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QUEWZ Work Zone Software

QUEWZ Work Zone Software: Methodology and Literature Review

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16. ABSTRACT

This report documents the results of a literature review and methodological analysis into the design and technical basis of the QUEWZ work zone road user cost estimation software tool. The report documents how key formulas/algorithms within the QUEWZ software were derived, describes ways that QUEWZ could be updated, and summarizes the literature regarding comparisons of QUEWZ with other tools used to evaluate work zone road user costs.

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1. Introduction

This technical paper documents the results of a literature review and formula analyses regarding the QUEWZ work zone road user cost estimation software tool. The goal of this project was to provide WSDOT staff with the information to better understand how key steps in the QUEWZ tool are computed, and to provide additional documentation regarding the overall QUEWZ methodology. The results can also be used to help determine if and how WSDOT staff can potentially tune/update the WSDOT tool to produce more current and/or project-specific estimates of road user costs associated with freeway work zone delays. This technical paper also provides information regarding comparisons between QUEWZ and other tools.

The project consisted of the following activities:

a) Collect information about computation methods used by QUEWZ;
b) Note if selected QUEWZ formulas are used in standard references such as the Highway Capacity Manual, and determine how the formulas were derived, if possible;
c) Evaluate the feasibility of updating QUEWZ to enhance its usefulness for WSDOT, and
d) Summarize the literature regarding comparisons of QUEWZ with other tools.

2. Overall QUEWZ Methodology

The QUEWZ work zone software tool estimates the overall cost to freeway users as a result of the introduction of a work zone, by estimating the additional user costs related to specific types of work zone effects, and then summing those individual effects. Those effects are primarily related to reduced capacity in a work zone, which in turn affects vehicle speeds in the work zone. The travel time delays that result from reduced work zone speeds are converted to a monetary cost, and those individual monetary estimates are then summed.

QUEWZ estimates costs for three segments of a freeway work zone:

- **The work zone** itself (a freeway segment with reduced capacity due to lane closures)
- **Speed-change areas** where vehicles decelerate to and accelerate from the work zone
- A **queueing area** upstream from the work zone, where vehicles queue when incoming traffic demand exceeds the work zone's capacity

Each of these segments contributes different cost components to the overall user cost, as follows:

Work zone:

Component 1. A cost to the user that reflects the additional time required to travel through the work zone

Component 2. A vehicle operating cost (running cost) that reflects the additional time required to travel through the work zone

Speed-change:

Component 3. A cost to the user that reflects the additional time required to decelerate when approaching the work zone and accelerate from the transition zone

Component 4. A vehicle operating cost (running cost) that reflects the additional time required to decelerate when approaching the work zone and accelerate from the transition zone

Queueing area:

Component 5. A cost to the user that reflects the additional time required to travel through the queue

Component 6. A vehicle operating cost (running cost) that reflects the additional time required to travel through the queue

Component 7. A cost that reflects the additional delay from stop-and-go actions while in the queue

After each of the above costs are estimated, those costs are then summed:

Total hourly per-user cost related to the work zone =

work zone delay user cost
+ work zone delay vehicle operating cost
+ speed-change delay user cost

+ speed-change delay vehicle operating cost
+ queue delay user cost
+ queue delay vehicle operating cost
+ queue delay stop-and-go cost

User costs are then scaled by the number of vehicles that traverse the work zone. All costs are computed relative to a baseline condition where the work zone does not exist.

3. Discussion of Selected QUEWZ Formulas

WSDOT staff identified selected formulas of interest that are used by six of the seven cost components listed above, and requested additional research to better understand how the selected formulas were developed, and when possible to document if they are considered part of traffic engineering standards or referenced in the technical literature. WSDOT staff also requested suggestions for updating the QUEWZ tool; potential updates and other activities are discussed in Section 4 of this document.

The QUEWZ formulas of interest to WSDOT staff are as follows (component numbering and variable names are based on WSDOT notes and QUEWZ documentation).

a) Average speed calculation SP

b) Minimum speed SP_{mn}

c) Component 1 (CDWZ) calculations: The effective length of the work zone closure (CLL)

d) Component 2 (OC) calculations: Estimated vehicle operating costs f(s) and g(s) (for cars and trucks respectively) as a function of speed

e) Component 3 (CDSC) calculations: Estimated distance of the speed change cycle (DSC), i.e., the distance traveled during the deceleration before and acceleration after the work zone

f) Component 4 (CSPC) calculations: Estimated vehicle operating costs SPCC and SPCT (for cars and trucks respectively) as a function of speed change due to deceleration before and acceleration after the work zone

g) Component 6 (OSC) calculations: Estimated average speed in a queue (SP_q)

h) Component 7 (CSPQ) calculations: Estimated cost of stop and go speed changes within a queue (CSPQ)

The following is a discussion of each of the QUEWZ formulas of interest noted above. For each formula, a brief definition is given, followed by a description of the equation(s). Supporting reference documents are then noted, as well as the method used to develop the formula (if known). This is followed by a discussion of notable points, issues, or unresolved questions related to the formula. Each formula discussion is accompanied by a graph of the formula; the graph was used to a) provide a visual reference for interpreting the general qualitative meaning of the formula, and b) help provide a "reality check" that the formula appears to be intuitively logical in terms of the function shape and magnitude. (Likely typographical errors were detected in two of the equations, as a result of reviewing the graphs.)

All of the following formulas were initially documented in an early Texas Transportation Institute (TTI) research document describing the QUEWZ model (Memmott and Dudek 1982), as well as a Transportation Research Record paper (Memmott and Dudek 1984). While these documents refer to an early version of QUEWZ, it is believed that they also represent essential features of the QUEWZ 85 PC version as well. Supplementary documents of interest for each formula are discussed in the "Supporting References" and "Discussion" sections for each formula.

Please note that while the focus of the discussion is on equations used in QUEWZ 85, subsequent PC versions QUEWZ 92 and QUEWZ 98 will also be discussed if information exists about formula changes in those versions.

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a) Average Speed (SP)

Definition and Use. QUEWZ estimates average vehicle freeway speed SP to help determine the effect of work zone activity on travel times and travel delay.

Equation. There are two types of equations that are used in the computation of average speed. First, there is the **speed formula** itself. The key input to the speed formula is the vehicle volume; more specifically, volume is converted to a volume/capacity ratio, which is the input to the speed formula. The v/c estimate requires an estimate of the denominator, the maximum roadway vehicle capacity. Therefore, QUEWZ uses a second formula to compute estimated **freeway capacity**. The following is a discussion of each of these two formulas.

Speed

The general speed estimation formula was based on an approximate relationship between volume and speed described in the Highway Capacity Manual (HRB 1965) and shown graphically in Figure 1. The relationship is defined by the following input parameters: the **freeflow speed**, the estimated **speed and volume at a breakpoint** between Level of Service (LOS) D and E, and the estimated **speed and volume at roadway capacity**.

The graphical relationship shown in Figure 1 was then converted to a mathematical form that can be used in the QUEWZ methodology; specifically, a linear approximation is used to estimate speeds for volumes from 0 to the LOS D/E breakpoint, and a second, non-linear, relationship is used for volumes greater than the breakpoint up to the normal capacity of the roadway. Volumes above the normal roadway capacity use a third formula based on a linear approximation that is capped at the upper limit by the capacity speed, with a lower floor limit at a fixed speed:

$$If\ (V_2/V_1) \geq V/C,\ then$$

$$SP = SP_1 + \frac{V_1(SP_2 - SP_1)}{V_2}(V/C)$$

$$If\ (V_2/V_1) \leq V/C \leq 1,\ then$$

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

$If\ (V_2/V_1) > 1$ or a queue is present, *then*

$SP = SP_3(2 - V/C),$ with the speed constrained to the following range

$$20 \leq SP \leq SP_3$$

where

V_1=volume at capacity
V_2=LOS D/E breakpoint volume
V/C= volume/capacity ratio
SP_1=freeflow speed
SP_2=LOS D/E breakpoint speed
SP_3= speed at capacity

QUEWZ uses the same average speed formula for work zone and non-work zone conditions. QUEWZ developers cited previous research that the same general formula could be used for speeds within a work zone and speeds outside of a work zone (Memmott and Dudek 1982). Figure 2 show a graph of the formula ("Revised SP").

Note: The speed-flow formula shown in the original TTI reference from 1982 and the TRR paper from 1984 both show the formula as being of the form

Speed = (LOS D/E breakpoint speed) + (…)

i.e.,

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

However, when this formula was reviewed, it was discovered that the formula as written produces a discontinuity of the speed function at the LOS D/E breakpoint. It appears that the two documents noted above had the same typographical error in the speed formula; replacement with a formula of the form

Speed = (normal roadway capacity speed) + (…)

i.e.,

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

removes the discontinuity. Figure 2 compares the results of these two forms. Support for this change was found in the original source code for the QUEWZ model, from which it is believed the QUEWZ 85 model was derived (Memmott and Dudek 1982, Copeland 1998), and was also noted in the documentation for a variant of the QUEWZ model, QUEWZEE, that was developed in 1993 to add work zone mobile source emissions effects (Seshadri and Harrison 1993).

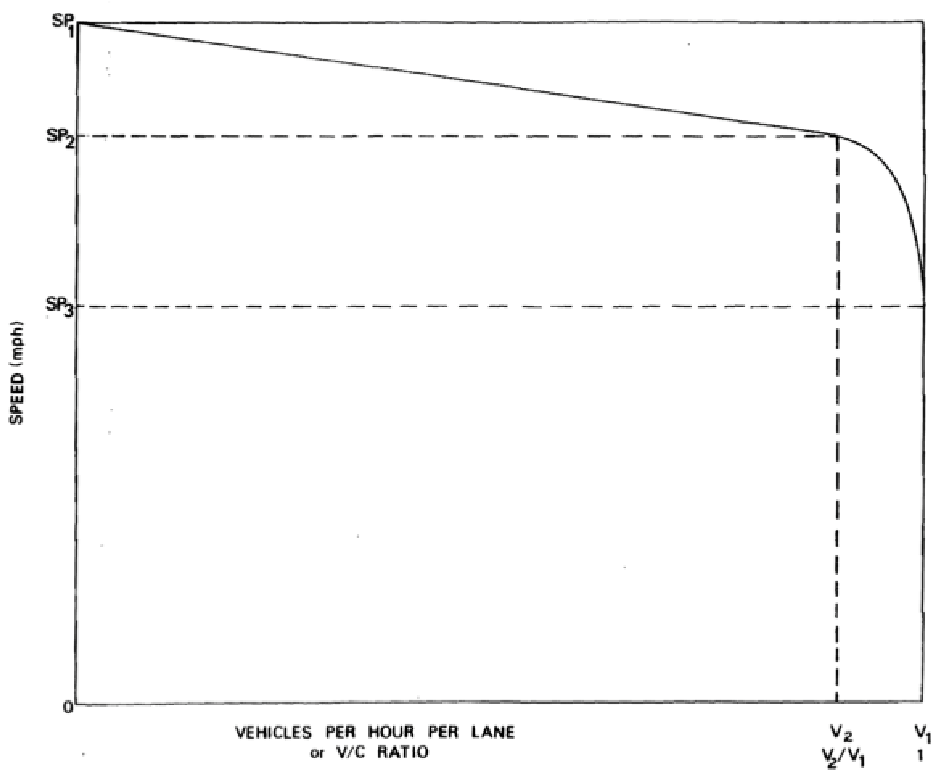

Figure 1. Basic HCM speed-flow relationship (from Memmott and Dudek 1982)

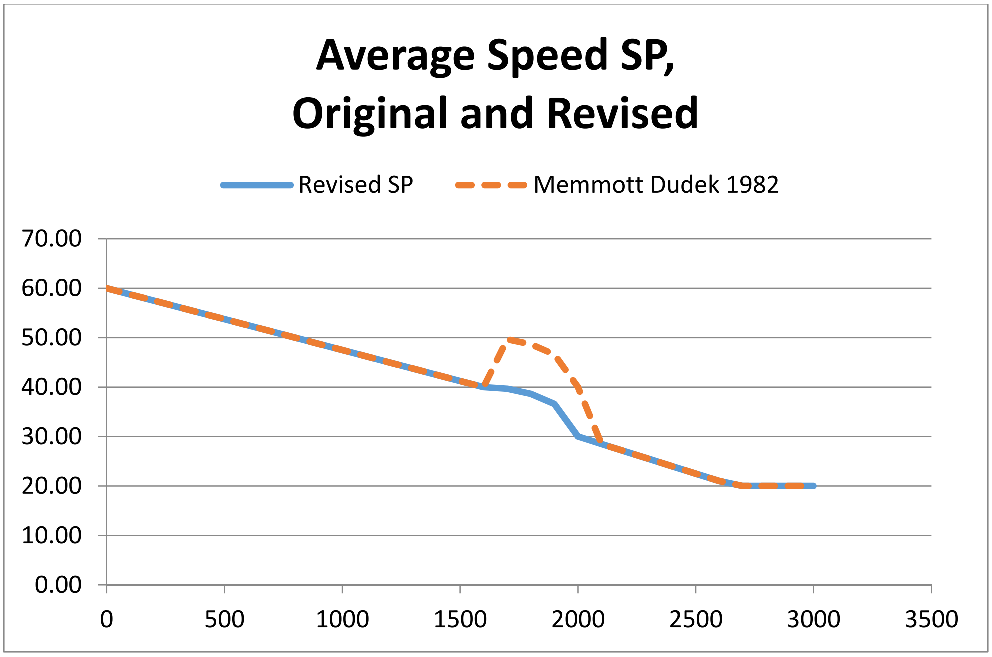

Figure 2. QUEWZ speed-flow relationship, based on two sources

Capacity

For the freeway capacity, QUEWZ uses different methods based on different work zone conditions. The default capacity used for normal conditions without a work zone is 2000 vehicles per hour per lane (vphpl). If a work zone exists, QUEWZ distinguishes between active and non-active work zones; when no work is actively being performed, work zone capacity is set at 1800 vphpl, or 90 percent of normal non-work zone per-lane capacity. For active work zones, the capacity estimation method uses linear approximations of field data, based on the work zone configuration (the total number of lanes vs. the number of open lanes). (For example, the (3,1) configuration indicates that there are 3 lanes total, with 1 lane open to traffic.) For a given work zone configuration, the capacity formula is described as a cumulative distribution function that shows the percentage of data points that are less than or equal to a particular capacity value. Figure 3 shows the results for specific configurations.

The linear approximations for each configuration are of the form

$$\text{Capacity} = a - (b*\text{CERF})$$

where a and b are parameters that vary by configuration, and CERF is the user-specified "capacity estimate risk factor" that the user could use to specify the probability that the estimated work zone capacity will be less than or equal to the actual capacity based on the field data (this can be used to indicate how conservative the estimate should be).

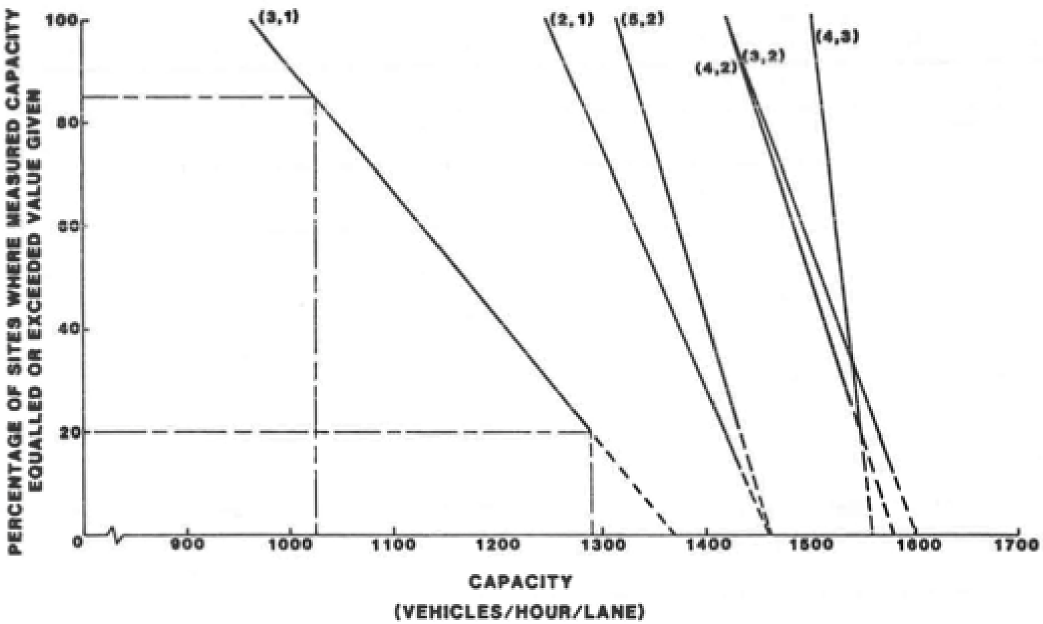

Figure 3. Cumulative distributions of work zone capacity data (from Memmott and Dudek 1982)

Supporting References and Formula Derivation. The following is a discussion of the references and derivation for the speed and capacity formulas.

<u>Speed</u>

The speed formulas used by QUEWZ were originally developed as part of work on the Highway Economic Evaluation Model (HEEM), according to the 1982 TTI description by Memmott and Dudek. HEEM is a cost-benefit evaluation model that was originally developed by McKinsey and Company Inc. as part of a Caltrans study, and was later used by the Texas State Department of Highways and Public Transportation for evaluations of highway improvements (Memmott and Buffington 1983).

Although the original HEEM reference noted by Memmott and Dudek was not available from the most likely resources (the Texas DOT library system, TTI library, or the UW library system), a companion document produced by Caltrans shed some light on the derivation of the speed formula (Caltrans 1973). Specifically, the speed formulas noted above were based on a general speed-volume relationship described in the 1965 HCM. The combined linear and non-linear formula was then developed for use in HEEM using data collected by Caltrans District 07, with the exact form of the non-linear element of the formula developed using a software model developed at CalTrans. Specifics about the exact process by which the non-linear component was developed have not been located (Caltrans 1973).

There are some differences in the literature regarding the speed formula used in the three PC versions of QUEWZ (85, 92, and 98). The formula noted above was based on a description in the original TTI document from Memmott and Dudek. However, that 1982 document is believed to have described the method used by an earlier version of QUEWZ. The QUEWZ 85 version was described as being "similar to (but not an exact replication of) QUEWZ" (Copeland 1998). A subsequent description specifically of QUEWZ 85 by Krammes, Marsden, and Dudek (1987) notes that the speed formula uses the idealized speed-volume curve described in the original TTI document, with a linear relationship for volumes below the LOS D/E breakpoint. However, the QUEWZ 85 speed formula is described as having a quadratic relationship for volumes greater than the LOS D/E breakpoint and less than capacity, while the formula shown in the original TTI document does not have the usual features of a quadratic relationship (second order polynomial form). The two subsequent software versions, QUEWZ 92 and 98, are both described as using the same quadratic form of speed formula (though the definition of the breakpoint speed and volume used to describe the idealized speed-flow curve is slightly different from the values used in the early version of QUEWZ). The manuals for QUEWZ 92 and 98 both mention updates to speed-volume parameters based on the most recent version of the Highway Capacity Manual.

<u>Capacity</u>

As noted above, the QUEWZ 85 work zone vehicle capacity method is based on field data that have been converted to formulas using linear approximations, based on the work zone configuration. The field data were collected at 41 work sites on urban freeways in Houston and Dallas TX in the 1970s and early 1980s (Dudek and Richards 1981, Krammes and Lopez 1992). This research was considered among the most up-to-date capacity estimation processes at that time, and was included in the 1985 Highway Capacity Manual, as well as subsequent minor revised editions (TRB 1985, Seshadri and Harrison 1993). Edara and Cottrell (2007) noted the regional limitations and age of the field data, as well as subsequent research that suggested the method underestimates capacity values for short-term freeway work zones for some configurations.

In the 1992 version of QUEWZ, the capacity method was significantly revised from the method described above, reflecting newer field data, a revised field data collection process designed to produce values that were consistent with the QUEWZ approach, and a revised formula format (Krammes and Lopez 1992). Unlike the parametric family of linear approximations used in QUEWZ 85, the revised method estimated work zone capacity by starting with a single base work zone capacity value, then applying a series of adjustment factors to that value to account for the nature of the work zone activity, the presence of ramps, the number of heavy vehicles (e.g., trucks), and the number of lanes that were open in the work zone. The general form of the capacity equation is

$$c = (1600 \text{ pcphpl} + I - R) * H * N$$

where

c = estimated work zone capacity (vph)
I = adjustment for intensity of work activity
R = adjustment for ramp presence
H = adjustment for number of heavy vehicles (trucks)
N = number of open lanes in the work zone

These adjustment values were based on the updated field data results, as well as values documented in the 1985 HCM. In some cases, however, there are only general guidelines for selecting the adjustment values (e.g., "intensity" of work activity). The QUEWZ 92 method for capacity estimation was also used in QUEWZ 98 (Krammes et al. 1993, Copeland 1998). This method was also documented in the 2000 edition of the HCM (Edara and Cottrell 2007).

Discussion. Nearly every component of QUEWZ's road user cost computation relies on estimating travel time changes, and therefore the speed formula and capacity formula play key roles in that estimate. Since 1998, when the most recent PC version of QUEWZ was produced, there has been significant national research to refine both the speed-flow formula and the capacity estimation formula, and there are now recent, well-documented methods that can be considered as alternatives to the existing QUEWZ approach. The "Potential Modifications and Activities" section later in this document provides descriptions of recently developed approaches to speed-flow relationships and capacity estimation.

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b) Minimum Speed (SP_{mn})

Definition and Use. QUEWZ estimates the minimum vehicle speeds in a freeway work zone to help determine the effect of speed-change activity on road user costs.

Equation. QUEWZ uses a single general formula for the minimum speed in the work zone. The minimum speed was a function of the average speed in the work zone and the volume/capacity ratio in the work zone:

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

When a queue exists upstream of the work zone, the minimum speed is defined to be zero. Figure 4 shows the resulting graph for the formula for an example where work zone speed is 50 mph.

Supporting References and Formula Derivation. The minimum speed formula was developed based on a linear regression of work zone data, as a function of the average speed and the square of the volume/capacity ratio in the work zone (Krammes, Dudek, and Memmott 1987).

Discussion. The original TTI document states that the minimum speed formula was derived from "unpublished work zone data" collected in a separate project using a regression process. The objectives of that project did not focus on the development of QUEWZ formulas; therefore, documents for that project do not describe the specifics of the regression process (Dudek, Richards, and Buffington 1985). A separate document (Krammes, Dudek, and Memmott 1987) confirms that linear regression was used.

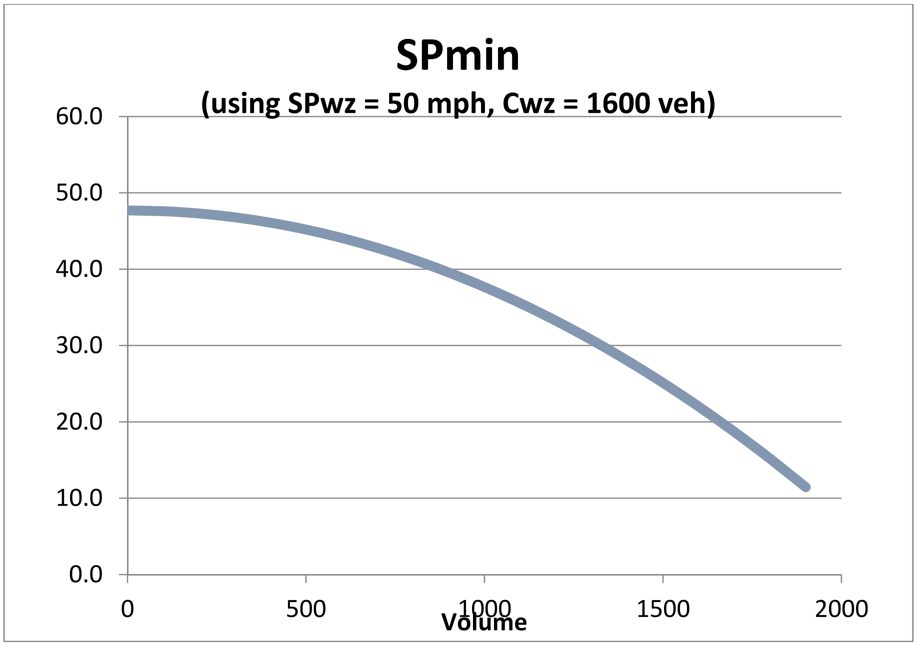

Figure 4. Minimum speed in work zone

The project documents do provide information about the nature of the data sets that were used to develop selected QUEWZ formulas; information about the nature of the data sample can be useful when evaluating the resulting formulas. The following is an outline of the project and the data collected:

- The data were originally collected for a project to examine the following:
  - Effects of traffic control on four-lane divided highways
  - Implementation of work zone traffic control
  - Abbreviated marking patterns in work zones
  - Speed control methods in work zones
- Work zone data were collected at projects in a two-state area (6 sites in Texas and 4 sites in Oklahoma), nearly all of which were 4-lane highways.
- Based on references to the specific projects in the documentation, the work zone data appear to have been collected in approximately the 1981-1982 time period (the project documentation was dated 1985).
- The data collection process included the following:
  - Volumes from tube counts for at least 24 hours to collect baseline data
  - 4+ hours data per site, for 1-2 days
  - Speeds from floating car speed profiles (via tachograph) on several runs per one-hour study period (starting at 9am, 10:30am, 1:30pm, and 3pm)
  - Various other field observations including vehicle classification and occupancy, video data, etc.
- Although QUEWZ was used during the project to estimate user costs from work zone delays, the project was not designed for the purpose of updating QUEWZ formulas or parameters; therefore, there is no discussion in the project documentation about QUEWZ formula derivations from the project data.

c) Effective Length of Work Zone Closure (CLL)

Definition and Use. QUEWZ estimates the length of the segment affected by work zone activity. This length is not necessarily the actual length of the segment with reduced capacity. The effective length CLL can differ from the actual work zone length when traffic volumes are lower, or when taking into account the transition zone to the slower speeds in the work zone.

Equation. QUEWZ uses a formula for effective work zone length that is a function of the actual length of reduced capacity in the work zone and the volume/capacity ratio. See Figure 5.

$$\text{If } WZD \le 0.1\text{, or if } V/C_{wz} \le 1\text{, then}$$
$$CLL = WZD + 0.2$$
$$\textit{else}$$
$$CLL = 0.1 + (WZD + 0.1)(V/C_{wz})$$

Supporting References and Formula Derivation. According to the original TTI description, the effective work zone length formula was based on empirical data collected in work zones for a separate project. No documentation was found regarding the exact process by which the work zone data was processed to produce the formula.

Discussion. In the TTI document, Memmott and Dudek state that the effective work zone length formula was derived from the same "unpublished work zone data" that was used for formula b) above. As the discussion for formula b) notes, that data collection project had a variety of

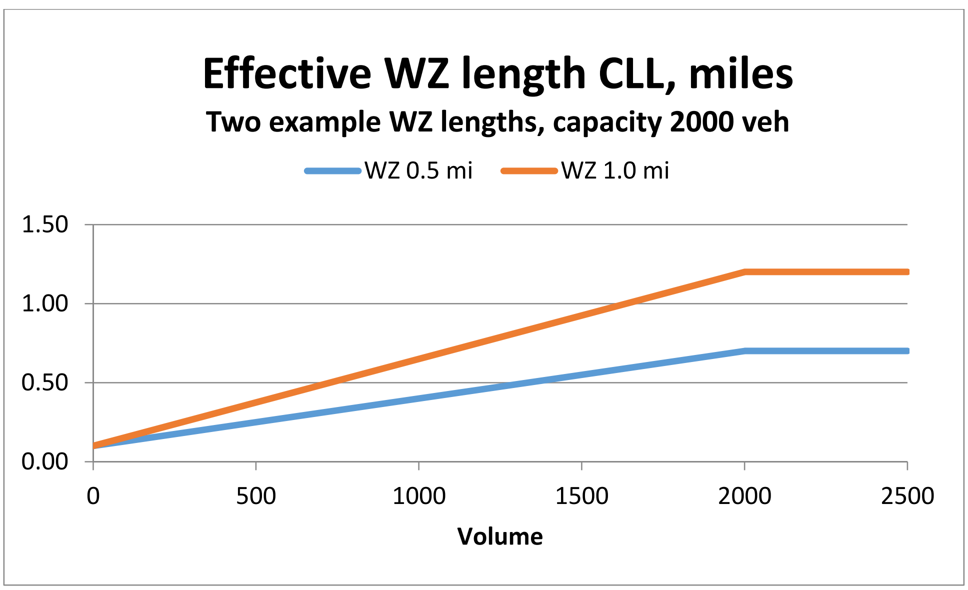

Figure 5. Effective WZ length

research objectives and did not focus on the development of QUEWZ formulas; therefore, while QUEWZ was used during the project, its documents do not describe how the data were used for QUEWZ development work (Dudek, Richards, and Buffington 1985).

Although no documentation was found about the effective work zone length formula's derivation, the simple form of the formula, combined with the fact that formula b) processed the same data set using linear regression, suggests that the effective work zone length formula might have been derived in a similar way. Also, just as with the formula b), the background about the data sets upon which the effective work zone length formula was based provide information that can be useful when evaluating the applicability of the resulting formulas for future uses. See the formula b "discussion" section for an outline of the project and the data collected.

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d) Estimated Vehicle Operating Costs (f(s) and g(s))

Definition and Use. QUEWZ estimates the vehicle operating costs for cars and trucks (f(s) and g(s), respectively) for a particular speed. The additional operating cost as a result of the reduced speeds in the work zone is then computed by looking at the change in f(s) and g(s), with and without the work zone.

Equation. QUEWZ uses a general formula for the vehicle operating costs for cars and trucks that is a function of the speed of the vehicles and the vehicle type:

$$f(SP) = (395.6898)e^{0.01537SP}SP^{-0.45525}$$
$$g(SP) = (17.1466)e^{0.02203SP}SP^{-0.35902} + 1201.8847e^{0.0322SP}SP^{-0.79202}$$

Supporting References and Formula Derivation. According to the original TTI document, the vehicle operating costs for cars and trucks were based on data tabulated by the American Association of Highway and Transportation Officials (AASHTO) for its 1977 guide to road user benefits, also known as the "Redbook" (AASHTO 1977). While operating cost data were found in tabular form, no documentation was found in the Redbook regarding the exact process by which the data was processed to produce the cost formula. However, Memmott (1984), co-author of the original QUEWZ documentation, discussed the AASHTO data set in the context of a separate research effort to develop an economic evaluation approach for highway improvement projects. In that discussion, he noted that tabular data such as the AASHTO data were converted into an equation, using the R^2 value to select the best equation form. The actual form of the fitted equation varied with the data set; however, there were some similarities in equation form between the examples in his discussion and those used in QUEWZ. This suggests that a regression process was used for QUEWZ as well.

Discussion. In the TTI document, Memmott and Dudek state that the vehicle operating cost formulas were "…estimated from tabular data in the AASHTO Redbook… updated to December 1981". An attempt was made to locate vehicle operating cost tabular data in the AASHTO Redbook and confirm that they were likely to be the source of the QUEWZ cost formulas. A table of vehicle "running costs" was located in Appendix B of the 1977 Redbook, showing estimated vehicle costs as a function of vehicle speed and 3 classes of vehicle type (passenger cars, single-unit trucks, and semi tractor-trailer combinations). Those tables were then compared to the values generated by the vehicle operating cost formulae. Specifically, Table B-1 (passenger cars) of the 1977 Redbook was compared to equation f(s), while Table B-3 (semi trucks) was compared to equation g(s). The results are shown in Figure 6 for varying work zone speeds, for cars and trucks. For each figure, three values are compared: The values from the QUEWZ formula, the operating cost values shown in the 1977 Redbook table, and the Redbook costs after adjusting for the year of the data (the Redbook tabular values are based on January 1975 costs, while the equations represented December 1981 costs). For passenger cars, that adjustment was performed by comparing the Consumer Price Index for all consumers (CPI-U) for December 1981 to that of January 1975, and using that ratio as a multiplier adjustment factor to the original Redbook values (Bureau of Labor Statistics 2018). For trucks, the same procedure was used, using the Producer Price Index (or PPI, formerly known as the Wholesale Price Index), as recommended in the Redbook.

The results show that the adjusted Redbook values (after CPI adjustment) are similar in magnitude and characteristics (curve shape) to the estimated values produced by the formulas for both cars and trucks. The values matched closely for passenger cars (adjusted Redbook values were 91% to 96% of the formula values), while for semi-trucks, adjusted values showed a similar shape to that of the g(s) truck formula, though the adjusted values were 84% to 99% of the formula values. The differences could be the result of different cost of living indices used in the different research projects; for example, the 1977 Redbook mentions CPI and WPI values that differ from those taken from the Bureau of Labor Statistics database used in the conversion in this document, suggesting that either a different index was used in the Redbook, or a reset of the index scale was performed at some time after the Redbook was published. The difference could also be the expected result of regression performed to develop the formulas, i.e., the regression formula should not be expected to exactly match the data to which it was fitted. Overall, these comparisons generally support the idea that the values shown in Tables B-1 and B-3 of the Redbook were the sources of data used to produce f(s) and g(s).

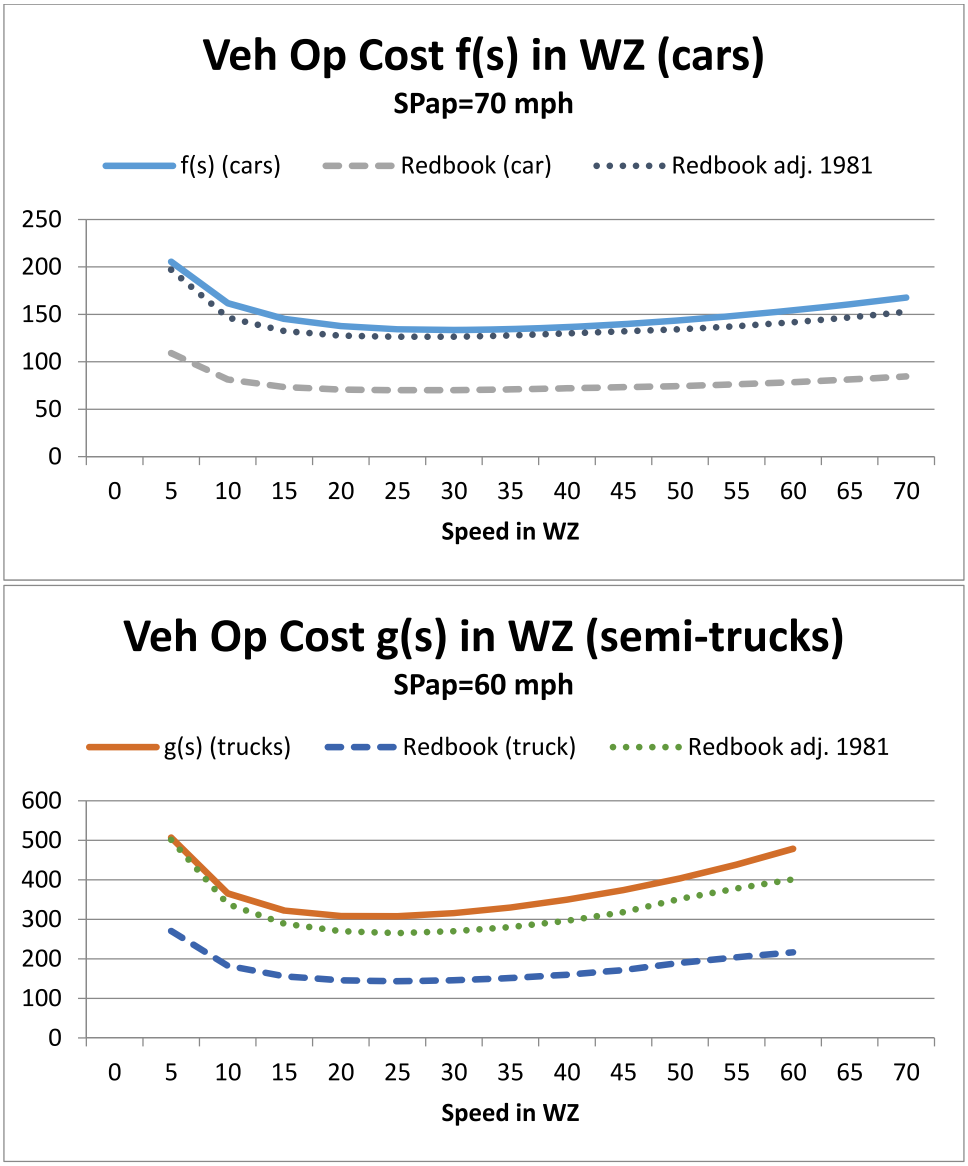

Figure 6. Vehicle operating costs: comparison of formulas and data

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e) Estimated Distance of the Speed Change Cycle (DSC)

Definition and Use. QUEWZ estimates the distance affected by the transition to and from the reduced work zone speed, also referred to as the speed change cycle. This transition distance, DSC, has an associated delay and user cost.

Equation. QUEWZ uses a general formula for the distance of the speed change cycle that is a function of the volume/capacity ratio for the work zone:

$$DSC = \max\left[0.5 + 0.25(\mathrm{V/C}_{wz}), 0.75\right]$$

See Figure 7 for an example.

Supporting References and Formula Derivation. According to the original TTI description, the formula for the distance of the speed change cycle was based on empirical data collected in work zones for a separate project. No documentation was found regarding the exact process by which the work zone data was processed to produce the formula.

Discussion. In the TTI document, Memmott and Dudek state that the formula for the distance of the speed change cycle was derived from the same "unpublished work zone data" that was used for formulas b) and c) above. As the discussion for those formulas notes, the project that collected that data had a variety of research objectives and did not focus on the development of QUEWZ formulas; therefore, while QUEWZ was used during the project, the project documents

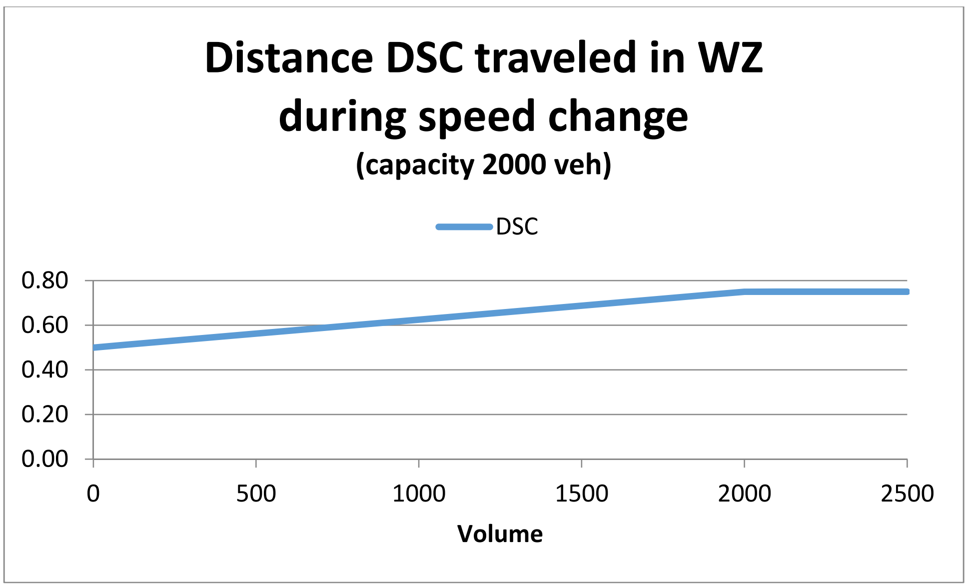


Figure 7. Distance traveled during speed change

do not describe how the data were used for QUEWZ development work (Dudek, Richards, and Buffington 1985). Although no documentation was found about the derivation of the DSC formula for the distance of the speed change cycle, the simple form of the formula, combined with the fact that formula b) used the same data set with linear regression, suggests that the DSC formula might have been derived in a similar way. Also, just as with the formulas b) and c), the background about the data sets upon which the DSC formula was based provides information that can be useful when evaluating the applicability of the resulting formulas for future uses. See the formula b "discussion" section for an outline of the project and the data collected.

f) Estimated Vehicle Operating Costs (SPCC and SPCT)

Definition and Use. QUEWZ estimates the vehicle operating costs for cars and trucks (SPCC and SPCT, respectively) due to deceleration before and acceleration after the work zone.

Equation. QUEWZ uses a general formula for the vehicle operating costs from deceleration/ acceleration of cars and trucks, that is a function of the approach speed (outside the work zone) and the minimum speed in the work zone:

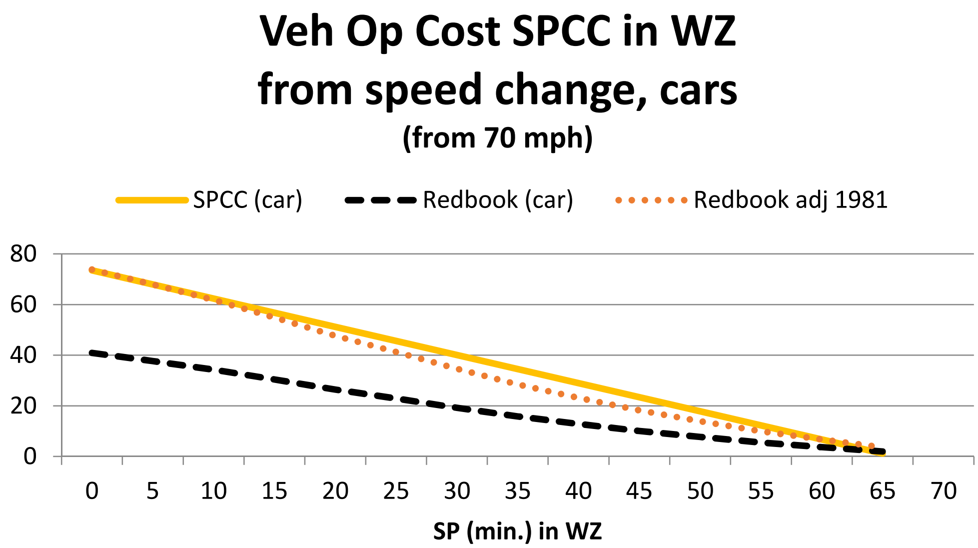
$$SPCC = -5.2187 + 1.1241\left(SP_{ap}\right) - 1.1125\left(SP_{mn}\right)$$

$$SPCT = -32.2883 + 7.1226\left(SP_{ap}\right) - 6.684\left(SP_{mn}\right)$$

Supporting References and Formula Derivation. According to the original TTI description, the vehicle operating costs because of deceleration/acceleration of cars and trucks were based on data tabulated by the American Association of Highway and Transportation Officials (AASHTO) for its 1977 "Redbook" guide to estimating road user benefits. As with the estimated vehicle operating costs (equation d) that were also based on the Redbook, no documentation was found regarding the exact process by which the data was processed to produce the cost formula, though there were suggestions in other documentation that a regression approach was used to convert tabular data to an equation format suitable for use in a software program. Memmott (1984), co-author of the original QUEWZ documentation, discussed such a process for the AASHTO data set, and described a fitted equation with similarities in equation form to some cost equations used in QUEWZ.

Discussion. In the TTI document, Memmott and Dudek state that the vehicle operating cost formulas "…were developed from tabular data in the AASHTO Redbook… and updated to December 1981". As with equation d (vehicle operating costs at reduced work zone speeds), an attempt was made to locate the tabular data from the AASHTO Redbook that were likely to be the source of those formulas. A table of vehicle "excess cost of speed change cycles" was located in Appendix B of the 1977 Redbook, showing estimated vehicle costs as a function of the initial vehicle speed, the subsequent reduced speed, and 3 classes of vehicle type (passenger cars, single-unit trucks, and semi tractor-trailer combinations). Those tables were then compared to the values generated by the vehicle operating cost formulae. Specifically, Table B-10 (passenger cars) of the 1977 Redbook was compared to equation SPCC, while Table B-12 (semi trucks) was compared to equation SPCT. The results are shown in Figure 8 for varying work zone speeds, based on the initial (approach) speed of 70 mph (cars) and 60 mph (trucks). For each figure, three values are compared: The values from the QUEWZ formula, the operating cost values shown in the 1977 Redbook table, and the Redbook costs after adjusting for the year of the data (the Redbook tabular values are based on January 1975 costs, while the equations represented December 1981 costs). The cost of living adjustment was performed using the same process used for equation d.

The results show that the adjusted Redbook values are similar in magnitude and characteristics (curve shape) to the estimated values produced by the formulas. The values matched more



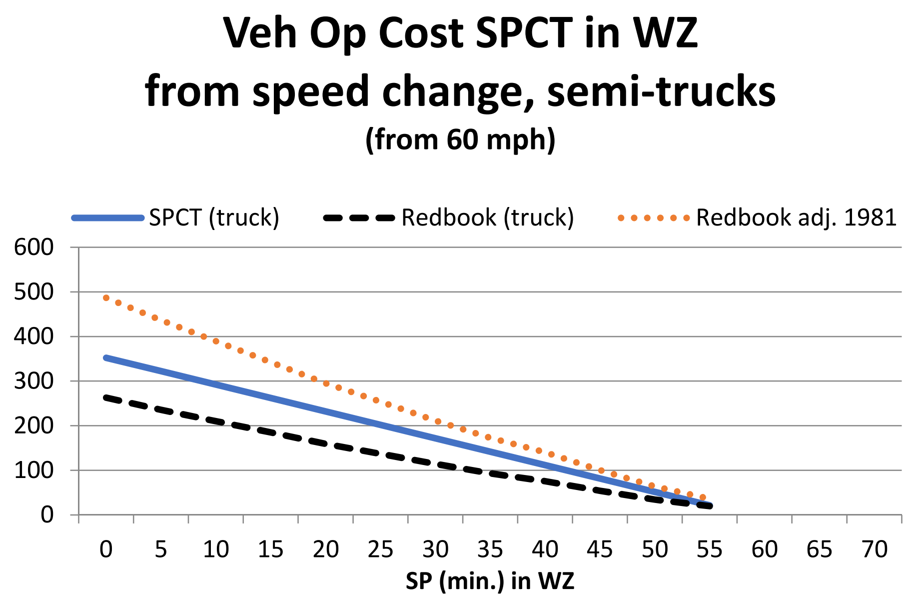


Figure 8. Vehicle operating costs from speed change

closely for passenger cars than for semi-trucks. (As with equation d, the differences could be the result of different cost of living indices used in the different research projects, or they could be the expected result of a regression process.) Overall, these comparisons generally support the idea that the values shown in Tables B-10 and B-12 of the Redbook were the sources of data used to produce SPCC and SPCT.

g) Estimated Cost of Vehicle Operations in a Queue (SP_q)

Definition and Use. QUEWZ estimates the average vehicle speeds in a queue upstream from a freeway work zone, to estimate the vehicle operating costs in the queue.

Equation. The QUEWZ formula for the average vehicle speeds in a queue is a function of the freeflow speed and the ratio of the capacity in the work zone to the capacity outside the work zone. The formula was shown as follows:

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

Supporting References and Formula Derivation. According to the original TTI document, the average vehicle speed formula was derived from research into travel time predictions during congestion and shock waves, as documented by Messer and Dudek (1974). The formula and corresponding research were also cited by the Federal Highway Administration as part of their online 2011 primer on "Work Zone Safety and Mobility Performance Measurement" (FHWA 2011).

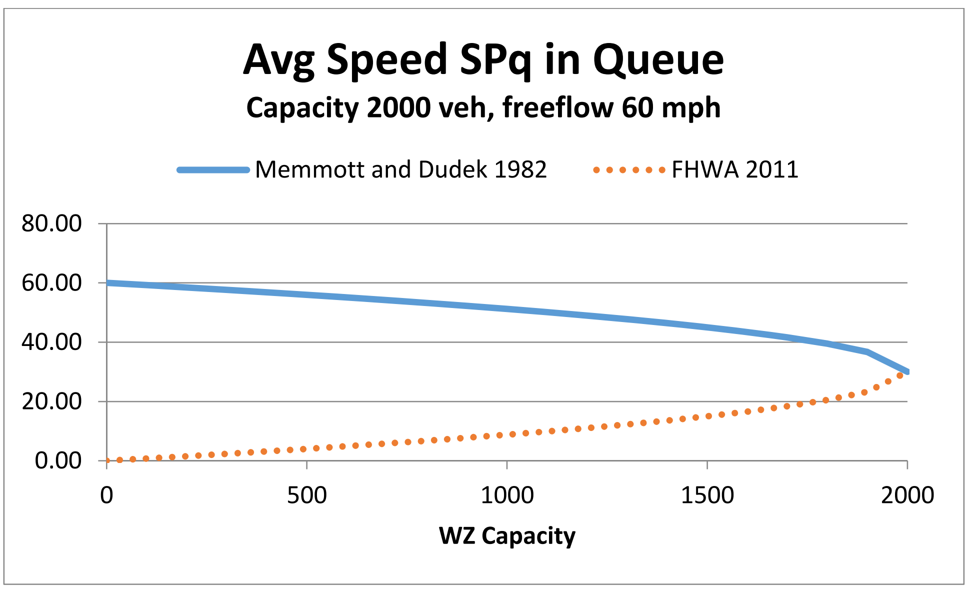


Figure 9. Average speed in queue

Discussion. Note that in the 2011 FHWA primer, the average queue speed formula differs from the form shown in the original QUEWZ references from Memmott and Dudek (both 1982 and 1984.) The revised formula from FHWA is as follows:

$$SP_q = \left(\frac{SP_1}{2}\right)\left[1-(1-\left(\frac{C_{wz}}{C_{ap}}\right))^{1/2}\right]$$

A review of a graph of the formulas shows that the revised formula used in the FHWA primer appears to be the proper formula to use. In particular, the original formula suggests that queue speeds should drop from free flow speed when the capacity of the work zone is zero, to a lower speed as the work zone capacity goes up, which is counterintuitive. The revised FHWA formula shows that average queue speed goes up as the work zone capacity goes up, which seems appropriate. See the comparison in Figure 9. The revised formula also matched the formula used in the source code for the original QUEWZ model as documented in Memmott and Dudek (1982). Based on this information, the revised FHWA version should be used.

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h) Estimated Cost of Stop and Go Speed Changes within a Queue (CSPQ)

Definition and Use. QUEWZ estimates the combined vehicle operating costs for cars and trucks (CSPQ) due to stop and go speed cycles in a queue upstream from the work zone.

Equation. QUEWZ uses a general formula for the vehicle operating costs caused by stop and go cycles in a queue that is a function of the vehicle volume, cost update factor, average queue length, and the percentage of cars and trucks.

$$CSPQ = \frac{VL}{1000}(CUF)(3(QUEL))(6.0223*PTC+31.8151*PTT)$$

See Figure 10 for examples at two queue lengths.

Supporting References and Formula Derivation. According to the TTI document, the formula for the vehicle operating costs caused by stop and go cycles in a queue was based on the 1977 American Association of Highway and Transportation Officials (AASHTO) “Redbook” guide to road user benefits. Also, the authors note that the “unpublished work zone data” used for equations b), d), and e) show that on average, approximately 3 speed cycles from 0 to 10 mph have been observed. However, as with the other vehicle operating costs that were based on the Redbook (equations d and f), no documentation was found regarding the exact process by which the data were processed to produce the cost formula.

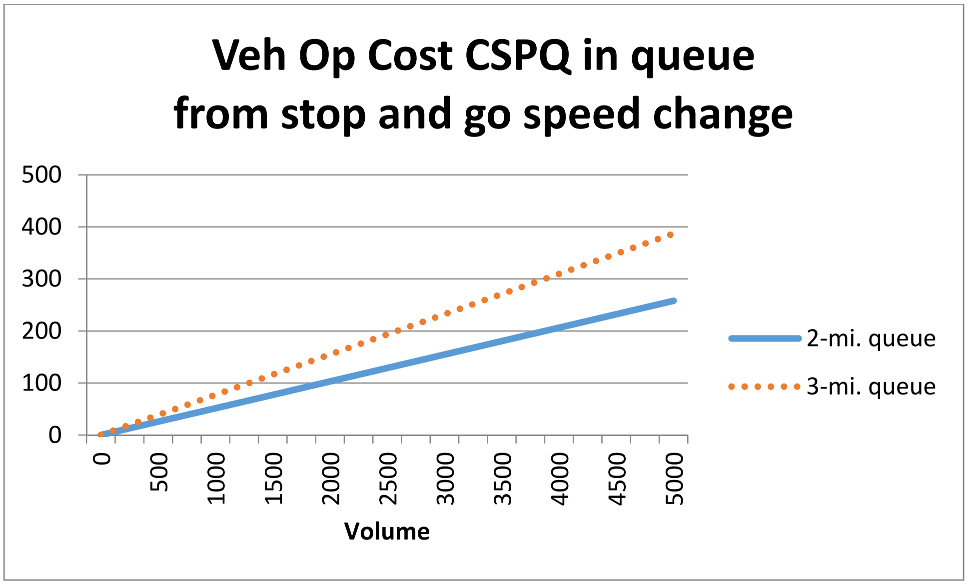

Figure 10. Vehicle operating cost in a queue due to stop and go

Discussion. Even though the TTI document by Memmott and Dudek did not describe the exact process by which the formula shown above was derived, it was hypothesized that the stop and go process in a queue could be treated similarly to a vehicle that is decelerating when approaching a work zone, then accelerating after the work zone. If so, the transition operating cost formulas SPCC and SPCT from equation f could be used to estimate the stop and go queue costs. The SPCC and SPCT formulas are a function of an approach speed and a minimum speed; if we treat the stop and go cycle in a queue as the equivalent of a transition from 10 mph to 0 mph, we can substitute 10 mph for the approach speed, and 0 mph for the minimum speed, in the SPCC and SPCT formulas, to get the approximate stop and go operating costs in the queue. (The 10 mph and 0 mph values reflect the nature of the speed cycles observed in the unpublished work zone data.)

If those values are then used in the overall cost formula CSPC used for transitions to/from the work zone, we get a formula that matches the one shown for CSPQ in Memmott and Dudek (1982).

Table 1 summarizes the results of the formula review.

Table 1. Summary of key QUEWZ formulas

Variable: Cost of…	Formula	Methods, Data	Comments
a) Delay in WZ **SP = Average speed**	$If\ (V_2/V_1) \geq V/C,\ then$ $SP = SP_1 + \frac{V_1(SP_2 - SP_1)}{V_2}(V/C)$ $If\ (V_2/V_1) \leq V/C \leq 1,\ then$ $SP = SP_2 + (SP_2 - SP_3)\left[1 - \left(\frac{(V/C)-(V_2/V_1)}{1-(V_2/V_1)}\right)^2\right]^{\frac{1}{2}}$ $If\ (V_2/V_1) > 1$ or a queue is present, *then* $SP = SP_3(2 - V/C)$, with the speed constrained to the following range $20 \leq SP \leq SP_3$	Speed is defined as an idealized function of v/c Originally based on Caltrans research and Caltrans field data Used 1965 HCM general speed-flow relationship, and regression based on field data	No information found about the exact method used to develop formula Same formula was used in non-work segments and work zones. Some research suggests that the speed formula would be different in a reduced-capacity work zone however Note: Appears to be a typographical error in the QUEWZ SP formula described in Memmott and Dudek 1982
b) Delay in WZ **SP_{mn} = Minimum speed**	$SP_{mn} = SP_{wz} - 2.3 - 25.7(V/C_{wz})^2$	Based on TTI work zone data Formula based on linear regression	TTI data from selected Texas work zones, collected in 1980s

c) Delay in WZ
 	
CLL = Effective length of WZ affected by delay
	If $WZD \leq 0.1$, or if $V/C_{wz} \leq 1$, then
	$CLL = WZD + 0.2$
	else
	$CLL = 0.1 + (WZD + 0.1)(V/C_{wz})$
		Based on TTI work zone data
		
		Formulas appear to be based on (linear) regression, plus professional judgment
			No information about the exact method used to develop formula, though format and other uses of the TTI data suggest linear regression was used
			
			TTI data from selected Texas work zones, collected in 1980s

d) Veh Op in WZ **f and g = cost functions vs. speed, for cars, trucks, resp.**	$f(SP) = (395.6898)e^{0.01537SP}SP^{-0.45525}$ $g(SP) = (17.1466)e^{0.02203SP}SP^{-0.35902} + 1201.8847e^{0.0322SP}SP^{-0.79202}$	Based on AASHTO User Benefits "Redbook" Formulas appear to be based on regression of Redbook table data	Redbook Appendix Tables B-1 and B-3 appear to be source of the tabular data; comparison of formula results with tabular data generally supports this No information about exact method used to develop formula, though other uses of same data by QUEWZ co-developer suggest regression was used

Table 1. Summary of key QUEWZ formulas

e) Delay in WZ from decel/accel **DSC = distance traveled during speed change cycle**	$DSC = \max\left[0.5 + 0.25(\mathrm{V/C}_{wz}), 0.75\right]$	Based on TTI work zone data Formulas appear to be based on (linear) regression, plus professional judgment	No information about the exact method used to develop formula, though format and other uses of the TTI data suggest linear regression was used TTI data from selected Texas work zones, collected in 1980s
f) Veh Op in WZ from decel/accel **SPCC, SPCT = extra veh op cost for cars, trucks vs. approach speed and min. WZ speed**	$SPCC = -5.2187 + 1.1241\left(SP_{ap}\right) - 1.1125\left(SP_{mn}\right)$ $SPCT = -32.2883 + 7.1226\left(SP_{ap}\right) - 6.684\left(SP_{mn}\right)$	Based on AASHTO User Benefits "Redbook" Formulas appear to be based on regression of Redbook table data	Redbook Appendix Tables B-10 and B-12 appear to be source of the data; comparison of formula results with table data generally supports this No information about exact method used to develop formula, though other uses of same data by QUEWZ co-developer suggest regression was used
g) Veh Op in queue (if present) **Avg. speed SPq in queue**	$SP_q = \left(\frac{SP_1}{2}\right)\left[1 - (1 - \left(\frac{C_{wz}}{C_{ap}}\right))^{1/2}\right]$	Based on TTI research to develop descriptions of shock waves	Same equation also used in 2011 FHWA primer on work zone performance measurement Note: Appears to be a typographical error in the QUEWZ SPq formula described in Memmott and Dudek 1982. FHWA 2011 primer has revised version.
h) Veh Op in queue from decel/accel **CSPQ= vehicle operating costs vs. volume VL and average queue length QUEL**	$CSPQ = \frac{VL}{1000}(CUF)(3(QUEL))(6.0223 * PTC + 31.8151 * PTT)$	Appears to be based on costs from AASHTO User Benefits "Redbook", as well as TTI WZ data	Specific derivation of the formula was not described; however, the formula appears to model stop and go changes in queues as equivalent to deceleration/acceleration to and from a work zone Relies on TTI WZ data to determine how frequently speed changes occur in queues

4. Potential Modifications and Activities

There are several options for modifying the QUEWZ tool; those modifications can vary from relatively limited updates to input parameters such as cost of living factors or per-unit costs, to more significant modifications such as revision or replacement of formulas/algorithms, or the addition of new features to improve the accuracy of the cost estimates. Also, there are potentially useful activities or tests to verify the functions of the model, including sensitivity tests to determine the relative significance of specific cost components as contributors to the overall cost. The most significant potential activity would be to locate or develop a new road user cost estimation tool that better meets the needs of WSDOT staff. The following is an outline of potential QUEWZ modifications and related activities.

a) Parameter-Level Modifications: Update input parameters

One way to update the model without requiring significant software changes would be to modify input parameters. These values could be updated to either reflect more recent conditions (e.g., updated costs), or reflect more relevant (project- or region-specific) conditions. Input parameters for QUEWZ include

- Cost computation factors
  - value of time for the individual traveler,
  - cost of living update factor (using the Consumer Price Index and/or the Producer Price Index),
- Vehicle operating (running) costs, by vehicle type
- Speed computation factors
  - speed-volume input parameters (freeflow, LOS D/E breakpoint, and capacity values)
  - capacity estimate risk factor (CERF)
- Other user-adjustable factors, such as the percentage of trucks in the vehicle stream

For some of these values, existing databases can be used, e.g., cost of living factors (Bureau of Labor Statistics CPI or PPI), vehicle operating costs (FHWA HERS-ST data), or value of time (USDOT guidelines on valuation of time). Other values are project-specific and require knowledge of local conditions.

There are also some input parameters that are computed internally and are not normally user-specified. In those cases, the values are often generated based on formulas derived from field data (e.g., the variables that are based on TTI work zone data). Those values could be updated by using newer field data and generating revised formulas. In those cases, a new field data collection effort (or locating newer existing data) might be appropriate to generate the most relevant inputs for the task.

b) Method-Level Modifications: Modify Speed and Capacity Formulas/Algorithms

In some cases, modification of an entire method could be beneficial if a suitable alternative exists. For example, because of the crucial role that speed estimates and work zone capacity values play in road user cost estimates, changes to speed and/or capacity formulas could have a significant effect on resulting model outputs. Significant research has been performed on speed-flow formulations in the past 30 years, and the results of that work have been documented in subsequent editions of the Highway Capacity Manual as a recognized speed estimation approach. Therefore, there are well-documented alternatives to the speed formula based on relatively recent research, that can be considered as a replacement of the existing QUEWZ method.

For example, the newest (6th) edition of the Highway Capacity Manual (HCM6), published in 2016, describes a new work zone evaluation methodology based primarily on research conducted in NCHRP 3-107. This includes a new speed estimation method that extends the approach used in recent editions of the HCM in ways that are particularly relevant for work zones. The following is a description of that alternative.

HCM6 describes a speed-flow curve with a general form as shown in Figure 11. The curve has the following characteristics: 1) At lower vehicle volumes (up to a breakpoint), the speed is constant and equal to the freeflow speed; and 2) for volumes from the breakpoint up to capacity, the speed gradually decreases in a parabolic form. This curve is similar in some ways to the general curve used to describe the original QUEWZ speed-flow curves, except that the low-volume segment has a constant speed (slope = 0), and the speed for higher volumes is defined to be specifically of a second order polynomial shape, and not the more complex form used by QUEWZ. The second order form has also been used in previous HCM editions before HCM6.

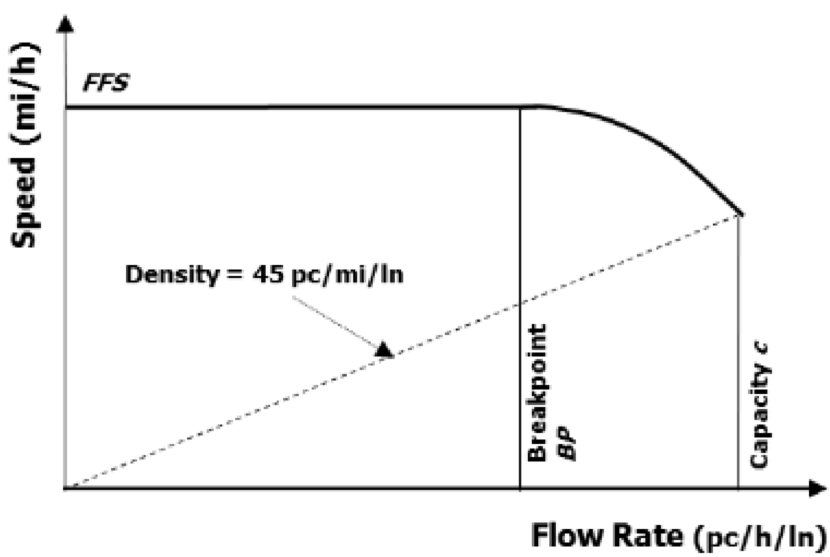

Figure 11. Basic HCM6 speed-flow relationship (from TRB 2016, Exhibit 12-5)

These characteristics are then represented by a formula of the form shown in Figure 12.

$$S = FFS_{adj} \qquad v_p \leq BP$$

$$S = FFS_{adj} - \frac{\left(FFS_{adj} - \frac{c_{adj}}{D_c}\right)\left(v_p - BP\right)^a}{\left(c_{adj} - BP\right)^a} \qquad BP < v_p \leq c$$

Figure 12. General HCM6 speed formula (from TRB 2016, Equation 12-1)

Note that this formula is basically a function of vehicle volume (v_p), along with several adjustment factors whose values are based on work zone and other external conditions. The parameters in the formula are defined in Figure 13 below. (Equation numbers and chapter numbers refer to HCM6.)

The parameters in Figure 13 factor work zone features into the speed computation. In particular, the speed adjustment factor (SAF) and capacity adjustment factor (CAF) are each a function of road geometry and specific work zone conditions. SAF is a function of normal freeflow speed, work zone speed limit, ramp density, light conditions, barrier type, and number of open lanes. CAF is a function of conditions such as number of lanes, number of open lanes in the work zone, lane barrier type, the region (urban or rural), the lateral distance between the lane edge and the work zone barrier, light conditions (day or night), and normal freeflow speed.

Because the speed formula is also a function of free-flow speed (FFS), HCM6 describes the formula using a "family of curves" approach that has been used in several editions of the HCM,

Parameter	Definition and Units	Basic Freeway Segments	Multilane Highway Segments
FFS	Base segment free-flow speed (mi/h)	Measured OR predicted with Equation 12-2	Measured OR predicted with Equation 12-3
FFS_{adj}	Adjusted free-flow speed (mi/h)	$FFS_{adj} = FFS \times SAF$	No adjustments
SAF	Speed adjustment factor (decimal)	Locally calibrated OR estimated with Chapter 11; *SAF* = 1.00 for base conditions	1.00
c	Base segment capacity (pc/h/ln)	$c = 2{,}200 + 10(FFS - 50)$ $c \leq 2{,}400$ $55 \leq FFS \leq 75$	$c = 1{,}900 + 20(FFS - 45)$ $c \leq 2{,}300$ $45 \leq FFS \leq 70$
c_{adj}	Adjusted segment capacity (pc/h/ln)	$c_{adj} = c \times CAF$	No adjustments
CAF	Capacity adjustment factor (decimal)	Locally calibrated OR estimated with Chapter 11; *CAF* = 1.00 for base conditions	1.00
D_c	Density at capacity (pc/mi/ln)	45	45
BP	Breakpoint (pc/h/ln)	$BP_{adj} = [1{,}000 + 40 \times (75 - FFS_{adj})] \times CAF^2$	1,400
a	Exponent calibration parameter (decimal)	2.00	1.31

Figure 13. Parameters for speed-flow formula (from TRB 2016, Exhibit 12-6)

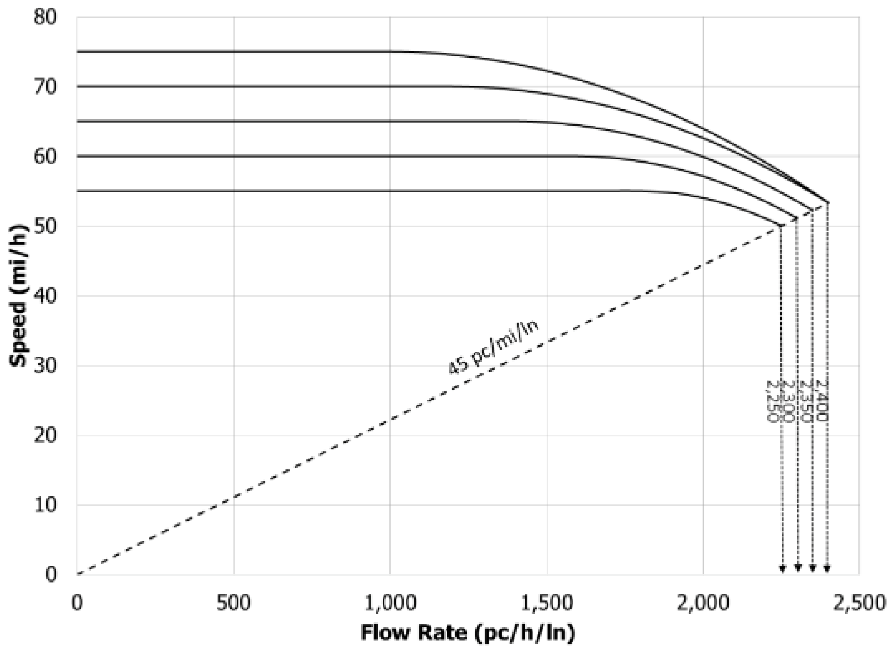

Figure 14. Speed-flow curves for freeways (from TRB 2016, Exhibit 12-7)

where for each of a series of freeflow speeds (e.g., 50 mph, 55 mph, 60 mph, etc.), a different speed vs. flow relationship is developed; each of these individual speed-flow curves has a similar shape, and the result is of the form shown in Figure 14. The diagonal line represents oversaturated conditions, based on a linear speed-density relationship suggested by HCM6.

For undersaturated or freeflow speed and freeway capacity in normal non-work zone conditions, HCM6 also suggests default values if project-specific data cannot be accessed. These values can be used for the baseline non-work zone condition. An extensive discussion of the formulas described above and the overall HCM6 approach to computations for non-work zone and work zone conditions can be found in Chapters 10, 12, and 25 of the 2016 Highway Capacity Manual (TRB 2016).

An alternative approach would be to use the methods described in the 2010 edition of the Highway Capacity Manual. The HCM 2010 speed-flow formulas reflected a significant change from previous editions, based on considerably more field data than in HCM 2000, and the capacity formula also reflects incremental modifications from previous approaches. The approach uses a family of curves, much like HCM6. However, the formulas are fixed for each level of freeflow speed. See Figures 15 and 16. Because the HCM 2010 methods have been in the technical literature for a longer time than the HCM6 methods, there are more examples of its use in the field, which might be useful for software development. For example, the ODOT models mentioned in Section 4 used HCM 2010 methods (the most recent HCM methods available at the time the ODOT tools were developed).

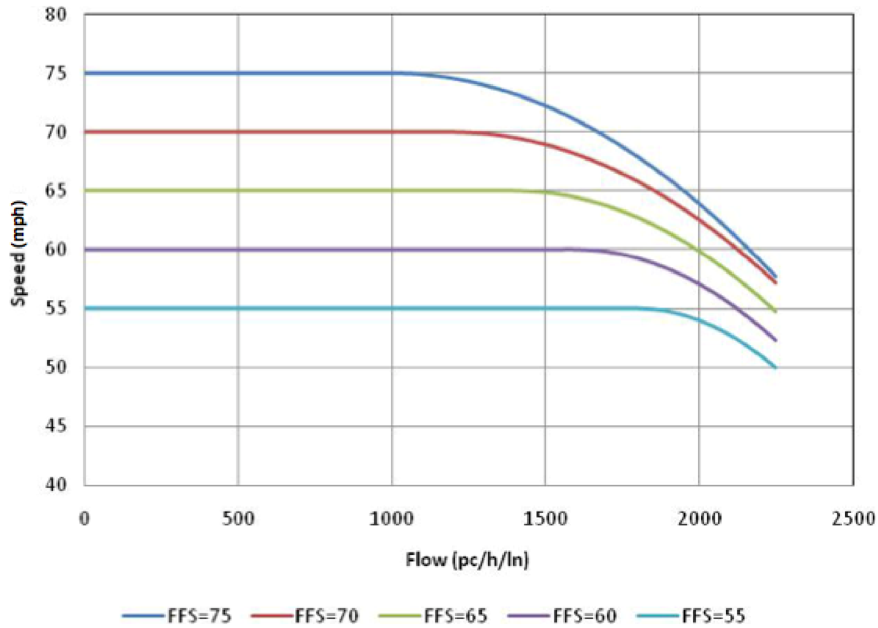

Figure 15. HCM 2010 speed-flow curves (from Roess 2011)

FFS (mph)	BP1 (pc/h/ln)	Segment 1 $S = v \leq$ BP1	Segment 2 $S = v >$ BP1
75	1,000	75	$S = 75 - 0.00001107(v - 1{,}000)^2$
70	1,200	70	$S = 70 - 0.00001160(v - 1{,}200)^2$
65	1,400	65	$S = 65 - 0.00001418(v - 1{,}400)^2$
60	1,600	60	$S = 60 - 0.00001816(v - 1{,}600)^2$
55	1,800	55	$S = 55 - 0.00002469(v - 1{,}800)^2$

Figure 16. HCM 2010 equations (from Roess 2011)

It should be noted that there have been some differing views about aspects of the method used for speed-flow formulas in recent Highway Capacity Manuals. Roess (2011) described the process by which the speed-flow formulas were developed for HCM 2010, and pointed out the difficulties of simultaneously developing a statistically good fit based on widely varying data from across the country, reconciling those issues with the desire to produce a consistent-looking family of speed-flow curves for different freeflow speed values, and adding to the process professional judgment about the preferred formats that best serve the needs of transportation professionals. While those comments were specifically about HCM 2010, it is useful to be aware that those types of issues can arise when using empirically derived approximate formulas; in fact, HCM6 notes a preference for project-specific data over such approximations whenever feasible. Some of the newest results described in HCM6 have also been discussed. Jeon and Benekohal (2018) noted that the HCM 2016 methods for capacity and freeflow speed computations can produce counter-intuitive results in some cases (e.g., work zone capacity is higher than non-work zone capacity, work zone freeflow speed is higher than non-work zone freeflow speed, and work zone freeflow speed is not consistent with the work zone speed limit). Nevertheless, the methods described in the Highway Capacity Manual, and HCM6 specifically, represent the most recent thinking and national research about speed-flow relationships and capacity estimation.

c) Tool Replacement: Explore benefits and costs of locating an existing tool as a replacement, or developing a new tool

There are a number of existing models that attempt to address the need to estimate road user costs in work zones. Section 5 of this document, "Selected Literature Review", describes discussions in the literature that compare the QUEWZ model to other options. These documents could serve as a starting point for exploring new tool options, if an existing tool is desired.

Among existing models, there are also examples of spreadsheet-based work zone cost models similar to the WSDOT tool, that were developed by state agencies. Depending on the nature and scope of the changes WSDOT is considering for its existing QUEWZ-based tool, WSDOT could consider the costs and benefits of developing its own spreadsheet tool designed to specifically meet WSDOT needs. That tool could continue in the mold of the existing deterministic Excel spreadsheet model, for ease of development, modification, and use. In-house development of a new tool would enable WSDOT to update key algorithms using well-documented methods (e.g., HCM6); update input parameters such as unit costs and price index values, increase the use of updated research results and reduce reliance on older data; customize the tool to meet specific WSDOT needs and utilize data sets specific to Washington state; improve the user interface; and more easily add new features, including those used in other deterministic spreadsheets.

One recent example of a state transportation department that explored options for replacing its existing use of QUEWZ is the Ohio Department of Transportation (ODOT). The following is a discussion of ODOT's experience searching for a replacement tool.

ODOT had been using QUEWZ to provide work zone capacity estimates that could then be used by two ODOT-developed spreadsheets to estimate queueing effects and road user costs. The ODOT queueing spreadsheet was used to determine if estimated queue lengths related to construction projects met thresholds for permitting exceptions to limitations on proposed lane closure schedules. The ODOT user cost spreadsheet was used to evaluate the costs of potential construction projects and help determine incentive amounts for a contractor's use of "innovative contract" methods. QUEWZ was specifically noted in ODOTs Traffic Engineering and Innovative Contracting manuals as an acceptable tool for work zone capacity estimation (Jenkins and McAvoy 2015).

However, because QUEWZ was no longer supported by its original developer, and was not compatible with Windows OS, ODOT sponsored a research effort in 2012 to locate a replacement for its use of QUEWZ. The initial RFP noted that ODOT was specifically interested in 1) replacing QUEWZ and their in-house queue tool with an existing sketch planning or deterministic tool that addressed work zones specifically; and 2) updating ODOT's existing road user cost tool. The resulting tools should also reflect Ohio state conditions. ODOT did not wish to develop its own software, reprogram QUEWZ, or adopt the use of complex existing software.

As the project evolved, research objectives were adjusted, and rather than choosing an existing queue modeling tool, a decision was made to develop a new queueing tool along with a new user cost tool, in Excel, based on the 2010 Highway Capacity Manual method for capacity estimation, with the features of the tools based on ODOT needs as well as a review of features of other existing deterministic spreadsheet tools.

The resulting two new spreadsheet tools took into account delays caused by reduced work zone capacity (and the related user costs) as well as queueing effects, and also had options to consider vehicle diversion, detours, and crash costs. Sources of methods and data sets included HCM 2010 methods, updated Bureau of Labor Statistics Consumer Price Index values specific to the major metropolitan areas of Ohio, safety data from the National Safety Council, and vehicle operating costs collected from the FHWA Highway Economic Requirements System (HERS) for benefit/cost evaluations. The tools were also evaluated and calibrated using data collected in work zones throughout Ohio over two construction seasons.

If development of a replacement tool is considered by WSDOT in the future, initial review of similar tools (deterministic spreadsheet-based) used by other states would help determine the state of the practice and guide the development of functional requirements for a new tool. The ODOT project described above conducted such a survey to help define the work zone evaluation criteria (e.g., queue lengths, road user delay costs), methods (e.g., 2010 HCM approach to capacity), and features (e.g., diversion, detours, and tabular/graphical output options) to be used for their own tool set.

d) Feature Additions: Add features to the WSDOT QUEWZ spreadsheet model

Other models include features that might be considered for implementation in the WSDOT tool. Examples include modeling traffic diversion when congestion or delays reach a threshold level, modeling detours around work zones, accounting for the costs of vehicle emissions, and adding the costs of safety effects. Other potential changes include user interface improvements and more detailed user control over input values (e.g., hour by hour truck percentages that accompany hour by hour volume input data).

e) Activities: Sensitivity Tests

Sensitivity tests can be performed to a) test the sensitivity of road user cost outputs to changes in individual input parameters or changes to algorithms, b) evaluate the relative contributions of individual cost components (e.g., work zone delay vs. queue delay) to the total user costs, and c) provide information to help prioritize future enhancements to the model based on the magnitude of their expected effects.

For example, the 2011 FHWA primer on work zone road user costs notes that the cost related to delay is the sum of additional travel time required to traverse the work zone, the additional time required to slow to the work zone speed then accelerate after the work zone, additional travel time required to traverse a queue that develops upstream of a work zone, stop and go delays, and delays because of detours. Of these, FHWA notes that “(s)ome highway agencies do not consider speed change delay and stopping delay in delay time computations, as these components may not contribute significantly to the overall delay time…" (FHWA 2011, Section 2.2.1). If sensitivity tests support this idea, and those components are removed from the WSDOT tool, it would also remove the need to devote resources to update the formulas that those components use (and reduce dependence on formulas that were originally derived from older data).

f) Activities: Check Formulas for Errors

The formula review in Section 3 noted two apparent typographical errors in published QUEWZ formulas. The existing model should be reviewed to verify that published equations for average speed and average queue speed (formulas a and g respectively) have already been modified.

5. Selected Literature Review

The following is a brief discussion of selected research results from the past 20 years (i.e., since the most recent PC version of QUEWZ was produced). These sources can provide a starting point for collecting information that would be useful for determining potential enhancements to the existing WSDOT tool, or locating candidates for a replacement tool.

These research results describe existing road user cost tools, results of surveys about road user cost tool use, and comparative reviews of specific tools that include QUEWZ. The tool descriptions include information about the features, input requirements, and output options of each tool, while the survey results describe which tools are used by individual state DOTs. The comparisons provide some information about the strengths and weaknesses of individual tools.

- Edara and Cottrell (2007) focused on identifying state-of-the-practice tools (as of 2007) via a survey of state DOTs as well as all districts within the Virginia DOT (VDOT). The document reviewed HCM-based tools, spreadsheets, and simulation models and summarized their strengths and weaknesses. They considered QUEWZ 98's strengths to be its ease of use and ability to develop estimates quickly; however, its diversion algorithm was considered to be "simplistic," with outputs affected by the use of Texas data collected from freeways with parallel frontage roads. The results of a survey of the state of the practice for the VDOT districts and 19 states were also summarized, along with tool usage for 10 other states based on literature searches.

- The 2011 Federal Highway Administration document "Work Zone Road User Costs" and related website "A Primer on Work Zone Safety and Mobility Performance Measurement" include a broad discussion of a variety of topics related to work zone performance measurement as they relate to road user costs, including tools ranging from sketch-planning approaches to microscopic simulation (FHWA 2011). In the sketch-planning category, the website discusses the features of spreadsheet-based tools developed and used by state agencies, as well as QUEWZ 98, Quick Zone, and CA4PRS.

- Qin and Cutler (2013) discussed the range of methods used by various states to estimate road user costs in the context of developing a road user cost estimation methodology specific to South Dakota. The discussion included an overview of spreadsheet-based models and the methodologies that they use to estimate road user costs, along with QUEWZ, Quickzone, and other commercial tools.

- Malaghan (2014) compared six deterministic Excel spreadsheet-based tools used by state DOTs. The comparisons focused on the degree to which the tools use Highway Capacity Manual methodologies for estimating work zone capacity, and the degree to which the model outputs match three case studies of field data collected in Ohio. A review showed that two of the six spreadsheets required that the user supply the capacity value as a user input. The other four spreadsheets used HCM capacity values or capacity estimation methods, though only two tools used some or all of the HCM 2010 methodology (HCM 2010 was the most recent HCM edition, as of the time of the research). None of the tools included HCM methods for handling oversaturated conditions. Comparisons of capacity outputs from the model vs. field data showed that the spreadsheet tools that adopted the HCM 2010 methods produced the closest estimates of field capacity values.

- Benekohal et al. (2003) surveyed Illinois DOT district offices and state DOTs about the methods they used to estimate work zone capacity, queueing, delay, and user costs, and evaluated the ability of selected tools (FRESIM, QUEWZ, and Quickzone) to accurately estimate queueing characteristics, based on construction field data from locations in Illinois. QUEWZ was found to underestimate capacity and overestimate average speed when no queueing was occurring, and to overestimate both capacity and average speed during queueing. The model also underestimated queue length, whether using default or adjusted capacity parameters.

- Schnell et al. (2002) collected queue length and delay data from Ohio construction zones, and compared the data to outputs from five tools: Synchro, CORSIM, QUEWZ 92, Highway Capacity Software (HCS), and an Ohio DOT proprietary spreadsheet. The results showed that the micro simulation tools (Synchro, CORSIM) significantly underestimated queue lengths, QUEWZ also generally underestimated queue length, and the ODOT spreadsheet produced the most accurate maximum queue lengths (if capacity inputs were accurate). QUEWZ produced the most accurate work zone capacity estimates.

- Zhu and Ahmad (2008) described research to develop a user-friendly road user cost estimation method and tool for Florida DOT. The research project included a literature review of road user cost methods, a comparison of three existing tools including QUEWZ, and a discussion of the new method that was developed from the project. The new method was based on established sources such as the AASHTO Redbook and the HCM. The new method was also compared with Arizona DOT's "ADOT" model and QUEWZ in terms of user input requirements and overall road user costs based on selected examples.

- Rister and Graves (2002) focused on developing a potential approach for estimating road user costs in a work zone for use in Kentucky. They compared three models, with the objective of selecting one model for subsequent tests with field data: Quickzone, QUEWZ 98, and DP-115. The researchers described QUEWZ 98's key features as the capacity estimation method, a diversion algorithm, the option to either estimate user costs or optimize a lane closure schedule, and emissions cost estimation. The weaknesses were its DOS requirement, a diversion algorithm based on Texas field data from freeways with parallel frontage roads, a simple queue length estimation process, the inability to carry queues past midnight, and volume distributions based on Texas field data. They ultimately selected a different tool (DP-115) for testing.

6. Conclusions and Recommendations

A review of the derivation of selected formulas in the QUEWZ model showed that equations were based on a combination of Highway Capacity Manual-based concepts, empirically derived formulas, supplementary research, and professional judgment. The authors of this report firmly believe that the QUEWZ process is defensible given its use of well accepted national research. We find it to be acceptably accurate; however, the historical QUEWZ model does use some older statistics that should be updated to reflect more modern conditions.

1. Update input parameters

The updates are the highest priority changes that WSDOT should consider as it continues to use QUEWZ. The highest priority refinements would be to ensure that the input parameters used within QUEWZ are updated. These include the following:

- Cost computation factors
  - value of time for the individual traveler
  - cost of living update factor (using the Consumer Price Index and/or the Producer Price Index)
- Vehicle operating (running) costs, by vehicle type
- Speed computation factors
  - speed-volume input parameters (freeflow, LOS D/E breakpoint, and capacity values)
  - capacity estimate risk factor (CERF)
- Other user-adjustable factors, such as the percentage of trucks in the vehicle stream.

2. Adopt speed/capacity algorithms

The next most important update would be to adopt speed/capacity algorithms included in the sixth edition of the HCM as they apply to work zones. These refinements are discussed in detail in Section 4b of this report.

3. Perform sensitivity tests

The third recommendation is for WSDOT to perform tests of the sensitivity of the various components of the QUEWZ approach. This would allow WSDOT to pinpoint specific features of the QUEWZ model that have the most impact on delay and delay cost estimates. Attention could then be focused on the specific parameters associated with those computations. This would then allow WSDOT to determine whether some of the parameters inherent in those algorithms need to be refined further to reflect state-specific driver behavior and vehicle characteristics.

4. Add model features or select replacement model

Next, WSDOT should consider adding model features to improve output accuracy or expand user options, or selecting or developing a replacement model that better meets WSDOT needs. The most potentially beneficial of these enhancements would be the development of a diversion estimation process. While the addition of such a process could result in a more accurate delay estimate for those work zones where diversion is likely, the difficulty and complexity of developing a useable and accurate diversion model make this a lower priority improvement than items recommended above.

Given the difficulty of adding a diversion component to the model, other feature additions, such as adding the cost of emissions (greenhouse gases and other pollutants) or making further improvements to the user interface or output details might provide a better return on investment to WSDOT. Determining a full set of potential feature additions, and estimating a cost and likely return on investment for those features, were outside of the scope of this project. As a result, it is not possible for the project team to make a prioritized list of recommended feature additions. Performing a study that identified, scoped, and prioritized such a list might be considered as the next logical step in the refinement of the QUEWZ model in order to meet changing WSDOT needs.

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