Computer Model for Evaluating and Scheduling Freeway Work-Zone Lane Closures

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QUEWZ is a computer model that was developed in 1982 as a tool for planning and scheduling freeway work-zone operations. The model analyzes traffic flow through lane closures in freeway work zones and estimates the queue lengths and additional road user costs that would result. Several applications of the model are reported and two enhancements that have been made to improve its utility and accuracy are documented. One enhancement is an analysis option to determine acceptable schedules for alternative lane-closure configurations based on a motorist-specified maximum acceptable length of queue or delay. The second enhancement is an algorithm to account for the natural diversion of traffic away from the freeway work zone to unspecified alternative routes.

Most maintenance and reconstruction operations on existing freeways are conducted in work zones through which traffic operates on a restricted cross section adjacent to the work area. The work zone itself must be planned and scheduled with three objectives in mind: *(a)* to protect the safety of both the workers in the work area and the motorists traveling through the work zone, *(b)* to maximize the efficiency with which the work is performed, and *(c)* to minimize the inconvenience and delay to motorists.

In 1984 Memmott and Dudek *(1)* reported the development of a computer model to perform a queue and user cost evaluation of work zones (hence the name QUEWZ). The model analyzes traffic flows through freeway work zones and estimates the queue lengths and additional road user costs caused by the work zone. It was designed to evaluate the effects on road users of alternative work-zone configurations and schedules. Several applications of the model are discussed and two recent enhancements that have been made to improve its utility and accuracy for planning and scheduling freeway work-zone operations are described. The two enhancements are *(a)* an analysis option that provides a preliminary assessment of acceptable schedules for alternative work-zone lane-closure configurations and *(b)* an algorithm that accounts for the natural diversion of traffic away from the freeway work zone to unspecified alternative routes.

BACKGROUND

QUEWZ is one of several models of freeway work zones that have been developed in recent years. In this section, the several models are briefly reviewed in order to clarify the differences among them.

Lytton et al. *(2)*, St. John et al. *(3)*, and Butler *(4)* developed algorithms to estimate the additional costs to road users per day of construction activity as part of broader economic evaluations of highway improvement alternatives. The methodologies of these models are consistent with standard procedures for calculating road user costs *(5)*, but the aggregate estimates, although appropriate for the purposes for which they were developed, are not at a sufficient level of detail to be useful in work-zone planning and scheduling.

Nemeth and Rouphail *(6)* and Rathi and Nemeth *(7)* developed a pair of microscopic models that simulate the movement of vehicles through lane closures in freeway work zones on the basis of drivers' responses to the stimuli presented at the lane closure. The main application of these models is the evaluation of the effect on traffic performance of different traffic control schemes at freeway lane closures.

The traditional input-output approach for estimating delays and queue lengths resulting from restricted capacities in work zones is described in Chapter 6 of the 1985 *Highway Capacity Manual* (HCM) *(8)*. Delay and queue-length estimates are based on the difference between cumulative arrivals at and cumulative departures from the work zone. Abrams and Wang *(9)* used this procedure to estimate the additional travel-time costs associated with these delays. Plummer et al. *(10)* used the input-output approach in estimating the fuel-consumption-related effect of freeway work zones. The procedure is a theoretically sound, macroscopic approach to delay and queue-length estimation, but the manual nature of the calculations limits its practicality for evaluating large numbers of alternative work-zone configurations and schedules.

DEVELOPMENT AND APPLICATIONS OF QUEWZ

QUEWZ was designed to evaluate traffic flows through lane closures in freeway work zones and to provide estimates of the queue lengths and additional road user costs associated with alternative closure configurations. In this section the methodology and applications of the model are summarized. More detailed descriptions of the computational procedures have been presented elsewhere *(1, 11)*.

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Methodology

The model can be applied to freeway facilities with as many as six lanes in each direction and can analyze any number of lanes closed in one or both directions. The model analyzes traffic flows through the work zone on an hourly basis to estimate the normal approach speeds and the average and minimum speeds through the work zone and, if demand exceeds capacity, the queue lengths, associated vehicle hours of delay, and average and minimum speeds through the queue. The additional road user costs due to the work zone are then estimated from these speeds and queueing characteristics by using the standard procedures presented in AASHTO's *Manual on User Benefit Analysis of Highway and Bus-Transit Improvements (5)*.

The normal approach speed and average speed through the work zone are computed from a relationship between speed and volume-to-capacity ratio similar to that presented in the 1965 HCM *(12)*. However, the user has the option of modifying the parameters to more accurately reflect the speed-volume relationship on the freeway of interest.

The minimum speed through the work zone was predicted from the average speed through the work zone and the square of the volume-to-capacity ratio through the work zone by using a linear regression model whose parameters were estimated from available work-zone data.

The minimum speed in a queue preceding a work zone is assumed to be zero. The average speed through the queue is estimated by using a kinematic wave model developed by Messer et al. *(13)* for predicting travel time on an urban freeway. The equation was derived directly from the Greenshields *(14)* speed-flow-density model, which assumes that space mean speed is a linear function of density.

Vehicle hours of delay and the length of queue when the approach volume exceeds the work-zone capacity are computed with an algorithm that replicates the traditional input-output approach presented in Chapter 6 of the 1985 HCM *(8)*.

The additional road user costs per hour of restricted work-zone capacity include *(a)* the additional travel-time costs due to delays in the queue, reduced speeds through the work zone, and the deceleration and acceleration between the normal approach speed and the minimum speed through the work zone; *(b)* the additional operating costs due to the speed-change cycle from the approach speed to the minimum speed in the work zone and due to the speed-change cycles in the queue; and *(c)* the differences among the operating costs at normal approach speeds, at the average speed through the work zone, and at the average speed through the queue.

Critical to the estimation of speeds and queue lengths and of the associated additional road user costs are the assumed speed-volume relationship and the assumed capacity of the work zone. There is some question whether the speed-volume relationship for a work zone is the same as that for a normal freeway segment. Butler *(4)* concluded that the speed-volume relationship for work zones did correspond to the typical relationship for normal freeway sections in the 1965 HCM *(12)*. Abrams and Wang *(9)* also used the typical relationships as the basis for their estimation of speeds through work zones. However, Rouphail and Tiwari *(15)* concluded that the speed-volume relationships at lane closures on four-lane freeways in Illinois were considerably different from those in the 1965 HCM *(12)*. Additional research will be necessary to determine which conclusion is the most accurate.

The work-zone capacities used in QUEWZ are those observed by Dudek and Richards *(16)* in Texas and by Kermode and Myyra *(17)* in California and reported in the 1985 HCM *(8)*. Dudash and Bullen *(18)* observed single-lane capacities at a reconstruction site in Pennsylvania that agreed well with the capacities observed by Dudek and Richards *(16)* for a similar lane-closure configuration. These capacity estimates are the best currently available. However, additional data will be necessary to quantify the effect on work-zone capacity of several factors, including the lane-closure configuration, the geometry of the work zone, the percentage of trucks, and the type and intensity of work activity.

Applications

QUEWZ has been used in several Texas cities, including Houston and Fort Worth. In Fort Worth, for example, maintenance engineers with the Texas State Department of Highways and Public Transportation (SDHPT) used the model to estimate queue lengths in order to determine the distance upstream of a lane closure at which supplemental advance-warning signs should be placed. Results, which have been reported on an informal basis, have been favorable.

Denney and Levine *(19)* have provided a more formal discussion of the use of the model for evaluating active traffic management strategies during work-zone activity on the Southwest Freeway in Houston. First, they divided the 4.2-mi work zone into 10 subsections that were homogeneous in terms of geometry and demand, and then they used QUEWZ to estimate the queue lengths that would result from closing one lane in each subsection between 9:00 a.m. and 4:00 p.m. They found that closing one lane in the five-lane subsections of the freeway segment would not cause significant queues but that in the four-lane subsections queues would exceed 2 mi, which they considered to be the boundary of acceptability. Next, they adjusted the model inputs to evaluate the effect of two active traffic management strategies on estimated queue lengths in the four-lane subsections. The first strategy was to use the right shoulder for carrying traffic in these subsections, which they estimated would increase the capacity of the work zone by 750 vehicles/hr. The second strategy was to close several entrance ramps and to divert ramp traffic to the parallel frontage road, which was evaluated by modifying the approach volumes for the affected subsections. Denney and Levine *(19)* concluded that "the QUEWZ computer model has been shown to provide reasonable evaluations of the effectiveness of these strategies."

Users of the model have generally been pleased with model results. However, they recommended some alternative forms of analysis and model output to correspond more closely to specific applications of the model for planning and scheduling work zones on urban freeways.

Field applications and additional validation of the model have suggested that the model performs well under many conditions. However, when demands greatly exceed work-zone capacity, the model's estimates of queue lengths are often much longer than those actually observed in the field. The model computes queue lengths by using the traditional input-output approach. With accurate inputs (approach volumes) and outputs (work-zone capacities), the model yields accurate queue-length estimates. In most cases, the approach volumes provided are based on historical data representing normal operating conditions. However, in Texas, where most urban freeways have parallel frontage roads, natural diversion commonly occurs and actual approach volumes during periods of work activity are less than normal approach volumes. Therefore, the problem is not with the methodology of the model but rather with the inputs to the model.

ENHANCEMENTS TO QUEWZ

Two major enhancements to the original QUEWZ model were made in response to the field applications and validation of the model. The first was the addition of an analysis option that determines acceptable schedules for alternative lane-closure configurations based on a motorist-specified maximum acceptable queue length or delay. The second enhancement was an algorithm that accounts for the natural diversion of traffic away from the freeway to unspecified alternative routes. Figure 1 is a flowchart that shows how these enhancements have been incorporated into the structure of the model.

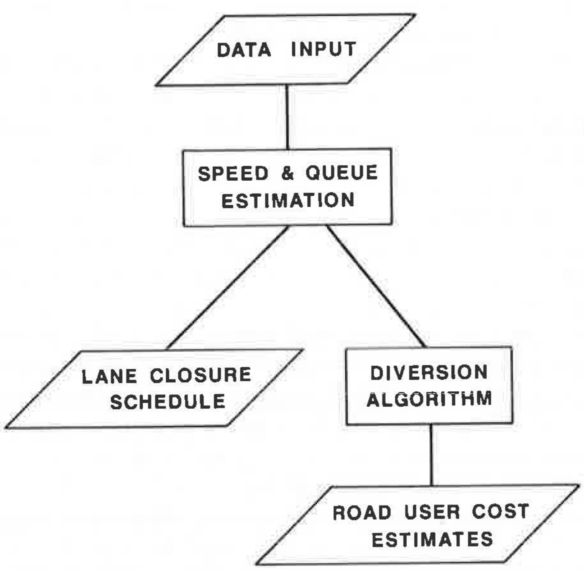

FIGURE 1 Flowchart of QUEWZ.

Lane-Closure Scheduling Option

As one part of an effort to improve the safety of freeway work zones and to minimize their impact on motorists, the Houston District Office of the SDHPT developed a set of guidelines to determine the optimum time for conducting short-term maintenance operations. The guidelines, which were reported by Levine and Kabat *(20)*, specify *(a)* that the delay to the traveling public should not exceed 20 min and *(b)* that the number of lanes that can be closed along a particular freeway section should be determined on a site-specific basis. This determination was to be based on a comparison of hourly flow rates and estimated capacities and on consideration of factors including the availability of shoulders, the existence of parallel frontage roads, and the volumes on entrance and exit ramps.

The Houston Urban Office of the SDHPT requested that QUEWZ be adapted to identify the proper times of day for closing freeway lanes. The algorithm that was developed to determine acceptable schedules for alternative lane-closure configurations at freeway work zones allows the user to define "excessive queuing" in terms of either the maximum acceptable length of queue in miles or the maximum acceptable delay to motorists in minutes *(21)*. When the lane-closure scheduling option is requested, QUEWZ evaluates all possible lane-closure configurations for the freeway facility described by the user. For example, if the user specifies a work zone that will affect both directions of an eight-lane freeway, the model evaluates the effect of closing one, two, and three lanes in each direction. For each lane-closure configuration, the model considers each hour of the day as a possible starting time and determines how many hours the lane closure could continue before queue lengths or delays to motorists became excessive.

If the user defines a critical length as the criterion for defining excessive queues, QUEWZ uses the user-supplied data on approach volumes to estimate the queue lengths that would develop during each hour of the day from each starting hour for each possible lane-closure configuration. These estimated queue lengths are compared with the critical length of queue to determine the number of hours, if any, that the lane closure could remain in place before queue lengths would become excessive.

The user may also specify a maximum acceptable delay to motorists as the criterion for determining acceptable lane-closure schedules. Dudek et al. *(22)* reported driver delay tolerances (the minutes of delay before a driver would divert from a freeway to a service road) of 15 to 20 min on the basis of a survey of drivers in College Station, Texas; Los Angeles; and St. Paul. Denney and Levine *(19)*, Levine and Kabat *(20)*, and Roper et al. *(23)* used 20 min as a maximum acceptable delay to motorists in their work-zone planning efforts. The user is given the option of either accepting a default value of 20 min or specifying another value.

Delay is defined as the difference between travel times on the section of freeway in question with and without the work zone. For each lane-closure configuration, delays are computed for each hour following each possible starting time. The travel time through the work zone is computed as the sum of the travel time through the work zone at the average work-zone speed plus, if applicable, the travel time through the queue at the average queue speed. The comparable travel time without the work zone is computed by dividing the sum of the queue length and work-zone length by the normal approach speed on the freeway. The acceptable lane-closure schedule for each configuration is determined by comparing the estimated delays with the user-specified criterion for maximum acceptable delays.

To illustrate the use of the lane-closure scheduling option, an example is provided. The example involves the evaluation of alternative lane-closure configurations for the inbound direction of a six-lane freeway. Required data for this option include directional hourly volumes for each hour of the day and work-zone capacities for each lane-closure configuration. The hourly volumes used in this example are shown in Table 1. The work-zone capacities, which correspond to the average values observed by Dudek and Richards *(16)*, are as follows:

TABLE 1 DIRECTIONAL HOURLY VOLUMES FOR EXAMPLE PROBLEM

Military Time (begin - end)	Approach Volume (vph)	Military Time (begin - end)	Approach Volume (vph)
0 - 1	340	12 - 13	2200
1 - 2	230	13 - 14	2230
2 - 3	240	14 - 15	2270
3 - 4	170	15 - 16	2330
4 - 5	320	16 - 17	2310
5 - 6	960	17 - 18	2480
6 - 7	4060	18 - 19	1920
7 - 8	4970	19 - 20	1630
8 - 9	3340	20 - 21	1220
9 - 10	2260	21 - 22	1100
10 - 11	2130	22 - 23	950
11 - 12	2130	23 - 24	590

Lane-Closure Configuration	*Work-Zone Capacity (vph)*
One of three lanes closed	2,983
Two of four lanes closed	1,127

A maximum acceptable delay to motorists of 20 min is specified as the criterion for determining acceptable lane-closure schedules. The model output identifying acceptable schedules in military time for each lane-closure configuration is presented in Table 2. The model also provides as output a matrix of estimated average queue lengths by hour of the day for each lane-closure configuration.

The results presented in Table 2 suggest that it would be acceptable to close one of three lanes either before 7:00 a.m. or after 8:00 a.m. A closure beginning at 7:00 a.m. could remain in effect only 1 hr, after which delays to motorists would exceed the 20-min criterion. Two of three lanes could be closed for more than 1 hr only before 6:00 a.m. and after 7:00 p.m. (hour 19 in military time). Delays to motorists would exceed 20 min in less than an hour if two of three lanes were closed at any other time.

The queue-length estimates for the lane-closure scheduling option are based on the assumption that none of the approach volume diverts from the freeway in response to the presence of the work zone. This assumption is appropriate for predicting whether a lane closure during a particular hour would have an unacceptable impact on the traveling public. However, the queue lengths that are predicted may be longer than would actually be observed if some traffic does divert. Therefore, diverting traffic must be taken into account to provide more accurate predictions of traffic patterns and additional costs to motorists.

Algorithm to Estimate Diverting Traffic

As shown in Figure 1, the diversion algorithm is used with the output option that provides road-user cost estimates.

Most urban freeways in Texas have parallel frontage roads. When queues develop upstream of a work zone on the main lanes of the freeway, some proportion of the approaching traffic may choose to divert to the frontage road or to another alternative parallel route, even though the traffic control for the work zone neither encourages nor requires them to do so. Such diversion is termed "natural diversion." When it occurs, the actual traffic volumes through the work zone are less than normal approach volumes. Therefore, queue lengths based on normal approach volumes overstate the queue lengths that are actually observed.

Very little quantitative data exist either on the proportion of traffic that "naturally" diverts or on the roadway or traffic conditions, or both, that influence the volume of diverting traffic. Research to address these questions is under way. However, as an interim approach to be used until additional data are collected, an algorithm that makes use of currently available data has been developed and is presented here for consideration of its theoretical approach.

One would expect diversion to occur when motorists perceive *(a)* that the delays they would experience by remaining on the freeway would be greater than they are willing to

TABLE 2 ACCEPTABLE LANE-CLOSURE SCHEDULES FOR ALTERNATIVE WORK-ZONE CONFIGURATIONS

	Hour of Maximum Lane Closure[a] by Closure Configuration	
Work Starting Hour	One of Three Lanes	Two of Three Lanes
0	7	6
1	7	6
2	7	6
3	7	6
4	7	6
5	7	6
6	7	6
7	8	7
8	24	8
9	24	9
10	24	10
11	24	11
12	24	12
13	24	13
14	24	14
15	24	15
16	24	16
17	24	17
18	24	18
19	24	20
20	24	24
21	24	24
22	24	24
23	24	24

[a]If work continues beyond this hour, the delay through the work zone will exceed 20 min.

tolerate and *(b)* that the travel time they would experience on an alternative route would be less than that on the freeway. The algorithm that has been incorporated into the cost-estimating option of QUEWZ assumes that diversion will occur so that no motorist experiences delays greater than some maximum acceptable level. This level may be specified as 20 min, which has been suggested by some researchers *(19, 20, 22, 23)*, or as another value. For freeway corridors where frontage roads or other alternative parallel routes are not available—and therefore diversion is unlikely to occur regardless of the magnitude of delay—the user may specify a large value for maximum acceptable delay (up to 99 min) to ensure that the model will not divert any traffic.

The first step in the diversion algorithm is to determine the critical length of queue at which delays to the last vehicle in the queue would equal the maximum acceptable delay. Then queue lengths that are estimated assuming that no traffic diverts are compared with this critical queue length. If queues do not exceed the critical length, it is assumed that no traffic diverts. If, in the absence of diversion, queue lengths exceed the critical queue length, it is assumed that enough traffic will divert so that queues never exceed the critical length.

The additional costs for diverting traffic are estimated by assuming that *(a)* the length of diversion equals the length of the work zone plus the critical length of queue, *(b)* the travel time for diverting traffic equals the time for a vehicle at the end of the critical queue to travel through the queue and the work zone, *(c)* the diverting traffic maintains a uniform speed equal to the length of the diversion divided by the travel time, and *(d)* trucks do not divert. The additional costs for diverting traffic are included in the total additional costs to road users that would result from the lane closure.

The algorithm produces queue-length estimates that more accurately reflect the queue lengths observed when diversion occurs and therefore is deemed an acceptable interim approach. When sufficient results from the current research concerning natural diversion become available, the assumptions in the algorithm will be evaluated and the algorithm will be refined to more accurately reflect the range of factors that influence under what conditions and to what extent natural diversion occurs.

The algorithm to estimate diverting traffic is used in conjunction with the cost-estimating option. The output provided by this option is illustrated by an example. A typical application of QUEWZ would be, first, to evaluate alternative lane-closure configurations on a freeway segment by using the lane-closure scheduling option and then to analyze in more detail a specific lane-closure configuration and schedule by using the cost-estimating option.

Suppose that on the freeway segment described in the previous example it was necessary to close one lane for 9 hr. Table 2 indicates that it would be acceptable to close one lane from 8:00 a.m. to 5:00 p.m. An analysis of this lane-closure schedule and configuration using the cost-estimating option yields the results in Table 3. The criterion specified for diverting traffic was a 20-min delay to motorists. The output provides hourly estimates for the volume and capacity through the work zone, the normal approach speed to the work zone, the average speed through the work zone, the average length of queue preceding the work zone, and the additional user costs. A comparison of the volumes through the work zone in Table 3 with the normal approach volumes in Table 1 indicates that no traffic diverts from the freeway. This result should be expected because a schedule was selected so that delays would not exceed 20 min. The estimated total additional daily user costs due to the lane closure are approximately $6,300.

CONCLUSIONS

QUEWZ is a computer model that has proved to be a useful tool for freeway work-zone planning and scheduling. A recent enhancement to the model has increased the utility of the model in identifying acceptable schedules for alternative lane-closure configurations. Another enhancement, the addition of an algorithm to account for the natural diversion of traffic away from the work zone, has improved the accuracy of the model's estimates of queue lengths at sites where natural diversion occurs.

In its present form, QUEWZ has two analysis options. The lane-closure scheduling option identifies acceptable schedules for all possible lane-closure configurations on a freeway segment based on a motorist-specified maximum acceptable length of queue or maximum acceptable delay. The second option provides estimates on an hourly basis of the additional road user costs that would result from a user-defined lane-closure configuration and schedule. The user cost-estimating option employs an algorithm that estimates the magnitude of diverting traffic based on the assumption that traffic will divert so that delays to motorists never exceed a user-specified maximum value. The additional costs to the diverting traffic are computed and included in the total additional road user costs that would result from the lane closure.

TABLE 3 SUMMARY OF ROAD USER COSTS

Military Time (begin - end)	Approach Volume (vph)	Work Zone Capacity (vph)	Approach Speed (mph)	Work Zone Speed (mph)	Queue Length (mi)	Additional User Costs ($)
8 - 9	3340	2983	52	30	0.5	3434
9 - 10	2260	2983	54	39	0.5	1500
10 - 11	2130	2983	55	49	0.0	164
11 - 12	2130	2983	55	49	0.0	164
12 - 13	2200	2983	54	49	0.0	181
13 - 14	2230	2983	54	49	0.0	189
14 - 15	2270	2983	54	48	0.0	201
15 - 16	2330	2983	54	48	0.0	218
16 - 17	2310	2983	54	48	0.0	212
Total Additional Daily User Costs Due to Lane Closure						6263

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