Modification of QUEWZ Model To Estimate Fuel Costs and Tailpipe Emissions

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Traffic congestion created by urban highway construction and rehabilitation activity imposes substantial cost burdens on highway users. In their attempts to quantify and predict such costs, transportation planners have customarily relied on computer models that focus principally on vehicle operating cost and time delay increases. Increasingly, however, planners are recognizing that highway users themselves can inflate system costs—particularly those costs associated with increases in tailpipe emissions. Thus, the challenge to highway planners is to model these effects so that a full range of cost effects can be used at the planning stages of a traffic engineering project. The preliminary results of a study undertaken to modify an existing work zone model—QUEWZ—to report net increases in energy and tailpipe pollution associated with various traffic-handling scenarios within construction zones are given.

Researchers have determined that net vehicle pollution tends to increase when vehicles travel at slower speeds (*1*), and recent research (*2,3*) has underscored the significance of this pollution problem in construction work zones, in which vehicle slowdowns and the concomitant congestion inevitably result from that construction activity. However, there are now strategies and technical solutions to mitigate the adverse effects of rehabilitation and reconstruction work. Because these strategies and solutions generally are more expensive, it is crucial when such options are being evaluated that the extra costs of the mitigation strategies be weighed against their social benefits, including those accruing to highway users. Increasingly, these costs must include pollution effects in construction work zones.

Work zone models were first developed using time delay as the main decision-making criterion (*4*). Currently, several manual and computerized procedures are available to evaluate the effects of work zone closures on traffic. In the United States there is a comprehensive, manual work zone evaluation procedure (*5*) that selects the most appropriate traffic control strategy for a particular maintenance task. Other manuals include a user guide on planning and scheduling (*6*), which evaluates the effects on the basis of accidents, vehicle stops and delays, vehicle operating costs, and fuel consumption. Another evaluation procedure is the 1985 *Highway Capacity Manual* (*7*), which provides estimates of work zone capacity and procedures for estimating queue lengths and delays using input-output analysis.

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Some of these assessment routines are available on microcomputers. For example, additional user costs (time and vehicle operation) associated with lane closures can be predicted using Queue and User cost Evaluation at Work Zones or QUEWZ (*8*). And a number of computer programs, including DELAY (*9*), FREWAY (*10*), and FREQ10PC (*11*), are able to evaluate freeway work zone lane closures.

Another program, Computer-Assisted Reconstruction–Highway Operations and Planning, or CARHOP (*12*), can model traffic disruption caused by maintenance projects. Although several comprehensive computer programs, such as FREECON (*13*), were developed to analyze work zones on freeways, few models have been developed to analyze the arterial system with the work zone as an overall comprehensive unit. One model, Work Zone Analysis Tool for the Arterial or WZATA (*14,15*), analyzes and evaluates the system consisting of the lane closure between two signalized intersections.

Evaluating these planning tools, we decided that QUEWZ best met the objectives of our research. Accordingly, we decided to modify the model, first to report fuel as a separate user cost element, and then to report tailpipe emissions. To differentiate between the two models, the new version was termed QUEWZ-E.

QUEWZ-E MODEL

The original QUEWZ model is a comprehensive evaluation tool that estimates vehicle operating and time delay costs, reporting the former as a total cost figure. Two general configurations of work zone lane closures are incorporated into QUEWZ. The first configuration models situations in which one or more lanes are closed in one direction, whereas the traffic moving in the opposite direction is not affected. The second configuration models crossover strategy, in which all lanes in one direction are closed and two-lane, two-way traffic is maintained in the other direction. A maximum of six lanes in each direction can be handled in the model.

In modifying the existing program, we first altered the vehicle operating costs subroutine in the personal computer version of QUEWZ to report energy consumption. Specifically, operating costs were disaggregated so that fuel and oil could be reported separately from total operating costs. This required reference to, and use of, research findings published by the

Texas Research and Development Foundation (*16,17*). Figure 1 illustrates the input and output for the new QUEWZ-E program.

Although the task of reporting fuel consumption was simple, that associated with predicting emissions was complex. The remainder of the paper therefore describes both the methodology developed for this process and the sources of data used to predict emission levels. The model calculates and reports the additional emission levels by first predicting free-flow pollution and then using that figure as a base case, comparing that level with the pollution from the various traffic-handling schemes. The model then reports the difference between the predicted and actual emission levels.

WORK ZONE MOBILE SOURCE EMISSION PREDICTION

The emission prediction function in QUEWZ-E uses a four-step process. Recognizing that traffic behavior varies according to the location being modeled, the first step involves characterizing the traffic where emissions are to be evaluated. For example, if emissions from free-flowing traffic on a highway are required, the key variable will be vehicle speeds and flow. These speeds can be used with an emission model that predicts the emissions of a vehicle cruising at a given speed to determine the source strength. On the other hand, if it is necessary to compute emissions at an intersection, then information may be required on traffic signal phasing, queue lengths, delay times, acceleration and deceleration rates, or capacity.

The second step is the estimation of the source strength, which requires an emissions model to account for vehicle conditions and driving patterns existing in the zone of interest. Most emission rate analysis models (both freeway and intersection air quality models) are based on data obtained from two major studies on mobile source emissions administered by the Environmental Protection Agency (EPA), namely, the Modal Analysis Model (*18*) and the MOBILE series of models (*19–22*).

The third step in modeling mobile source pollution near a roadway uses the emission profile from Step 2 to model the dispersion of the emitted gases along, and in the vicinity of, the roadway. The dispersion of the emissions is dependent on several factors, including source strength, width of roadway, wind direction and speed, source height, and mixing height. The fourth step involves the calibration of the dispersion model using actual dispersion data collected from the site being modeled.

Because the scope of this study was limited to the determination of the source strength of work zone traffic emissions, we modeled the carbon monoxide, hydrocarbon, and nitrogen oxide emissions of passenger cars and trucks.

Traffic Analysis Model

The flow of traffic in the region of a work zone on a freeway is unique to the extent that it needs to be described by a combination of free-flowing traffic and stop-and-go traffic. When traffic volumes are not large enough to cause congestion and queueing, the traffic can be characterized entirely by the volume and speeds. When congestion occurs, additional information (such as queue lengths) is needed to characterize the traffic. Hence, a traffic model that is capable of comprehensively defining the work zone problem is required. In pursuing such a traffic model, we characterized traffic passing through a work zone in three ways, from the viewpoint of emission prediction (*23*):

- *Vehicles proceeding undelayed through the work zone*—When the capacity of the work zone is sufficiently greater than the demand, the vehicles passing through the work zone

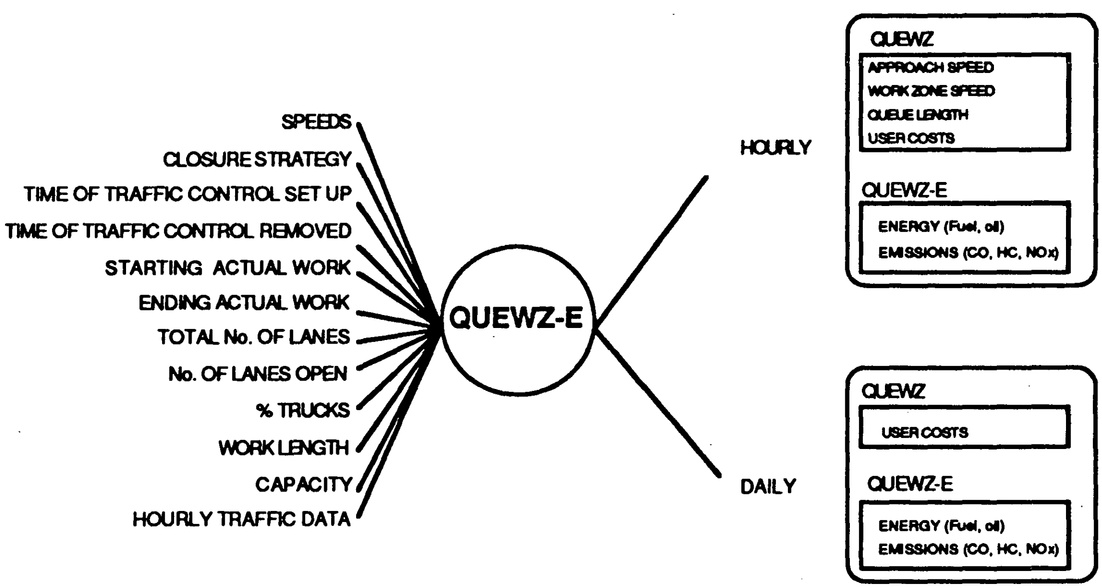

FIGURE 1 Input and output for QUEWZ-E program.

are processed without any delay. This scenario does not contribute toward excess emission levels.

• *Vehicles proceeding through the work zone at a reduced speed*—As the traffic demand at the work zone approaches the capacity of the work zone, the rate at which vehicles are processed through the work zone decreases, lowering the overall speeds of vehicles. This involves a deceleration from the approach speed to a minimum speed near the work zone, an acceleration to the work zone average speed from this minimum speed, travel at a lower average speed through the work zone, and an acceleration from the work zone speed to pre–work zone speed at the end of the work zone. The lower average speeds in the work zone might result in less pollution when compared with cases in which vehicles proceed unhindered at higher average speeds.

• *Vehicles stopping near the work zone because of queue formation*—When the traffic demand at the work zone exceeds the capacity of the work zone, queue formation takes place upstream of the work zone and involves a deceleration from the approach speed to idling at the end of the queue, short acceleration-deceleration movements (creeping motion) through the queue, acceleration to work zone speed at the beginning of the work zone, passage through the work zone at the average work zone speed, and acceleration to prework zone speed at the end of the work zone. The characteristics of this traffic behavior are illustrated in Figure 2. Because this scenario has the maximum impact in terms of excess emissions, an appropriate analysis is needed.

Excess vehicle emissions at a work zone are defined as the difference between the total emissions produced at and near the work zone minus those produced had traffic cruised unhindered through the work zone. These excess emissions can be determined as follows. The time spent by each vehicle in each mode of operation (accelerate, decelerate, cruise, queue) is first computed. The average emission rate for each mode and for each pollutant is then multiplied by the time spent in that mode to obtain the emission values. These emission values, when multiplied by the total number of vehicles in the analysis period, give the total mass of pollutants. The mass of pollutants generated if the vehicles were traveling over the affected length in the absence of the work zone is also computed. The difference between the two gives the required excess emissions of the given pollutant during the analysis period.

If the speeds at the beginning and end of the zones described in Figure 2 are known, the time spent by the vehicle in these zones can be calculated by assuming constant acceleration and deceleration rates for the vehicles. To provide information on speeds at and near the work zone, as well as the time spent

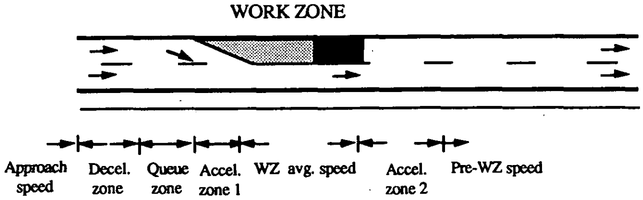

FIGURE 2 Traffic behavior near a work zone as a result of queue formation.

by vehicles in each zone, the traffic analysis model would require the following data:

1. Work zone capacity,
2. Speed-flow relationship,
3. Length of work zone,
4. Average length of queue,
5. Average vehicle speeds in queue,
6. Vehicle mix, and
7. Acceleration and deceleration rate of vehicles.

The QUEWZ work zone model (*24*) satisfies most of these data requirements, which led to its adoption over other, more complex models. The acceleration and deceleration rates of passenger cars and trucks, however, are not provided by the QUEWZ model. For the work zone emissions problem, the acceleration rates for passenger cars and trucks were assumed to be constant values of 4.5 and 1.6 ft/sec^2, respectively, and the deceleration rates were assumed to be constant values of 6.0 and 2.2 ft/sec^2, respectively, on the basis of values given previously (*25,26*).

Using the information on vehicle speeds provided by QUEWZ, the time spent by each vehicle in each mode can be determined using kinematics.

Modal Emission Rate Models

The pollution emission rates under various modes of operation (e.g., acceleration, cruise, deceleration, and idling) now need to be quantified so that the excess work zone emissions can be computed. And because the emission levels of pollutants vary widely with the mode of operation of the vehicle, modal emission rates are required to model air quality where there are wide variations in the traffic flow speeds.

In this context, the unusually high levels of pollution associated with high traffic volume at urban intersections has led highway planners to focus on modeling air quality specifically at intersections. Accordingly, various approaches have been used to obtain the modal emission rates of vehicles. One approach has been to use modal emissions from the Modal Analysis Model and to correct this using the ratio of the results from the MOBILE model for actual and base scenarios. The base scenario is for conditions used in the modal model, namely, a 1977 calendar year, a light-duty vehicle fleet, 100 percent hot stabilized operating conditions, a temperature of 75°F, and the average speed of the user-defined driving sequence. The actual scenario is for the corresponding conditions in the calendar year being modeled.

This approach is used in the IMM (*27*) and the TEXIN2 (*28*) models. The main problem associated with this strategy is that for every speed at which modal emissions are required, the MOBILE model must be run for the base and actual scenarios for that speed. This implies that the MOBILE model should be merged with the traffic analysis model, which in the present context is the QUEWZ model. If this operation is performed, the work zone model will grow cumbersome, will require more inputs, and will take a much longer time to run. Also, only a specific version of the MOBILE model can be coded into the work zone model. Frequent updates of the work zone emissions model will be required as the EPA updates the MOBILE model.

The second approach has been to use emission rates from the MOBILE model and to correct them using modal correction factors. These correction factors have been derived using limited sets of emissions data from the SDS and FTP driving cycle tests (*29*). The correction factors are usually functions of the vehicle speed and acceleration. This approach has been used in the MICRO2 (*30*) and CALINE4 (*31*) models.

The CALINE4, TEXIN2, and IMM programs were developed exclusively for modeling carbon monoxide (CO) hot spots at intersections. The equations used for modeling modal CO emissions for the purpose of work zone emission prediction will follow closely those used in MICRO2 and CALINE4. The approach used in IMM and TEXIN2 is not used for reasons stated previously.

MICRO2 is the only program among these four that models hydrocarbons (HC) and nitrogen oxide (NOx) emissions. The modal HC and NOx emission models for the work zone problem will make use of the results from the MICRO2 model.

All the modal emission rate models in the CALINE4 and MICRO2 programs were developed using data from light-duty gasoline vehicles. However, the work zone model also requires modal emission rates for diesel trucks. If we assume that the behavior of diesel vehicles in various modes of operation is similar to that of gasoline vehicles, then the modal correction factors developed for passenger cars can be applied to the composite emissions from trucks to obtain the modal emission rates for trucks.

Modal CO Emission Rates

The MOBILE4.1 model (*22*), which is the recent update of the MOBILE series of models, provides idle emission factors for the hot stabilized mode of operation. Hot stabilized idle emissions have been included in the MOBILE models to facilitate quantification of emissions resulting from idling in queues. These idle emission factors are used for the idle emission rate model.

In the development of the CALINE4 model, an analysis of the data from the California Air Resources Board (CARB) study (*32*) showed that emission rates under deceleration were relatively constant over the 16 deceleration modes of the surveillance driving sequence (SDS) driving cycle. These rates were approximately 50 percent higher than the idle emission rates. This observation was found to be consistent with the practice of decelerating by gradually releasing the accelerator during a planned deceleration. Hence, deceleration mode emissions are assumed to be 1.5 times the idle mode emissions in the work zone emissions model.

The MICRO2 model assumes that emissions in the cruise mode are constant and equal to the idle emission rates. However, as a vehicle cruises at higher speeds, the CO emissions increase. The CALINE4 model uses a cruise correction factor to the MOBILE model scenario rate emissions, which was derived as follows.

SDS emissions test data for various idling, acceleration, cruise, and deceleration segments were given artificial time weightings to provide a simulated federal test procedure (FTP) stabilized mode sequence. Data from the cruise portion of the SDS testing cycle were then analyzed to develop correlations with the SDS simulation of the FTP stabilized mode emission rates. The dependent variable was the ratio of SDS to FTP (simulated using SDS) emission rate. The independent variable was cruise speed. The following relationship was obtained from this analysis:

$$\begin{aligned}&\text{cruise emission rate (g/hr)}\\&\quad = 16.2\,\text{mph MOBILE scenario rate}\\&\qquad \times (\text{g/mi}) * 16.2\,(\text{mph}) * (0.494 + 0.000227 * S^2) \qquad (1)\end{aligned}$$

where S is the cruise speed of the vehicle. This result is consistent with the fact that the drag force on a vehicle cruising at a speed S is proportional to the square of the speed, S^2. Hence, as the vehicle cruises at higher speeds, the higher drag force exerts a greater load on the engine, leading to increased CO emissions. This cruise emission model is used in the work zone emissions model.

The MICRO2 and CALINE4 models develop acceleration correction factors to the composite MOBILE emission value as a function of the product of acceleration and speed (AS). The product of acceleration and speed is equivalent to power per unit mass. Therefore, the power expended by a vehicle during acceleration is proportional to AS. As power demand approaches engine capacity, vehicles tend to burn fuel less efficiently, resulting in higher carbon monoxide emissions (*30*).

The acceleration model in MICRO2 was based on data from 45 light-duty, 1975 vehicles tested in Denver on the SDS cycle (*33*). Results were analyzed using a ratio of the time rate of modal emissions and the time rate of FTP emissions. Use of this ratio allowed the direct conversion of average route speed emission factors to modal emission rates. The acceleration model developed through this analysis was

$$\begin{aligned}&\text{acceleration emission rate (g/hr)}\\&\quad = \text{MOBILE scenario rate (g/mi)} * S\,(\text{mph})\\&\qquad * [0.182 - 0.00798(AS) + 0.000362 * (AS)^2] \qquad (2)\end{aligned}$$

with AS representing the product of the average acceleration and average speed for the acceleration event in units of ft²/sec³. This acceleration emission rate model is adopted for the work zone emissions model. Internally, the model assumes a constant AS value. For passenger cars this value is 97 ft^2/sec^3, representing an average acceleration of 4.5 ft/sec^2 from 0 to 30 mph. For each speed at which the acceleration emission rate is required, the MOBILE scenario rate needs to be determined for an average route speed equal to that speed. To circumvent this problem, an equivalent regression model was developed using MOBILE4.1 scenario rates for average route speeds from 2.5 to 65 mph. The acceleration and cruise emission rate models for CO for passenger cars are shown in Figure 3.

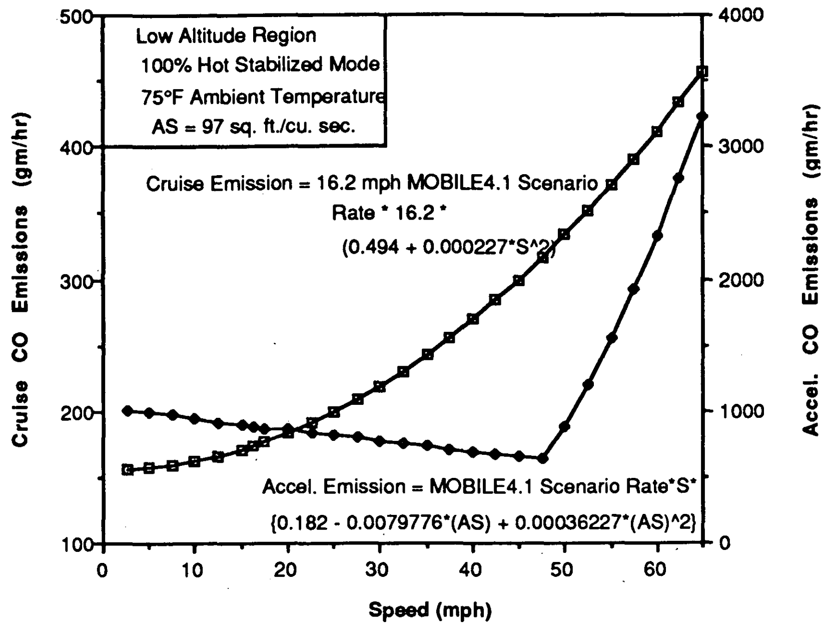

FIGURE 3 Plot of CO acceleration and cruise emission rate models for passenger cars.

Modal HC Emission Rates

As in the case for idle carbon monoxide emissions, hot stabilized idle hydrocarbon emissions can be obtained directly from the base scenario run of the MOBILE4.1 model. As in the MICRO2 model, the deceleration and cruise emission rates are assumed to be equal to the idle emission rate.

For emission of hydrocarbons under acceleration, the MICRO2 model applies correction factors to the composite MOBILE emission value as a function of AS. The hydrocarbon acceleration model in MICRO2, presented below, was developed in a manner similar to that described for carbon monoxide.

acceleration emission rate (g/hr)

$$= \text{MOBILE scenario rate (g/mi)} * S \text{ (mph)} * \{[0.018 + 5.266 \times 10^{-4}(AS)] + 6.1296 \times 10^{-6}(AS)^2\} \quad (3)$$

Modal NOx Emission Rate Models

As in the case for idle carbon monoxide and hydrocarbon emissions, hot stabilized idle nitrogen oxide emissions can be obtained directly from the base scenario run of the MOBILE4.1 model. The cruise emission rate is assumed to be equal to the idle emission rate, as in the MICRO2 model.

For emission of nitrogen oxides under deceleration, the MICRO2 model applies correction factors to the composite MOBILE emission value as a function of the deceleration-speed product ($-AS$). The resulting equation is presented here.

deceleration emission rate (g/hr)

$$= \text{MOBILE scenario rate (g/mi)} * S \text{ (mph)} * [0.00143 - 1.7005 \times 10^{-4}(-AS)] \quad (4)$$

The acceleration model for nitrogen oxide emissions uses results from the MICRO2 model, which applies correction factors to the composite MOBILE emission value as a function of AS. The resulting equation is

acceleration emission rate (g/hr)

$$= \text{MOBILE scenario rate (g/mi)} * S \text{ (mph)} * [0.00386 + 8.1446 \times 10^{-4}(AS)] \quad (5)$$

Default MOBILE4.1 Scenario Rates

The emission rate equations described in the previous sections apply modal correction factors to the composite emission rates from the MOBILE model to arrive at the modal emission rates. The composite emission rates used in the QUEWZ model were obtained from MOBILE4.1 (*22*), which is the latest update in the MOBILE series of models. To run the MOBILE4.1 model, reasonable assumptions have to be made regarding input variables that influence emissions so as to obtain a representation of the work zone problem. These assumptions constitute the default scenario used in the work zone emissions model, the main elements of which are the following:

- A low-altitude region is modeled,
- An ambient temperature of 75°F is used,
- All vehicles are assumed to be operating in a hot stabilized mode,
- No antitampering program is in effect,
- No inspection/maintenance program is in effect, and
- MOBILE4.1 default vehicle age distributions are used.

To model scenarios other than this default scenario, correction factors need to be applied to the emission rate equations used in the work zone model. Correction factors based solely on the ratio of idle emissions in the actual scenario being modeled to the idle emissions in the default scenario are used in the work zone emissions model.

QUEWZ-E Model

The methodologies and models described in the preceding sections were implemented in the QUEWZ program. The revised version of the QUEWZ model has been dubbed QUEWZ-E, indicating the additional capability of emission-value prediction. The only additional inputs needed by the program for emissions calculation are the hot stabilized idle emission rates of CO, HC, and NOx for passenger cars and trucks for the scenario being modeled.

The program gives an output of the CO, HC, and NOx emissions for each hour that the work zone is in operation. In addition, the program gives an output of the total daily excess emissions of these pollutants.

To test the model and to illustrate its use, eight sample work zone problems were analyzed. All the sample problems use an average daily traffic (ADT) of 25,000 vehicles in each direction of the freeway. The original number of lanes, the number of open lanes at the work zone, the work zone length, and the work zone activity period were the various parameters used in these sample problems. Table 1 summarizes and shows that queueing creates significant excess emissions in the work zone.

This model can be usefully applied when various work zone traffic management strategies are being evaluated. Say, for example, that a planner must choose between Problems 5 and 7. The QUEWZ-E model shows that the excess emissions caused by the closure of two lanes at the same time is more than double the excess emissions created by the closure of one lane at a time. In a similar manner, planners can compare various strategies to arrive at desirable work zone configurations and work schedules.

This model could also be applied when analyzing the work zone (and the elements affected by it) as a total system. Indeed, such a systems approach in the analysis of a work zone has been recently proposed (*34*). Given a major freeway or highway reconstruction or rehabilitation project, the analysis would take into account the agency costs, the business costs, the road user costs, the environmental costs, and costs to other parties (e.g., utility companies). The construction strategy that resulted in the lowest total system cost would then be selected. The results could also be used as leverage for construction strategies that make use of expediting techniques.

To illustrate the enormous impact imposed by work zones on freeways, we estimated the excess emissions at reconstruction and rehabilitation sites on the nation's deficient bridge infrastructure. Research conducted by Weissmann and Harrison (*35*) to predict user costs for similar purposes was used as the basis for this analysis. In their study, only bridges having high traffic levels were considered, defined by an ADT >20,000. The authors identified 524 deficient two-lane bridges, 297 deficient three-lane bridges, and 363 deficient four-lane bridges. Bridges with ADTs between 20,000 and 30,000 were assumed to be two lanes one way, with one lane closed during work. Bridges having ADTs between 30,000 and 45,000 were assumed to be three lanes one way, with two lanes closed and one lane of traffic from the bridge under construction being switched to run counterflow in the closed inside lane. Bridges with ADTs greater than 45,000 were assumed to be four lanes one way, with two lanes closed during work. The total user costs of reconstruction work on these bridges were calculated to be approximately $6 billion.

TABLE 1 Summary of Inputs to and Outputs from Test Problems

Prob. No.	No. of Lanes	No. of Open Lanes	WZ Length (mi)	Normal Capacity (vph)	Restricted WZ Capacity		Hours of Restr. Capacity		Hours of WZ Activity		Longest Queue (mi)	Total Emissions		
					Inactivity Hrs. (vph)	Activity Hrs. (vph)	Beg.	End	Beg.	End		CO (Kgs)	HC (Kgs)	NOx (Kgs)
1	2	1	1.0	4000	1800	1485	8	17	9	16	0.8	96.5	9.1	2.0
2	2	1	2.0	4000	1800	1485	8	17	9	16	0.8	101.7	11.7	2.6
3	2	1	1.0	4000	1800	1485	0	24	9	16	2.2	449.1	42.3	9.6
4	2	1	2.0	4000	1800	1485	0	24	9	16	2.2	464.5	48.5	11.1
5	3	2	1.0	6000	3600	2970	8	17	9	16	0.0	6.7	0.2	0.0
6	3	2	2.0	6000	3600	2970	8	17	9	16	0.0	6.4	0.4	0.1
7	3	1	1.0	6000	1800	1250	8	17	9	16	1.6	449.2	42.6	9.7
8	3	1	2.0	6000	1800	1250	8	17	9	16	1.6	459.1	46.9	10.8

TABLE 2 Predicted Emissions Using QUEWZ-E Model

ADT	No. of Lanes[1]	No. of Def. Bridges	CO/day/ Bridge (kgs)	HC/day/Bridge (kgs)	NOx/day/Bridge (kgs)	Total[2] CO Em. (tons)	Total[2] HC Em. (tons)	Total[2] NOx Em. (tons)
> 20,000 < 30,000	2	524	70.6	6.4	1.4	11098.32	1006.08	220.08
> 30,000 < 45,000	3[3]	297	41.8	2.0	0.4	3724.38	178.20	35.64
> 45,000	4	363	493.3	46.6	10.9	53720.37	5074.74	1187.01
Totals		1184				68543.07	6259.02	1442.73

[1] One lane closed for two-lane capacity, two lanes for four-lane capacity.
[2] Total Emissions assume a 300-day contract cycle per structure.
[3] Construction first rehabilitates two lanes, then the third. Two lanes always open to traffic. When only one lane is open, the matching bridge is opened to diverted traffic and both bridges are reduced to two-lane travel.

We then performed a similar analysis for the emission of CO, HC, and NOx. Applying QUEWZ-E to these bridge scenarios, we found that the predicted CO emissions totaled 68,543 tons, HC emissions totaled 6,259 tons, and NOx emissions totaled 1,443 tons, as shown in Table 2. Like the estimates of user costs, these emissions figures are conservative; that is, they relate only to a subset of the rural bridge population and use a truck ADT of only 14 percent, which is lower than most Interstate values. Thus, the results presented above give an indication of the magnitude of the emissions problem at work zones.

CONCLUSIONS

This paper has described the development of QUEWZ-E, a computer model used to predict excess energy consumption and excess mobile source emissions at freeway work zones. Given the characteristics of the work zone (e.g., configuration, schedules), the characteristics of traffic at the work zone (e.g., volume, percent trucks), and the emissions characteristics of vehicles in the area, the model is capable of providing the excess emission values for two vehicle types and three pollutant types. Thus, QUEWZ-E can be used for comparing work zone construction and traffic management strategies specifically in terms of air pollution, with the results from the model then used for expedited construction strategies that reduce air pollution.

There are still a few shortcomings. The model as structured currently does not take into account the diversion of traffic away from the work zone that results when long queues form. Further research is needed to quantify the nature of this traffic diversion.

Also, the lack of validated models characterizing modal emissions tends to handicap the present study. But as new data and modal emission rate models become available, the QUEWZ-E model can be easily updated to incorporate the new findings.

We should also note that the increase in truck traffic on freeways has resulted in an increase in particulate emissions. The nature of these emissions, as well as their quantification by mode of operation, needs to be explored in greater detail.

Nonetheless, the study shows that even when conservatively estimated, emission levels at work zones represent a substantial problem and cost burden. The QUEWZ-E model can be useful in identifying the construction strategy that most effectively reduces emission levels.

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