Queue and User Cost Evaluation of Work Zones (QUEWZ)

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ABSTRACT

An important aspect of a highway work zone is the lane-closure strategy and the movement of traffic through the work zone. As part of the evaluation to determine the effects of different lane-closure strategies (e.g., one-, two-, or three-lane closures on a four-lane section), the additional costs to vehicle users should be considered. It is therefore necessary to have a model that will improve the accuracy of user cost estimates resulting from the forced movement through a restricted work zone. A computer model, Queue and User Cost Evaluation of Work Zones (QUEWZ), developed to estimate the additional user costs resulting from lane closures in one or both directions of travel is described. User costs can be estimated when one or more lanes are closed in just one direction of travel or when a crossover is used. Hourly as well as daily user costs are estimated, and when vehicle demand exceeds capacity, the model also estimates the length of queue. The model is designed specifically for freeway conditions, but it can be used in other situations if appropriate adjustments are made in the input data. Two vehicle types are used in the model--passenger cars and trucks.

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There are several models that attempt to measure those costs (1-3), but each one has several limitations that prevent it from accurately calculating user costs or is so complicated that it cannot be used quickly or easily. Those limitations include use of average daily traffic (ADT) volume instead of hourly traffic volumes, large amounts of required input data, no adjustment for stop-and-go conditions in a queue, and no adjustment for the effective length of reduced speed through the work zone for low traffic volumes. Plummer et al. (4) described a manual method of computing the change in fuel consumption for a work zone. Although the method incorporates hourly traffic volumes, it would be very time consuming to use for a number of work zones and it does not handle delay costs resulting from work zones.

A computer model, Queue and User Cost Evaluation of Work Zones (QUEWZ), developed to estimate the additional user costs resulting from lane closures in one or both directions of travel is described. User costs can be estimated when one or more lanes are closed in just one direction of travel or when a crossover is used. Hourly as well as daily user costs are estimated, and when vehicle demand exceeds capacity, the model also estimates the length of queue. The model is designed specifically for freeway conditions, but it can be used in other situations if appropriate adjustments are made in the input data. Two vehicle types are used in the model--passenger cars and trucks.

CHARACTERISTICS OF MODEL

User costs resulting from restricted capacity through a work zone can be grouped in four general categories: delay or travel-time costs, vehicle running costs, speed-change cycling costs, and accident costs. Delay costs result from reduced speeds through the work zone, delay in slowing down from and returning to the approach speed, and delay in a queue if demand exceeds capacity. Changes in vehicle running costs result from reduced speeds through the work zone and queue, if any. Speed-change cycling costs are generated from slowing down to go through the work zone and stop-and-go conditions if a queue is present. Changes in accident costs are not calculated in this model because of the lack of data on changes in accident rates through a typical work zone.

Two general configurations of lane closures through a work zone are incorporated into QUEWZ. These configurations are shown in Figure 1. The first configuration involves situations where one or more lanes are closed in one direction, whereas traffic moving in the opposite direction is not affected. The second configuration involves a cross-

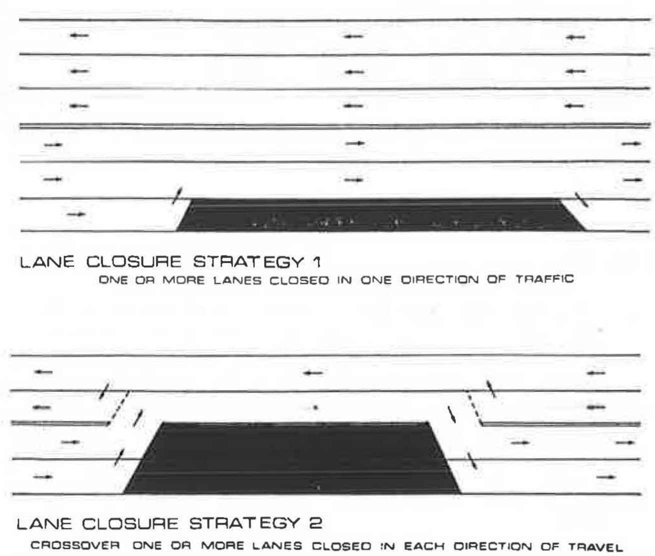

FIGURE 1 Traffic closure configuration through a work zone.

over, where all lanes in one direction of travel are closed and two-lane two-way traffic is maintained on the other directional lanes. A maximum of six lanes in each direction can be handled in the model.

Most other models use ADT as the input data for vehicle volume (1,2). However, the daily peaking pattern can have a significant impact on average speeds and queues during the day. Therefore hourly traffic volumes are used in this model, and the user costs are calculated for each of those hourly traffic volumes. The hourly user costs are then summed, giving the daily user costs. The input and output data for the model are listed as follows. Details of the input as well as the program documentation are contained in a report by Memmott and Dudek (5).

1. Input data
   a. Required
      (1) Lane-closure strategy (see Figure 1)
      (2) Total number of lanes
      (3) Number of open lanes through work zone
      (4) Length of closure
      (5) Time of lane closure and work-zone activity
      (6) Actual traffic volumes by hour
   b. Optional
      (1) Factor to update cost calculations
      (2) Percentage of trucks
      (3) Speeds and volumes for speed-volume curve
      (4) Capacity estimate risk reduction factor or work-zone capacity
      (5) Problem description
2. Output data
   a. Vehicle capacity
   b. Average speed through work zone by hour
   c. Hourly user costs
   d. Daily user costs
   e. Average length of queue each hour (if queue develops)

Many of the items in the foregoing list are apparent. A few need some explanation:

1. Currently QUEWZ handles two lane-closure strategies, as shown in Figure 1. The user is required to identify the time when lanes will be closed and reopened. For long-term road work that lasts for more than one day, the time of day when the work crews are at the site must also be specified.

2. The factor to update cost calculations is used to update the dollar user costs from December 1981 to current prices. The consumer price index can be used as the price index to update the user costs for inflation.

3. QUEWZ also allows the user to include a problem description. Such information as highway number, work-zone location, and so forth, can be included.

4. The program has constant values built into the model for all optional inputs. If the user does not specify values for the optional inputs, the program automatically uses its preset values. These program constant values, or default values, and details of the user cost calculations are contained in the section on user cost calculations.

Strategy 1: Single-Direction Closure

QUEWZ assumes a typical speed-volume relationship. The user of the program has the option of defining a different speed-volume relationship by inputting the free-flow speed, speed and lane volume at the dividing point between level of service D and E, speed at capacity, and lane volume at capacity.

The user has an option of including a capacity estimate risk reduction factor. Because QUEWZ uses a capacity probability distribution for each type of lane-closure configuration, the user can select a level of confidence that his work-zone capacity estimate will cover a certain percentage of those capacities observed to date in Texas. For example, if the user selects a risk reduction factor of 100, the estimated work-zone capacity will be low, but the user can be assured at a 100 percent level of confidence that the actual work-zone capacity will be equal to or larger than the estimated capacity (based on capacities observed thus far for single-direction closures in Texas). A lower risk reduction factor will yield a higher estimated work-zone capacity with an associated risk that the actual work-zone capacity will be less than the estimated capacity (6). The program uses a preset risk factor of 60, which will give approximately the mean capacity for each closure configuration. If a lower risk reduction factor is used in the input data, the result will be a higher estimated capacity through the work zone than the mean capacity observed to date for work zones in Texas. A value more than 60 would have exactly the opposite effect on the estimated capacity. Additional information on the factor is contained in the section on user cost calculations.

Strategy 2: Crossover

Because of the lack of capacity and speed data for crossover configurations, the same approach and parameters previously described for strategy 1 are used for the crossover strategy. In effect each direction of travel through the work zone is treated independently. The same speed-volume relationship is assumed for each direction of travel.

The capacity in each direction is estimated based on the previously described Texas capacity data for closures affecting a single direction of travel. For example, a crossover for a four-lane freeway would consist of two-lane two-way traffic through the work zone. The capacity for each direction of travel would be estimated using the lane reduction in that direction. In this case each direction is being reduced to one lane in a single direction, which would be treated as a single-direction closure for both directions of travel. This is the same way crossovers are handled in the Flexible Pavement System (FPS) Model (1) and the Economic Analysis of Roadway Occupancy for Freeway Pavement Maintenance and Rehabilitation (EAROMAR) Model (3).

USER COST CALCULATIONS

The calculation of user costs in QUEWZ, in most respects, is typical of user cost calculations elsewhere. There are significant differences, however, for several aspects of speeds, capacities, and queues that incorporate some recent findings by Texas Transportation Institute (TTI) concerning work zones. As a result, several different equations and approaches are presented here that are not found in other models.

Estimation of Vehicle Capacity Through Work Zone

Generally, the primary effect work zones have on traffic is the restricted capacity through the work area and the resulting effect on average speeds. The model assumes that highway capacity under normal conditions will be 2,000 vehicles per hour per lane (vphpl), but this can be changed as part of the input data. When lanes are closed for prolonged periods (i.e., longer than one day) but activity is not taking place in the work zone, previous research by TTI has found the capacity to be about 1,800 vphpl, or about 90 percent of normal capacity, which is used in this model.

Data on work-zone capacities during work hours are reported in a report by Dudek and Richards (6). From the data in that report, linear approximations of the cumulative distributions for each reported closure combination are estimated. These capacity approximations are shown in Figure 2. The numbers in the parentheses indicate the original number of lanes and the number of open lanes through the work zone. The function of Figure 2 is to assist the users in identifying risks in using certain capacity values for a given lane-closure situation to estimate the effects of the lane closures (e.g., queue lengths).

For example, the 85th percentile for the (3,1) situation is 1,030 vphpl. This means that 85 percent of the studies conducted on three-lane freeway sections with one lane open through the work zone resulted in capacity flows equal to or greater than 1,030 vphpl. The capacity flow was equal to or greater than 1,290 vphpl in only 20 percent of the cases studied. Thus, to assume a higher capacity of 1,500 vphpl [which is the mean capacity for (3,2) and (4,2) closures] for (3,1) work zones would tend to underestimate the length of queues caused by the lane reduction at the majority of these work zones. Although these data apply only to single-direction closure strategies, the same capacities are used here for the crossover strategy until capacity data are available for crossover strategies.

For those lane-closure combinations that did not have capacity data [i.e., (4,1), (5,1), (5,3), (5,4), (6,1), (6,2), (6,3), (6,4) combinations], the closure capacities in NCHRP Report 160 (1) are used. For freeways with four, five, or six lanes in each direction and only one lane left open through the work zone, an average capacity of 1,200 vphpl is used. For five or six lanes with three lanes left open, 1,500 vphpl capacity is used; for five or six lanes with four lanes left open, 1,550 vphpl capacity is used; and for six lanes with five lanes left open, 1,580 vphpl capacity is used. Estimated capacity is calculated in the program with the following equation:

CAPW = a - b(CERF),

where CAPW is the restricted capacity during work-zone activity hours and CERF is the capacity estimate risk factor, or the probability that the estimated capacity will be less than or equal to the actual capacity.

The values for coefficients a and b are listed in Tables 1 and 2. The coefficients were obtained through regression analyses of the capacity data presented by Dudek and Richards (6) and shown in Figure 2. CERF in the previous equation can take any value from 1 to 100. The value of CERF can be specified as part of the input data, but this is not necessary. If the value is left blank or is zero, a value of 60 is automatically used in the model, which yields the approximate mean capacity for Texas work zones. This work-zone capacity generated within the program can be overriden by a user-specified capacity as part of the input data.

Calculation of Average Speeds

The average approach speed is calculated by using the assumed speed-volume curve shown in Figure 3. Truck speeds are assumed to be 90 percent of car speeds (7). The three speed parameters (SP_1, SP_2, and SP_3) along with the volume parameters (V_1 and V_2) have preset constant values or default values if the user does not specify them. Those default values are as follows: SP_1, 60 mph; SP_2, 40 mph; SP_3, 30 mph; V_1, 2,000 vphpl; and V_2, 1,600 vphpl.

The hourly traffic volume specified by the user is

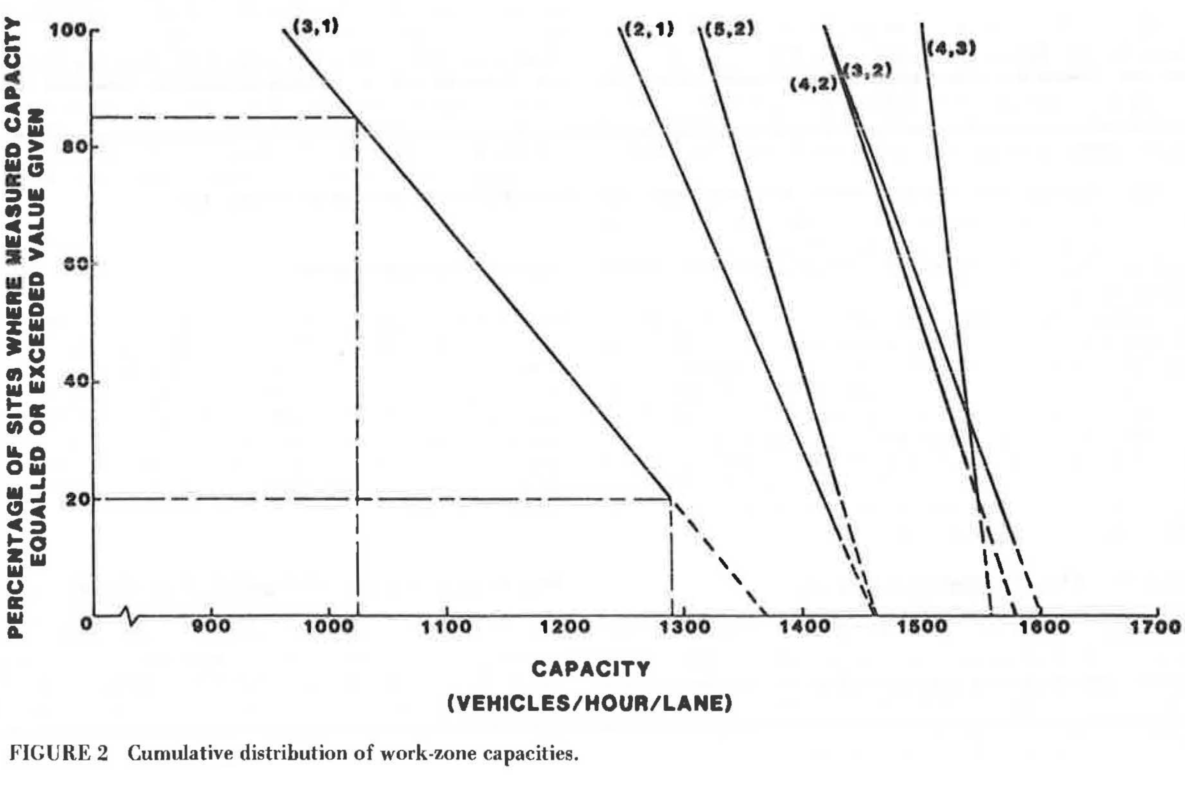

FIGURE 2 Cumulative distribution of work-zone capacities.

TABLE 1 Restricted Capacity Coefficients During Work-Zone Activity Hours: Intercept Term (a)

Normal No. of Open Lanes in One Direction	No. of Open Lanes Through Work Zone in One Direction				
	1	2	3	4	5
2	1,460				
3	1,370	1,600			
4	1,200	1,580	1,560		
5	1,200	1,460	1,500	1,550	
6	1,200	1,400	1,500	1,550	1,580

TABLE 2 Restricted Capacity Coefficients During Work-Zone Activity Hours: Slope Term (b)

Normal No. of Open Lanes in One Direction	No. of Open Lanes Through Work Zone in One Direction				
	1	2	3	4	5
2	2.13				
3	4.05	1.81			
4	0.00	1.60	0.57		
5	0.00	1.46	0.00	0.00	
6	0.00	0.00	0.00	0.00	0.00

converted into a volume-capacity (V/C) ratio, and the approach speed in miles per hour is calculated using the following equations, which are based on the assumed speed-volume relationship. The equations are taken from the Highway Economic Evaluation Model (HEEM) (7).

If $V_2/V_1 \geq V/C$,

$$SP = SP_1 + [V_1(SP_2 - SP_1)/V_2] \cdot (V/C).$$

If $V_2/V_1 < V/C \leq 1$,

$$SP = SP_2 + (SP_2 - SP_3)\{1 - \{[(V/C) - (V_2/V_1)] \div [1 - (V_2/V_1)]\}^2\}^{1/2}.$$

If $V/C > 1$ or a queue is present,

$SP = SP_3[2 - (V/C)]$ with the speed constrained to the following range: $20 \leq SP \leq SP_3$.

The average speed through the work zone (SP_{wz})

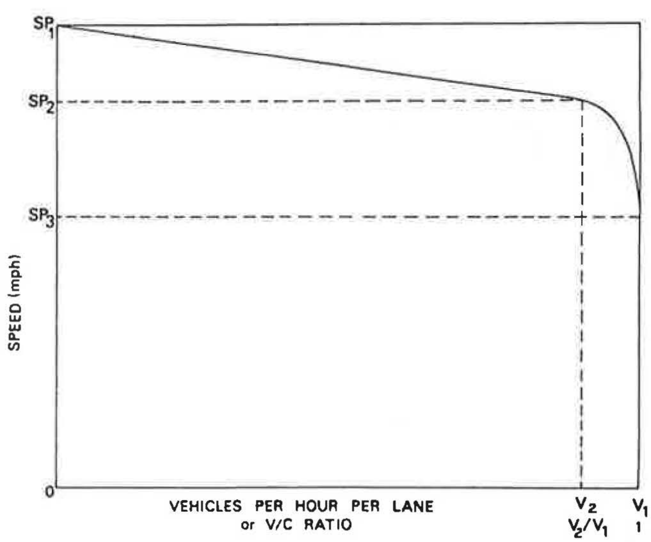

FIGURE 3 Hourly speed-volume curve.

is calculated from the same speed equations given previously using the V/C ratio of the work-zone area. Unpublished data on work zones in Texas collected by TTI (8) (which will be referred to in this paper as the work-zone data) indicate that the speed-volume relationship does not change if capacity is restricted through a work zone. The higher V/C ratio accounts for the lower average speeds.

The same work-zone data also indicate that the minimum speed (SP_{mn}) of vehicles is somewhat lower than the average speed through the work zone and it can be estimated using the V/C ratio of the work zone:

$$SP_{mn} = SP_{wz} - 2.3 - 25.7(V/C_{wz})^2.$$

If there is a queue, $SP_{mn} = 0$.

Calculation of Delay Through the Lane-Closure Section

The work-zone data also indicate that the distance over which vehicles slow down through a work zone is not always the entire distance of restricted capacity. When the traffic volume is light, vehicles tend to slow down only when passing the paving machine or other major work activity. An adjustment distance of 0.1 mile on each side of the work zone is also included to account for the effects of reduction in average speed upstream of the lane closure. If the work-zone closure is less than 0.1 mile, the model assumes that traffic will slow down through the entire work zone. The following equations are used to estimate the effective length of closure (CLL) in miles of reduced average speeds:

$$CLL = 0.1 + (WZD + 0.1)(V/C_{wz}),$$

where WZD is the length of restricted capacity around the work zone in miles. If $WZD \leq 0.1$ or if $V/C_{wz} > 1$,

$$CLL = WZD + 0.2.$$

The dollar delay cost of going through the work zone at reduced speed (CDWZ) is calculated as follows:

$$CDWZ = (CLL)[(1/SP_{wz}) - (1/SP_{ap})](VL)(CUF)\{(PTC \cdot VLT_c) + [(PTT \cdot VLT_t)/0.9]\},$$

where

SP_{ap} = approach speed (mph),
VL = hourly vehicle volume (vph),
CUF = factor to update cost calculations,
PTC = percentage of cars + 100,
PTT = percentage of trucks + 100,
VLT_c = car value of time ($/hr), and
VLT_t = truck value of time ($/hr).

Calculation of Queue Delay

If demand exceeds capacity of the work zone, the program assumes that a queue will form. The model also assumes that there will be no change in demand as the queue forms and that no traffic will divert to avoid the queue. If vehicles are assumed to arrive at a constant rate during a given hour and enter the work zone at a constant rate during a given hour, the average delay for each hour a queue is present (DQUE) in vehicle hours is simply the average of the accumulated vehicles in the queue at the beginning of hour i ($ACUM_{i-1}$) and at the end of the hour i ($ACUM_i$):

$$DQUE_i = (ACUM_{i-1} + ACUM_i)/2,$$

where

$ACUM_i = ACUM_{i-1} + VL_i - CAPW_i$,
CAPW = restricted capacity through work zone (vph) for hour i, and
VL_i = vehicle demand during hour i.

An example is presented graphically in Figure 4. The times along the horizontal axis represent hours, so T_1 = hour 1, T_2 = hour 2, and so on. The V's along the vertical axis represent the amount of accumulated vehicle demand at any given time. For example, V_1 represents the total number of vehicles in the first hour, V_2 represents the total number of vehicles in the first 2 hr, and so on. The C's represent the work-zone capacity. C_1 represents vehicle capacity for the first hour, C_2 represents vehicle capacity for the first 2 hr, and so on. The shaded area represents the queue delay, the excess of vehicle demand above capacity. In the first hour, there is no queue at the beginning of the hour, so $ACCUM_0 = 0$. The queue at the end of the hour is $ACCUM_1 = V_1 - C_1$, so the average delay during the first hour is

$$DQUE_1 = [0 + (V_1 - C_1)]/2 = (V_1 - C_1)/2.$$

The average delay for each of the next 2 hr can be calculated in exactly the same fashion. However, in the fourth hour the queue dissipates; therefore an adjustment must be made for that portion of the hour when the queue was present. The point E, the time when the queue dissipates, can be calculated by solving the following equation. The left side of the equation is the capacity line during the fourth hour, and the right-hand side is the volume demand line during the same hour.

$$(E - T_3)(C_4 - C_3) = (E - T_3)(V_4 - V_3) + (V_3 - C_3),$$

$$(E - T_3)[(C_4 - C_3) - (V_4 - V_3)] = V_3 - C_3,$$

$$E - T_3 = (V_3 - C_3)/[(C_4 - C_3) - (V_4 - V_3)],$$

$$E = T_3 + \{(V_3 - C_3)/[(C_4 - C_3) - (V_4 - V_3)]\}.$$

Therefore if the queue dissipates during hour i, the delay calculation must be modified by the proportion of the hour that a queue was present ($PQUE_i$):

$$PQUE_i = (V_{i-1} - C_{i-1})/[(C_i - C_{i-1}) - (V_i - V_{i-1})] = ACUM_{i-1}/(CAPW_i - VL_i).$$

Average delay is then calculated as

$$DQUE_i = (ACUM_{i-1}/2) \cdot PQUE_i.$$

Once the average delay has been calculated, the cost of the delay ($CQUE_i$) is calculated as

$$CQUE_i = (DQUE_i)(CUF)[(PTC \cdot VLT_c) + (PTT \cdot VLT_t)].$$

The average length of queue ($QUEL_i$) in miles can also be estimated, assuming an average distance of 40 ft for each vehicle and that vehicles in the closed lane or lanes will merge to the open lane or lanes after the queue has formed. It appears that the number of vehicles remaining in the closed lane or lanes is a function of the sight distance to the work zone and traffic volumes (9). Until more definitive data become available, the foregoing assumption on vehicle merging will be used.

$$QUEL_i = 40(DQUE_i)/5{,}280(TL),$$

where TL is the total number of lanes upstream of the work zone. For the hour when the queue dissipates,

$$QUEL_i = 40(DQUE_i)/5{,}280(TL) \cdot PQUE_i.$$

Cost of Speed-Change Cycles

An additional delay cost included in QUEWZ is the delay cost of slowing down and returning to the approach speed as a result of the presence of a work zone (CDSC). The work zone data indicate a relationship between the distance traveled in miles during the speed-change cycle (DSC) as a function of the V/C ratio through the work zone:

$DSC = 0.5 + 0.25(V/C_{wz})$, with the constraint that $DSC \leq 0.75$.

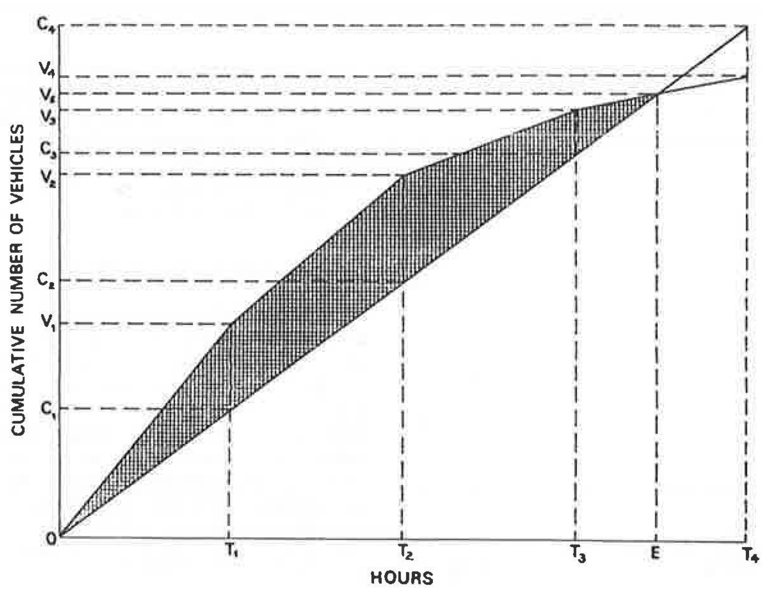

FIGURE 4 Calculation of queue delay.

If the speed is reduced and increased at an approximately constant rate, the delay cost can be calculated as follows:

$$CDSC = (DSC)\{[2/(SP_{ap} + SP_{mn})] - (1/SP_{ap})\}(VL)(CUF) \cdot \{PTC \cdot VLT_c) + [(PTT \cdot VLT_t)/0.9]\}.$$

In order to estimate the change in vehicle operating costs resulting from the speed-change cycles, cost equations were developed from tabular data in the AASHTO Redbook (10) and updated to December 1981. The speed-change costs per 1,000 vehicle miles for cars (SPCC) and trucks (SPCT) are calculated as follows:

$$SPCC = -5.2187 + 1.1241(SP_{ap}) - 1.1125(SP_{mn}).$$

$$SPCT = -32.2883 + 7.1226(0.9SP_{ap}) - 6.684(0.9SP_{mn}).$$

The additional operating cost of the speed-change cycle (CSPC) is

$$CSPC = (VL/1{,}000)(CUF)[(PTC \cdot SPCC) + (PTT \cdot SPCT)].$$

If a queue is present, additional speed-change operating costs (CSPQ) must be added. The work-zone data indicate that approximately three speed-change cycles of 0 to 10 mph occur per mile of queue; therefore the cost can be calculated as follows:

$$CSPQ = (VL/1{,}000)(CUF)(3 \cdot QUEL)[(6.0223 \cdot PTC) + (31.8151 \cdot PTT)].$$

During the hour that the queue dissipates, the foregoing equation for CSPQ is multiplied by PQUE.

Change in Vehicle Running Costs

Vehicle running costs are also affected by changes in average speeds. The change in car running costs (VOC_c) and truck running costs (VOC_t) per 1,000 vehicle miles can be calculated by the following equations. These equations were also estimated from tabular data in the AASHTO Redbook (10), updated to December 1981.

$$VOC_c = f(SP_{wz}) - f(SP_{ap}),$$

$$VOC_t = g(0.9SP_{wz}) - g(0.9SP_{ap}),$$

where

$$f(SP) = (395.6898)e^{0.01537(SP)}SP^{-0.45525} \text{ and}$$

$$g(SP) = (179.1466)e^{0.02203(SP)}SP^{-0.35902} + (1201.8847)e^{0.0322(SP)}SP^{-0.79202}$$

The change in vehicle running costs (OC) is then calculated as follows:

$$OC = (VL/1{,}000)(CUF)(CLL)[(VOC_c \cdot PTC) + (VOC_t \cdot PTT)].$$

If a queue forms, the average speed through the queue (SP_q) can be calculated using a formula in TTI Research Report 165-8 (11):

$$SP_q = (SP_1/2)\{1 + [1 - (C_{wz}/C_{ap})]^{1/2}\},$$

where C_{ap} is the normal capacity in vehicles per hour.

The cost equations are as follows:

$$QVOC_c = f(SP_q) - f(SP_{ap}),$$

$$QVOC_t = g(0.9SP_q) - g(0.9SP_{ap}),$$

$$OCQ = (VL/1{,}000)(CUF)(QUEL)[(QVOC_c \cdot PCT) + (QVOC_t \cdot PTT)].$$

During the hour that the queue dissipates, OCQ is multiplied by PQUE.

Total User Costs

Total hourly user costs (THC) in each direction are merely the sum of the component user costs:

$$THC = CQUE + CDWZ + CDSC + CSPC + CSPQ + OC + OCQ.$$

In similar fashion, the costs can be summed to yield the daily user costs resulting from restricted capacity through the work zone.

EXAMPLES OF THE MODEL'S USE

In the examples used to test the model, the same hourly traffic volumes are used for each problem. The freeway work zone is assumed to be 1 mile in length and work activity begins at 9:00 a.m. and ends at 3:00 p.m. It is also assumed that the lane closures through the work zone remain closed for an entire 24-hr period for some problems, and for others it is assumed that closure begins at 8:00 a.m. and ends at 4:00 p.m. A vehicle mix of 8 percent trucks is also assumed.

Table 3 presents some summary results of 20 test problems. Complete output for each problem is contained in TTI Research Report 292-1 (5). In several of the test problems, demand exceeded capacity for some hours and a queue formed. The user costs increased substantially for those hours when a queue was present, which dramatically increased the total daily user costs.

An interesting comparison can be made with problems 5 and 6. Suppose an engineer has to perform maintenance work on a freeway and has the choice of closing one or two lanes of the three inbound lanes. If the hourly traffic volumes were similar to those assumed in these test problems, a one-lane closure would not be expected to produce any queues and a small amount of user costs. If the second lane is closed, however, very long queues could be expected along with substantial user costs. This is the sort of situation in which QUEWZ could be very useful, providing relevant information concerning the available alternatives.

SUMMARY AND RECOMMENDATIONS

A model has been presented to calculate the additional user costs generated by restricted capacity through a work zone. The model goes through a number of calculations to estimate the various user costs associated with work zones. Those user costs, presupposing an adequate traffic control plan, include delay costs and change in vehicle running costs through the work zone, speed-change cycle costs in slowing down and returning to the approach speed, and costs if a queue forms as delay costs, vehicle running costs, and speed-change cycle costs. The accuracy of the cost calculations has been increased significantly over previous models by using hourly rather than daily traffic volume and by incorporating recent findings regarding work-zone capacities and average speeds.

Additional work remains in order to accurately estimate the effect on average speeds from varying

TABLE 3 Summary of Sample Problems

Problem No.	Total No. of Lanes		No. of Open Lanes Through Work Zone		Length of Work Zone (miles)	Normal Capacity Each Direction (vph)	Restricted Capacity (vph)				Time of Restricted Capacity[a]		Longest Est. Queue Length (miles)		Total Additional Daily User Costs Due to Lane Closure ($)
							Work-Zone Inactivity Hours		Work-Zone Activity Hours						
	Inbound	Outbound	Inbound	Outbound			Inbound	Outbound	Inbound	Outbound	Begin	End	Inbound	Outbound	
1	2	2	1	2	1.00	4,000.	1,800.		1,332.		8:00	4:00	1.9	0.0	17,647.
2	2	2	1	1	1.00	4,000.	1,800.	1,800.	1,332.	1,332.	8:00	4:00	1.9	3.0	38,211.
3	2	2	1	2	1.00	4,000.	1,800.		1,332.		–[b]	–[b]	1.9	0.0	35,923.
4	2	2	1	1	1.00	4,000.	1,800.	1,800.	1,332.	1,332.	–[b]	–[b]	1.9	3.8	83,756.
5	3	3	2	3	1.00	6,000.	3,600.		2,983.		8:00	4:00	0.0	0.0	546.
6	3	3	1	3	1.00	6,000.	1,800.		1,127.		8:00	4:00	3.6	0.0	64,108.
7	3	3	2	3	1.00	6,000.	3,600.		2,983.		–[b]	–[b]	0.0	0.0	847.
8	3	3	1	3	1.00	6,000.	1,800.		1,127.		–[b]	–[b]	4.1	0.0	120,878.
9	4	4	4	3	1.00	8,000.		5,400.		4,577.	–[b]	–[b]	0.0	0.0	368.
10	4	4	4	2	1.00	8,000.		3,600.		2,968.	–[b]	–[b]	0.0	0.0	986.
11	4	4	4	1	1.00	8,000.		1,800.		1,200.	–[b]	–[b]	0.0	3.2	101,485.
12	5	5	4	5	1.00	10,000.	7,200.		6,200.		–[b]	–[b]	0.0	0.0	214.
13	5	5	3	5	1.00	10,000.	5,400.		4,500.		–[b]	–[b]	0.0	0.0	436.
14	5	5	2	5	1.00	10,000.	3,800.		2,745.		–[b]	–[b]	0.0	0.0	1,126.
15	5	5	1	5	1.00	10,000.	1,800.		1,200.		–[b]	–[b]	1.7	0.0	81,736.
16	6	6	5	6	1.00	12,000.	9,000.		7,900.		9:00	3:00	0.0	0.0	64.
17	6	6	4	6	1.00	12,000.	7,200.		6,200.		9:00	3:00	0.0	0.0	113.
18	6	6	3	6	1.00	12,000.	5,400.		4,500.		9:00	3:00	0.0	0.0	217.
19	6	6	2	6	1.00	12,000.	3,600.		2,800.		9:00	3:00	0.0	0.0	551.
20	6	6	1	6	1.00	12,000.	1,800.		1,200.		9:00	3:00	0.8	0.0	27,495.

[a] Work-zone activity began at 9:00 a.m. and ended at 3:00 p.m.
[b] Closure for 24 hr.

shoulder widths, and the change in accident rates should be the subject of further research. In addition, more work should be done on the user costs generated in a queue, including diversion of vehicles to avoid waiting in the queue, which is not currently accounted for. This additional information would increase the accuracy of the user cost calculations, which in turn would increase the reliability of decisions regarding work-zone configurations and the trade-offs involved. The program should also be written to output alternative traffic control strategies that can improve traffic operations if excessive queues develop. This will assure that the user explores all alternatives, and it increases the probability of completing the required work at minimum cost and time. A few alternative traffic control strategies include closing entrance ramps, temporary use of the shoulder as an operating lane, diverting traffic to the frontage road, and splitting traffic during middle-lane closures.

ACKNOWLEDGMENT

This paper was prepared in cooperation with the Texas State Department of Highways and Public Transportation and FHWA, U.S. Department of Transportation.

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Publication of this paper sponsored by Committee on Traffic Safety in Maintenance and Construction Operations.