced by the first and 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 period ($i-1$), which can be obtained from Eq. 8.

$$t_F(i) = \frac{q(i)}{C_w} \tag{8}$$

In order to find $t_L(i)$ in Eq. 7, 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 Figures 2 and 3. Since the queuing delay increases linearly with the demand as assumed in deterministic models, $t_L(i)$ can be derived as

$$t_L(i) = 2t_a t_p(i) \tag{9}$$

Based on the values of $t_F(i)$ and $t_L(i)$ obtained from Eqs. 8 and 9, the total queuing delay $T_Q(i)$ can be determined from Eq. 7.

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

Under this situation, the number of vehicles discharged by the end of the period is $[Q(i) + q(i)]$. Thus, only a fraction of the approaching flow in 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 $Q(i)/t_p(i)$.

$$t = \frac{q(i)}{[C_w - Q(i)/t_p(i)]} \tag{10}$$

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

$$p_a(i) = \frac{tQ(i)}{t_p(i)} \tag{11}$$

The queuing delay experienced by $p_a(i)$ can be estimated by Eq. 7, in which $t_L(i)$ can be estimated by Eq. 12.

$$t_L(i) = 2t_a t \tag{12}$$

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. 6 where $t_p(i)$ is replaced by $[t_p(i) - t]$, while the ratio of V / C_w is $\frac{Q(i)}{t_p(i)C_w}$.

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 on eastbound I-80, while the construction work requires the closing of an 0.5-mile lane and devotes the remaining three lanes to traffic. The work zone capacity is 6238 vph (equivalent to 6550 pcph), and the average vehicle approaching speed and work zone speed are 70 and 50 mph, respectively. The construction will last 16 hours (from 6:00 am to 11:00 pm) during which the traffic flow distribution is shown in Figure 5. The truck volume is assumed to be 10% of the traffic flow.

Estimation of Moving Delay

The estimated moving delays over a 16-hour maintenance period are illustrated in Table 4, where columns 1 through 4 are user specified input information, including an index of the period and its corresponding duration, work zone capacity and flow rate. The output information contains queue length, moving delay by 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 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 periods is shown in column 8 of Table 5.

Table 4. Estimation of Moving Delay

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

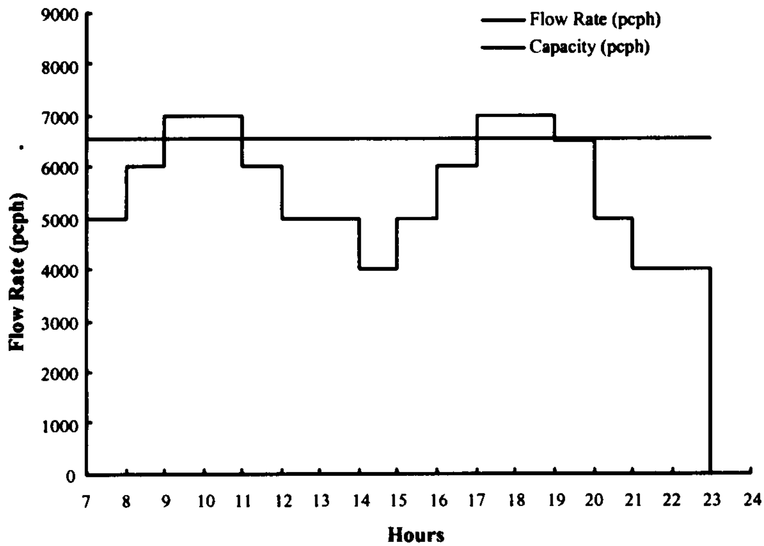


Fig. 5. Traffic Flow Rate Over Time

Estimation of Queuing Delay

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

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

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
i **Time Period**	$Q(i)$ **(pcph)**	$q(i)$ **(pc)**	$\frac{V}{C_w}$	$t_F(i)$ **(min)**	$t_L(i)$ **(min)**	t_a **(min/pc)**	$T_Q(i)$ **(pch)**	$\sum_{i=1}^{16} T_Q(i)$ **(pch)**
7-8	5000	0	0.76	-	-	.44	2212.06	
8-9	6000	0	0.92	-	-	1.42	8537.96	
9-10	7000	0	1.07	-	-	4.81	33635.39	
10-11	7000	450	1.14	4.12	14.14	7.07	63916.73	
11-12	6000	900	1.05	8.24	8.68	4.34	50785.73	361150
12-13	1129	350	1.00	3.21	1.23	2.72	2503.85	
12-13	3871	0	0.76	-	-	.334	1292.91	
13-14	5000	0	0.76	-	-	.44	2212.06	
14-15	4000	0	0.61	0	0	.13	516.00	
15-16	5000	0	0.76	0	0	.44	2212.06	
16-17	6000	0	0.92	0	0	1.42	8537.96	
17-18	7000	0	1.07	0	0	4.81	33635.39	
18-19	7000	450	1.14	4.12	14.14	7.07	63916.73	
19-20	6500	900	1.13	8.24	13.60	6.8	71002.63	
20-21	2750	850	1.00	7.79	2.99	2.72	14767.63	
20-21	2250	0	0.76	-	-	.194	436.50	
21-22	4000	0	0.61	-	-	.13	516.00	
22-23	4000	0	0.61	-	-	.13	516.00	

Comparison of Estimated Queuing Delays

In order to verify the accuracy of the estimated queuing delay obtained with the proposed model, a four-hour simulation wit CORSIM for the same network is conducted. After simulating a given traffic demand distribution (7205, 7450, 6295, and 5400 vph in each hour for consecutive 4 hours with capacity 6550 vph), the resulting queuing delays estimated by CORSIM (an average of delays obtained from 25 simulation runs) is 349,099 veh-min (with standard deviation of 4,911 veh-min). On the other hand, the delay estimated with the deterministic queuing model is 216,868 veh-min, and that estimated by the proposed method is 361,150 veh-min. Assume that a well-calibrated simulation model can represent real-world traffic operation, the simulation results can be viewed as real-world data. It shows that the queue delay estimated by the proposed method is very close (e.g., 3.5% difference) to the simulation result but the deterministic queuing model significantly the queuing delay underestimates (e.g., 37% below the simulated delay) in this experiment.

Conclusions

In this study a simulation-based model is developed for estimating freeway work zone delay. From the example, it has demonstrated that the proposed method is efficient to quickly produce accurate total delay, including the queuing and moving delays. The queuing delay was estimated by the relationship between delay and demand/capacity ratio derived from limited simulation results, while the moving delay was calculated based on work zone length and average speed within the zone. The findings of this study are summarized below:

(1) To generate a creditable result from simulation, CORSIM has been calibrated with traffic data on Interstate I-80 collected from NJDOT. The calibrated parameters were found, which enables CORSIM properly emulating traffic operations on Interstate I-80. The delay estimated by CORSIM is thus treated as the "real-world" delay and used to evaluate delays estimated by the proposed method and deterministic queuing model.

(2) To produce a reasonable performance measure (e.g., delay, speed, capacity, etc.) with CORSIM, it is recommended that 25 simulation runs should be conducted for congested situation. The

number of runs can be reduced as the v/c ratio of the study network is reduced.

(3) The queuing delay curves for three-lane and four-lane freeways considering various V/C ratios have been derived and shown in Figures 2 and 3, respectively. The moving delay has been formulated and can be estimated by Eqs. 2 and 4, depending on whether the traffic volume exceeds the work-zone capacity.

(4) Comparisons of delays estimated by the deterministic queuing model and the proposed model is conducted. After analyzing the difference between the delays produce by both model and that estimated by CORSIM, we found that the proposed model can produce more accurate results than the deterministic queuing model, especially during congested periods (e.g. $V/Cw > 0.8$).

(5) The work-zone related total delay (including queuing and moving delays) estimation procedure with the use of the proposed method has been summarized in Tables 4 and 5. This procedure can be easily programmed with computer packages (e.g., MS-EXCEL, LOTUS-123) and integrated to traffic information and management systems for diverting traffic as well as disseminating delay information to motorists.

Extensive calibration and validation of CORSIM may be required in the future after obtaining traffic data (e.g., speeds, headway, volume, density, queue length, etc.) incurred under various work zone activities (e.g., configurations and duration of work zones). The delay curves derived in this study with CORSIM can thus be appropriately adjusted. The credibility of the proposed simulation-based delay modeling approach fully depends on the accuracy of data obtained from CORSIM. Thus, the accuracy of performance measures (e.g., capacity, speed, delay, etc) relies on the validity of the simulation model and required simulation runs to produce reasonable delay estimates. Finally, the queuing delay model formulated in Eq. 6 is developed subject to an assumption that that the queuing delay will be linearly increased over time. The sensitivity analysis of queuing delay for different duration of time periods under various v/c ratios would be our immediate extension that can also calibrate Eq. 6 and further improve the accuracy of the method developed in this study.

Acknowledgements

This work was conducted under a research project titled "Lane Occupancy Charges Studies," sponsored by the University Transportation Research Center (UTRC) Region II and New Jersey Department of Transportation.

References

Al-Deck, H. M., Garib, A., and Radwan, A. E. (1995) "New method for estimating freeway incident congestion," Transportation Research Record 1494, Transportation Research Board, 30-39.

Abraham, C. M., and Wang, J. J. (1981) "Planning and scheduling work zones traffic control," US Department of Transportation, FHWA-IP-81-6.

Bloomberg, L., and Dale, J. (2000) "Comparison of VISSIM and CORSIM traffic simulation models on a congested network," Transportation Research Record 1727.

Chien, S., and Chowdhury, M. (1998) "Freeway capacity analysis with microscopic simulation model (CORSIM)," Phases I & II, FHWA-RD-97, USDOT, Final Reports.

Cohen, S., and Clark, J. (1986) "Analysis of freeway reconstruction alternative using traffic simulation," Transportation Research Record No. 1132, Transportation Research Board, 8-13.

Dixon, K. K., Hummer, J. E., and Lorscheider, A. R. (1995) "Capacity for North Carolina freeway work zones," Transportation Research Record 1529, 27-34.

Dudek, C. L., and Richards, S. H. (1982) "Traffic capacity through urban freeway work zones in Texas", Transportation Research Record 869, 14-18.

Federal Highway Administration (1992) "TRAF user reference guide, "Report No. FHWA-RD-92-103.

Goulias, D. G., Yahalom, S. Z., and Chien, S. (2001) "Lane occupancy charges", Research Project prepared for NJDOT, Division of Research and Technology and USDOT-FHWA.

Jiang, Y. (1999) "Traffic characteristics and estimation of traffic delays and user costs at Indiana freeway work zones," Project Final Report, Indiana Department of Transportation.

Krammes, R. A., and Lopez, G. O. (1994) "Updated capacity values for short-term freeway work zone lane closures," Transportation

Research Board, the 73rd Annual Meeting, Preprint Paper No. 940725.
McShane W., and Ross. R. (1992) "Traffic engineering," Prentice Hall.
Memmott, J. L., and Dudek, C. L. (1984) "Queue and user cost evaluation of work zone (QUEWZ)," Transportation Research Record 979, 12-19.
Morales, J. M. (1986) "Analytic procedures for estimating freeway traffic congestion," Public Roads, Vol. 50, No.2.
Nam, D. D., and Drew, D. R. (1998) "Analyzing freeway traffic under congestion: traffic dynamics approach," Journal of Transportation Engineering, ASCE. pp. 208-212.
Nemeth, Z. A., and Rathi, A. K. (1985) "Potential impact of speed reduction at freeway lane closures: a simulation study," Transportation Research Record No. 1035, 82-84.
Pain, R. F., McGee, H. W., and Knapp, B. G. (1981) "Evaluation of traffic control for highway work zones," NCHRP Report 236.
Rathi, A. K., and Venigalla, M. M. (1992) "Variance reduction applied to urban network traffic simulation," Transportation Research Record 1365.
Richards, P. I. (1956) "Shock waves on the highways, "Operations Research, Vol. 4, pp. 42-51.
Rouphail, M. N., and Tiwari, G. (1985) "Flow characteristics at freeway lane closures," Transportation Research Record 1035, pp. 50-58.
Rouphail, N. M., Yang, Z. S., and Fazio, J. (1988) "Comparative study of short and long-term urban freeway work zones," Transportation Research Record 1163, 4-14.
Schonfeld, P., and Chien, S. (1999) "Optimal work zone lengths for two-lane highways," Journal of Transportation Engineering, Urban Transportation Division, American Society of Civil Engineers, 21-29.
Texas State Department of Highways and Public Transportation (1976) "Programmer's supplement to highway economic evaluation model," Austin, Texas.
Tian, Z., Urbanik II, T., Engelbrecht, R., and Balke, K. M. (2002) "Variations in capacity and delay estimates from microscopic traffic simulation models," The 81st Annual Meeting, Transportation Research Board, Washington, DC.
Transportation Research Board (1994) "Highway capacity manual, "Special Report 209, National Research Council.

Wirasinghe, S. C. (1978) "Determination of traffic delays from shock wave analysis," Transportation Research, Vol. 12, pp. 343-348.