WORK ZONE QUEUE LENGTH & DELAY METHODOLOGY

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ABSTRACT

Development of reliable strategies to overcome adverse mobility impacts of highway work zones requires accurate computation of delay and queues in work zones. This paper presents a methodology for quantifying the mobility impacts that considers the effects of roadway and traffic on speeds (and delays) of cars and heavy vehicles separately. Several factors such as roadway width, speed variation, and differences in speed of cars and heavy vehicles on delay and queue length are considered. The delay caused due to the differences in speeds of different vehicles can be significant when there is limited opportunity for passing or there are significant slow-moving vehicles. It is proposed to determine the impact of such factors on the operating speeds of the vehicles in work zones and use it to compute the capacity-at-operating-speed from the speed-flow curves developed for work zones. Then the speed and capacity are used to compute delay and queue length. Delay is divided into queue delay and moving delay. The moving delay is computed using delay-based passenger car equivalent (PCE) values for work zones. Queue delay is computed based on input-output analysis approach using the capacity as determined in this study. The methodology is illustrated by a step-by-step procedure for computing delay and queue length.

INTRODUCTION

Work zones have become the rule rather than the exception on highways today. About 20 percent of the U.S. National Highway System has been reported to be under construction during the peak summer road work season (*1*). For any queue/delay mitigation strategy to be effective in work zones reliable and accurate information on delays in work zones is required.

The Work Zone Safety and Mobility Rule (*2*) requires that all the state and local governments comply with the “rule” by Oct 12, 2007 to continue to receive federal aid. One of the three main components of the rule is to develop procedures to assess and manage work zone safety and mobility impacts of individual projects. User delay is a measure of mobility in a work zone and some state DOTs such as Illinois and Wyoming specify the maximum user delay for a project. User delay is also used by state DOTs, such as Arizona (*3*) and Illinois (*4*) to determine the incentive/disincentive for the contractor. Thus, there is a need for accurate and reliable methodologies for computing delay and queue length in work zones.

This paper presents a methodology for computing queue length, delay and user costs in work zones that considers the effects of road and traffic on speeds (and delay) of cars and heavy vehicles separately. It accounts for the effects of various work zone factors such as lane widths, lateral clearances, speed limit, and speed enforcement on speeds of cars and trucks. In addition, in this methodology, the difference in the speeds (and delay) of cars and heavy vehicles is considered. It also accounts for the delay due to the differences in the desired speeds of different drivers. This can be significant when there is only one lane for travel and/or there are significant slow-moving vehicles. Past research (*5-12*) reported that heavy vehicles travel at slower speeds than cars in work zones even on level terrain. This methodology uses a few of the steps outlined in a previously proposed methodology developed by Chitturi et al. (*13*). This methodology can be used in the design stage as well as for real-time implementation if data are available. One real-time application can be to forecast the queue length, delay and appropriately provide information to motorists upstream of the work zone.

First, a literature review of the previous methodologies for computing delay is presented. Second, the concept behind the delay-based methodology is explained. Third, how delay-based

PCE is used to compute the moving delay is explained and illustrated with an example. Finally a step-by-step methodology for computing user delays is presented.

LITERATURE REVIEW

Jiang (*14-17*) collected data from four work zones on 4-lane interstate highways with congested traffic conditions and determined the capacity, queue-discharge rate, mean speeds during congested and uncongested traffic conditions. A model for user costs was developed considering both traffic delay costs and additional vehicle operating costs. This work assumes one single number for capacity and speed in work zone regardless of work intensity, lane widths, lateral clearances, speed enforcement strategies etc. In other words, it does not consider the effect of work zone factors on capacity and speeds in work zones.

Jiang and Adeli (*18*) developed a freeway work zone traffic delay and cost optimization model considering the length of the work zone segment and the starting time of the work zone. The total work zone cost that included user delay, accident, and maintenance costs is minimized. Some of the factors like number of lane closures, darkness factor, and seasonal variation in travel demand that were not considered in previous research were considered in this research. Essentially the user delay costs are computed using the deterministic queuing analysis. The global optimum of the cost optimization problem for short-term work zones was solved using a Boltzmann-simulated annealing neural network. Some of the assumptions that make this model unrealistic are that all the vehicles travel at the same speed while approaching the work zone, in the work zone and exiting the work zone and the capacity of the work zone is a constant for any given number of lane closures. Also, Chien et al. (*19*) showed that using only the deterministic queuing theory approach always underestimates the delay. This model requires that the user input the work zone capacity without any guidance as to how to determine the capacity.

Karim and Adeli (*20*) developed a radial-basis function neural network to obtain the work zone capacity for a given work zone traffic control setup. The factors considered were number of open lanes, work zone layout, length, lane width, percentage trucks, grade, speed, work intensity, darkness factor, and proximity of ramps. The neural network was trained using forty examples. The network was tested using 27 capacity values from field data. The errors ranged from 0.4% to 71%. The reason for higher errors was stated to be higher percentage heavy vehicles in the test cases than the percentage heavy vehicles used in the training set. This capacity is used in a deterministic traffic model to determine the queue delays and lengths. It should be noted that in this model the moving delay or delay due to slower travel speed in work zones is not considered.

Adeli (*21*) developed an adaptive neuro-fuzzy logic model for estimation of the freeway work zone capacity considering seventeen different factors that can impact the work zone capacity. The parameters associated with the bell-shaped Gaussian membership functions used in the fuzzy inference mechanism were determined using a neural network. One hundred thirty three datasets obtained from the previous studies were used for training the model. Twenty one sets were used for checking and fourteen were used for testing the model. The capacity values predicted by the neuro-fuzzy model were compared to two empirical equations proposed by previous researchers. The root mean squared error was the lowest (127) for the neuro-fuzzy model than the other two empirical equations. The percentage error varied from 0.9 to 13.5%. One factor not considered by this model is the speed difference between cars and heavy vehicles. It should be noted that the testing datasets were drawn from the similar group as used for training. How the model performs when it is used for other datasets was not evaluated.

Adeli (*21*) developed clustering-Radial Basis Function neural network and Back Propagation neural network for estimating the work zone capacity considering seventeen factors that can affect capacity. Thirty nine datasets were used to train the neural network. Eight datasets were used for validation of the developed models. The values predicted by the neuro-fuzzy logic model of Adeli are compared to the values predicted by the two neural network models. It was reported that the RBFNN model had the least error of the three models and the error ranged from 0.1% to 8.7%. In this study also the datasets used for validation came from similar datasets used for training the models. As with Adeli (*21*) these models do not consider the speed difference between cars and heavy vehicles.

Chien et al. (*19*) developed a method to determine delays by using limited simulation data from CORSIM and deterministic queuing model. Delay was considered to have two components: moving delay and queuing delay. A calibrated and validated simulation model of an interstate highway was used to generate the relationship between volume to capacity ratio and average queuing delay per vehicle. However, it should be noted that Chitturi and Benekohal (*22*), found CORSIM could not represent the work zone speeds for oversaturated conditions, even when it was properly calibrated based on field data from work zones on interstate highways. Therefore, as the authors conclude this model needs further calibration and validation.

Chitturi and Benekohal (*22*) compared the outputs of QUEWZ, QuickZone and CORSIM with field data from work zones on interstate highways. They reported that QUEWZ overestimated the capacity when there was queuing and underestimated capacity when there was no queuing. Also, QUEWZ overestimated the average speed, but underestimated the average queue length. Speeds computed in FRESIM were comparable to the average speeds from the field data, when there is no queuing at work zones. However, when there was queuing, FRESIM overestimated the speed. Queue lengths obtained from the FRESIM results did not match the field data. The queue lengths from QuickZone did not match the field data and generally QuickZone underestimated the queue lengths. QuickZone consistently underestimated the total delay observed in the field.

Chitturi et al. (*13*) developed a methodology for computing queue length, delay and users costs in work zones considering the effect of various work zone factors such as narrow lane widths, lateral clearances, work intensity etc. They developed a speed-flow curve for work zones based on field data and their knowledge. In this methodology the speed reduction values recommended were taken from HCM for basic freeway sections due to lack of work zone data. Also this methodology does not consider the effect of speed difference between cars and heavy vehicles in the work zones.

PROPOSED METHODOLOGY

Need for a New Methodology

Several methodologies have been proposed by previous researchers to compute the delays and user costs in work zones. However they do not consider the variability in the desired speeds of the drivers within a vehicle type and between vehicle types. Figure 1 shows the desired speed distributions of the drivers in work zones on interstate highways. Desired speed refers to the speeds of the drivers when they are free flowing or in other words when they not constrained by any other vehicles. Figure 1 shows that the desired speeds of cars are significantly different from the desired speeds of heavy vehicles. The average desired speed of the heavy vehicles is about 8 km/h (5 mph) lower than the desired speed of cars. Even within a single vehicle type, there is a significant variability in the desired speeds. The difference between max and min desired speeds for cars is about 48 km/h (30 mph) and for heavy vehicles 32 km/h (20 mph). Even when the traffic stream is composed of only cars the stream can experience a significant delay because of the wide range in the desired speeds of cars. Therefore, the variability of the desired speeds (within and between vehicle types) can cause significant delay to the users and must be accounted for in computing the delays. This factor becomes all the more significant when there is only one lane for travel in a work zone. Therefore, the methodology presented here accounts for the speed difference between cars and heavy vehicles and the variability in the desired speeds of cars which was not done before.

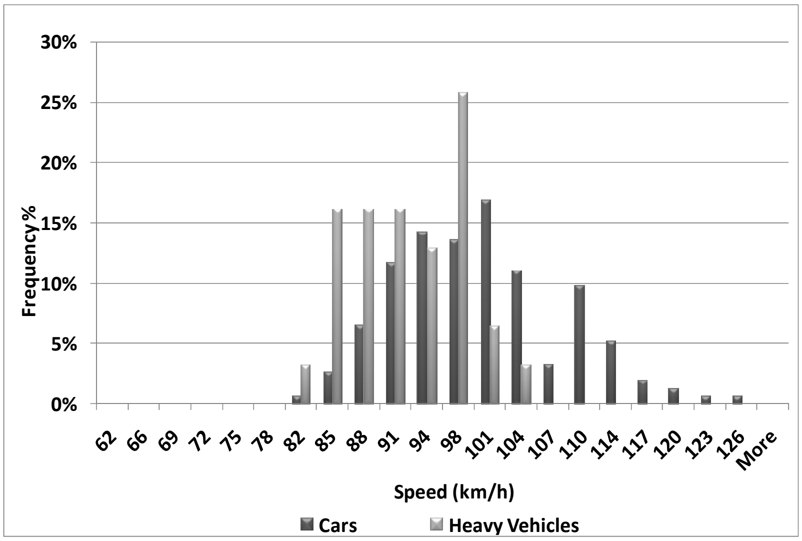


FIGURE 1 Desired speed distribution of drivers in a work zone.

This methodology builds on the methodology developed by Chitturi et al. (*13*) for work zones. Capacity is determined from speed flow curves developed for work zones considering this speed difference between cars and heavy vehicles. In addition, the values used for reductions in free flow speed due to narrow lane widths used in this methodology were obtained from field data as reported in Chitturi and Benekohal (*9*).

Concept Behind The Proposed Methodology

In this methodology, delay has two components: queue delay and moving delay. Moving delay refers to the delay experienced by the users in the lane closure area. Queue delay refers to the delay experienced by the users before they enter the lane closure area which could be due to demand exceeding capacity.

Speeds of the vehicles in the lane closure section and consequently moving delay are influenced by several work zone factors such as work intensity, narrow lane widths and lateral clearances, speed enforcement etc. In addition if there is only one lane for travel, the difference in the desired speeds of different vehicles can cause significant moving delay. Also, previous research has shown that the speeds of the heavy vehicles and cars are different in the work zone even on level terrain. Delay-based PCE (D_PCE) is computed considering these factors and is used to compute the moving delay (*23*). The computational procedure for determining D_PCE is explained in the next section.

Queue delay is computed by considering cumulative arrivals and cumulative capacity-at-operating-speed. Computing queue delay from cumulative arrival and departure curves has been used by many publications including HCM. In the proposed methodology, however, the departure rate is determined based on the operating speed in the work zone. Finding the capacity-at-operating-speed from operating speed is similar to the approach used in Chitturi et al. (*13*), but in the proposed approach the decision about which speed-flow curve should be used is made in a different way. Speed flow curves were found to differ depending on the percentage heavy vehicles and the speed difference between cars and heavy vehicles. Therefore, the capacity-at-operating-speed is determined from the speed-flow curve that corresponds to the speed difference between cars and heavy vehicles and the percentage of heavy vehicles in the work zone. These speed-flow curves were developed using data from calibrated VISSIM.

USING D_PCE TO COMPUTE MOVING DELAY

The moving delay is computed using the delay-based PCE values. By definition, delay-based PCE (D_PCE) ensures that the converted volume (of only passenger cars) and original mixed traffic stream have the same total delay (*23*). Therefore the delay experienced by a mixed traffic stream is computed by converting the volume of mixed traffic into equal-delay-volume (EDV) in passenger cars and multiplying it with the delay experienced by cars in the basecase.

This involves three steps:

1. determine the equal-delay-volume (EDV)
2. determine the base delay
3. compute the moving delay by multiplying EDV with base delay.

Computation of Equal-Delay-Volume (EDV)

Equal-delay-volume is that volume of cars-only traffic stream that would have the same delay as the mixed traffic stream. EDV is determined by using D_PCE as shown in equation 1.

$$EDV = V * (1+P_{HV}(D\_PCE-1)) \quad (1)$$

Where

EDV = Equal-delay-volume (in pc)

V = Volume of mixed traffic (in vph)

P_{HV} = Percentage heavy vehicles (%)

D_PCE= Delay-based PCE for the particular scenario

As explained before D_PCE ensures that the mixed traffic stream and the passenger car only stream have the same total delay. The D_PCE values depend on the length of the work zone, traffic volume, truck percentage, speed difference between cars and heavy vehicles. The delay-based PCE values for various scenarios were developed and recommended by Chitturi (*13*) and are used here.

Computation of Base Delay

It should be noted that because all the motorists do not have the same desired speed, the car-only traffic stream also would experience some delay. In other words the delay in the basecase is due to the slow-moving cars delaying other cars. Consequently the average travel speed of cars in the basecase is less than the average desired speed. As expected, the longer the work zone or the higher the volumes the greater will be the difference between the average travel speed and the average desired speeds.

Table 1 shows the reductions in the average desired speed of cars for various work zone lengths and volume levels. These values were computed by obtaining the average travel speeds under various scenarios using the calibrated VISSIM. Chitturi (*23*) validated the average speeds in work zones obtained from the VISSIM. The speed limit of the work zone was assumed to be 88 km/h (55 mph). The desired speeds were generated from a normal distribution with mean of 96 km/h (60 mph) and standard deviation of 8 km/h (5 mph) because the speed limit is 88 km/h (55 mph) and as Chitturi and Benekohal (*9*) recommended, it is reasonable to assume that the desired speed of the drivers in work zones or freeways or freeway work zones is 8 km/h (5 mph) over the speed limit.

TABLE 1 Reduction In Average Desired Speed Of Cars For Various Volumes And Work Zone Lengths

Volume (pc/hr)	Speed Reduction in km/h (in mph)		
	1.6 km (1 mi) WZ	8 km (5 mi) WZ	16 km (10 mi) WZ
200	3.7 (2.3)	6.2 (3.9)	8.8 (5.5)
400	6.1 (3.8)	9.3 (5.8)	12.0 (7.5)
600	8.0 (5)	11.8 (7.4)	14.1 (8.8)
800	9.8 (6.1)	13.8 (8.6)	16.0 (10)
1000	11.5 (7.2)	15.4 (9.6)	17.4 (10.9)
1200	13.0 (8.1)	16.8 (10.5)	18.6 (11.6)
1300	13.8 (8.6)	17.4 (10.9)	19.4 (12.1)
1400	14.7 (9.2)	18.2 (11.4)	19.7 (12.3)
1500	15.7 (9.8)	18.9 (11.8)	20.3 (12.7)
1600	16.5 (10.3)	19.7 (12.3)	20.8 (13)
1700	17.8 (11.1)	20.5 (12.8)	21.6 (13.5)
1800	19.5 (12.2)	21.4 (13.4)	22.2 (13.9)

The delay in the basecase is computed relative to 112 km/h (70 mph) (speed limit +5 mph) as shown in equation 2. Speed limit outside the work zones was 104 km/h (65 mph).

$$d_{base} = L \times \left(\frac{1}{v_{des} - v_{red}} - \frac{1}{v_{ref}} \right) \qquad (2)$$

Where
d_{base} = delay in basecase (hrs/car)
L = Length of work zone (km)
v_{des} = average desired speed of cars (8 km/h or 5mph over the speed limit) (km/h)
v_{red} = reduction in average desired speed of cars (obtained from Table 1) (km/h)
v_{ref} = reference speed or speed relative to which delay is computed.(km/h)

Computation of Delay For Mixed Traffic Stream

The moving delay is computed by multiplying the EDV with the base delay as shown in equation 3.

$$d_{moving} = EDV * d_{base} \quad (3)$$

Example of Moving Delay Computation

Consider a traffic volume of 1200 vph with 20% heavy vehicles in a ten mile work zone with 24 km/h (15 mph) speed difference between cars and heavy vehicles. The recommended D_PCE value for this scenario is 7.4 (*23*).

Computation of EDV

Traffic Volume (V) = 1200 vph

Heavy Vehicle Percentage (P_{HV}) = 20%

D_PCE = 7.4

$$EDV = V * (1+P_{HV}(D\_PCE-1))$$
$$= 1200 * (1 + 0.20 (7.4-1))$$
$$= 2736 \text{ pc}$$

Therefore the EDV of 2736 passenger cars would cause the same amount of total delay as a 1200 vph traffic stream with 20% heavy vehicles traveling 24 km/h (15 mph) slower than passenger cars. It should be noted that the total delay experienced by the 1200 vph of mixed traffic stream (actual mixed vehicles) is same as the total delay experienced by 2736 pc (assumed traffic composed of only cars travelling at a higher speed than the mixed traffic) going through the work zone. It should be noted that EDV of 2736 pc does not indicate that 2736 pc can be processed by the work zone in an hour.

Computation of Base Delay

From Table 1 it can be found that the reduction in average desired speed (v_{red}) for 1200 pcph and 16 km (10 mi) work zone is 18.6 km/h (11.6 mph). The average desired speed is 8 km/h (5mph) over the speed limit resulting in 96 km/h (60 mph). Therefore the average travel speed of cars is 96 – 18.6 which is equal to 77.4 km/h (48.4 mph).

Base delay is computed using equation 2.

$$d_{base} = L * ((1/(96-18.6)) – (1/112))$$
$$= 16 * ((1/77.4)-(1/112))$$
$$= 0.0638 \text{ hrs}$$

Computation of Moving Delay

User delay is the product of EDV and base delay. Therefore,

$$d_{moving} = EDV * d_{base}$$
$$= 2736 * 0.0638$$
$$= 174.56 \text{ hrs}$$

Traffic volume of 1200 vph with 20% heavy vehicles was simulated through a 16 km (10 mile) work zone with 24 km/h (15 mph) speed difference between cars and heavy vehicles using VISSIM. The delay obtained from VISSIM for this scenario was 176.18 hours which is very close to the computed delay of 174.56 hours. The computed delay using D_PCE is 0.9% less than the delay obtained from simulation. This example illustrates that the delays computed by using D_PCE are close to the delays found from simulation.

STEP-BY-STEP METHODOLOGY FOR DETERMINING USER DELAY AND USERS COSTS IN WORK ZONES

This methodology has 12 steps of which some may be skipped depending on whether demand exceeds the capacity or not. Speed adjustments due to lane width, lateral clearance, work intensity and other factors are done in Steps 1 thru 4 to determine the operating speed in the work zone. In step 4, the reduction in speed due to the variability in desired speeds of cars is accounted for. In Step 5, the difference in the speeds of cars and heavy vehicles is computed. The operating speed is used to find the capacity-at-operating-speed of the work zone in Step 6. If demand is greater than capacity-at-operating-speed, calculations for Steps 7 and 8 are performed to find queue length and queue delay respectively otherwise these two steps are skipped. Then in Steps 9 thru 11 delays are computed and finally in Step 12 the user costs are computed. Now the details of the steps are presented:

1. Find speed reductions due to narrow lane width (R_{LW}) and less than ideal lateral clearance (R_{LC}) from Table 2. The reductions due to lane width were recommended by Chitturi and Benekohal (*9*) using data from work zones and the reductions due to narrow right shoulder widths are from the HCM (*24*).

For left shoulders narrower than 2 ft, the HCM (*24*) does not have any speed reduction values for basic freeway sections. Until such data are available for work zones the following numbers are recommended by the authors based on their knowledge. When the number of travel lanes is 1 or 2 in the work zone the recommended speed reduction due to a 1 ft left shoulder is 1.6 km/h (1 mph) and due to no left shoulder is 3.2 km/h (2 mph). When more lanes are present in the work zone the recommended speed reduction should be adjusted. Specifically it should be multiplied by (2/number of lanes in work zone). Future research is recommended to quantify these values for work zones.

TABLE 2 Adjustments Due to Lane Width and Lateral Clearance (from HCM 2000 (*24*) and Benekohal et al. (*25*))

Adjustment for lane width				
Lane width in m (ft)	**Reduction in speed in km/h (mph)**			
3.6 (12) or more	0.0			
3.45 (11.5)	3.4 (2.1)			
3.3 (11)	7 (4.4)			
3.15 (10.5)	11.2 (7)			
3 (10)	16 (10)			
2.7 (9)	24* (15)			
2.4 (8)	40* (25)			
Adjustment for right shoulder				
Right shoulder width in m (ft)	**Reduction in speed in km/h (mph)**			
	No of Lanes in one direction			
	2	**3**	**4**	**>= 5**
1.8 (6) or more	0	0	0	0
1.5 (5)	1 (0.6)	0.6 (0.4)	0.3 (0.2)	0.2 (0.1)
1.2 (4)	1.9 (1.2)	1.3 (0.8)	0.6 (0.4)	0.3 (0.2)
0.9 (3)	2.9 (1.8)	1.9 (1.2)	1 (0.6)	0.5 (0.3)
0.6 (2)	3.8 (2.4)	2.6 (1.6)	1.3 (0.8)	0.6 (0.4)
0.3 (1)	4.8 (3.0)	3.2 (2.0)	1.6 (1.0)	0.8 (0.5)
0	5.8 (3.6)	3.8 (2.4)	1.9 (1.2)	1 (0.6)

2. Compute the work intensity ratio (WI_r) using Equation 4.

$$WI_r = \frac{w + e}{p} \quad (4)$$

Where,
WI_r = Work intensity ratio
w = Number of workers working together as a group in the work activity area (w varies from 0 to a maximum of 10)
e = Number of large construction equipment in work activity area near the workers group (e varies from 0 to a maximum of 5)
p = Lateral distance between the work area and the open lane (feet) (p varies from 1 to a maximum of 9 ft)

3. Using the work intensity ratio (WI_r) computed in step 2, compute the speed reduction (R_{WI}) due to work intensity from Equation 5 for short-term work zones and Equation 6 for long-term work zones. These relationships were developed by Benekohal et al. (*25*) and "ln" stands for natural logarithm in them.

$$R_{WI} = \begin{cases} SR_S \text{ in} & \text{short} - \text{term} WZ \\ SR_L \text{ in} & \text{long} - \text{term} WZ \end{cases}$$

$$SR_S = 11.918 + 2.676 \ln(WI_r) \quad (5)$$

Where,
SR_S = Speed reduction in short term work zones (in mph)
WI_r = Work intensity ratio
Speed reduction for long term work zones is computed from Equation 6.

$$SR_L = 2.6625 + 1.2056 \ln(WI_r) \quad (6)$$

Where,
SR_L = Speed reduction in long term work zones (mph)
WI_r = Work intensity ratio

4. Calculate the Operating speed (U_O) based on Equation 7.

$$U_O = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \quad (7)$$

Where,
U_o = Operating Speed (km/h)
FFS = Free flow speed (It is assumed that FFS= Speed limit + 8 km/h)
R_{LW} = Reduction in speed due to lane width (km/h), see Table 2
R_{LC} = Reduction in speed due to lateral clearance (km/h), see Table 2
R_{WI} = Reduction in speed due to work intensity (km/h)
R_O = Reduction in speed due to all other factors that may reduce speed (km/h)

It should be noted that all the drivers do not have the same desired speed. Consequently the slow-moving cars would delay other cars as they traverse the work zone. The reduction in the average speeds of the vehicles due to the variation in their desired speeds is included in R_O. The amount of difference between the average speed and the mean desired speed increases with the volume of traffic and length of work zone. The corrections to the mean desired speed to obtain the average speed of cars (R_O) are shown in Table 1 for various volume levels and work zone lengths.

5. Determine the speed difference between cars and heavy vehicles using equation 8. This can comprise difference in the speed reductions due to narrow lanes, narrow shoulders, work intensity, speed enforcement and other factors that can cause speed difference between the two vehicle types.

$$\Delta_{total} = \Delta_{LW} + \Delta_{LC} + \Delta_{WI} + \Delta_{ENF} + \Delta_O \quad (8)$$

Where,
Δ_{total} = Difference in speeds of cars and heavy vehicles due to all the factors (km/h)
Δ_{LW} = Difference in speed reductions of cars and heavy vehicles due to narrow lane widths (km/h)

Δ_{LC} = Difference in speed reductions of cars and heavy vehicles due to narrow lateral clearance (km/h)

Δ_{WI} = Difference in speed reductions of cars and heavy vehicles due to work intensity (km/h)

Δ_{ENF} = Difference in speed reductions of cars and heavy vehicles due to speed enforcement (km/h)

Δ_{O} = Difference in speeds of cars and heavy vehicles due to other factors (km/h)

It should be noted that the differences between the speeds of the vehicles have not been quantified, although several researchers have reported speed difference between cars and heavy vehicles in work zones even on level terrain. Nevertheless, this methodology is designed to consider this speed difference between vehicle types. It is strongly recommended that these differences are quantified by future research.

6. Determine the appropriate speed-flow curve according to the length of the work zone, speed difference between cars and trucks, and percentage heavy vehicles. Find the capacity-at-operating-speed (C_{Uo}) corresponding to the operating speed by entering the operating speed on the vertical axis. The speed-flow curves for 16 km (10mi) WZ with 16 km/h (10 mph) speed difference and different heavy vehicle percentages are shown in Figure 2.

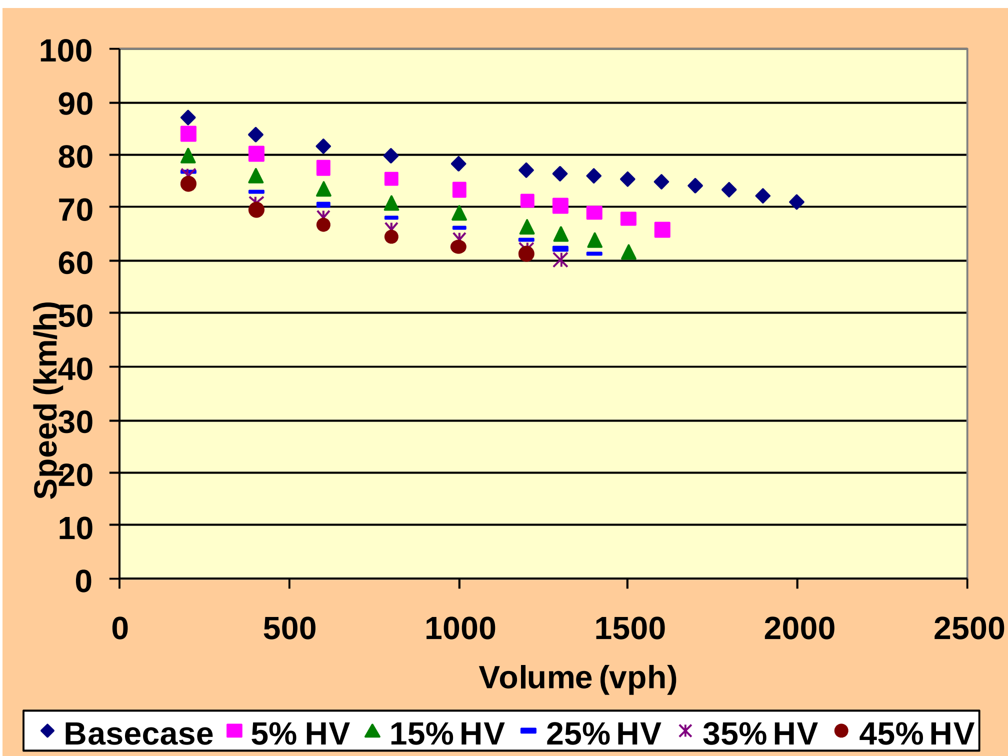


FIGURE 2 Speed- flow curve for 16 km (10 mi) Work Zone with 16 km/h (10 mph) speed difference.

The curves shown in Figure 2 were developed by using the data obtained from the VISSIM simulations. The congested part of the speed flow curve needs to be determined. Figure 2 clearly shows that when there is a speed difference between vehicle types, the speed flow curve depends upon the percentage of heavy vehicles. Consequently it is proposed that such curves be developed using a combination of simulation and field data for use in this methodology.

7. If demand is less than capacity-at-operating-speed skip to step 9, otherwise continue.
Estimate the queue length at the end of every hour using the following procedure.
Compute number of vehicles in queue (n_{i+1}) at the end of $(i+1)^{th}$ hour using Equation 9.

$$n_{i+1} = n_i + V_{i+1} - C_{Uo} * N_{op} \quad (9)$$

Where,

n_i = Number of vehicles in queue at the end of i^{th} hour
n_{i+1} = Number of vehicles in queue at the end of $(i+1)^{th}$ hour
V_{i+1} = Total demand in $(i+1)^{th}$ hour (vph)
C_{Uo} = Capacity-at-operating-speed (vphpl)
N_{op} = Number of lanes open in the work zone

Compute l_{eff} (effective spacing between vehicles) using Equation 10.

$$l_{eff} = (P_T * l_T + P_C * l_C) + buffer\ space \quad (10)$$

Where,

l_{eff} = Effective spacing between vehicles (m)
P_T = Percentage of heavy vehicles (entered as a fraction)
l_T = Length of heavy vehicles (m)
P_C = Percentage of passenger cars (entered as a fraction)
l_C = Length of passenger cars (m)
buffer space = Distance between vehicles when they are stopped (3.3 m)

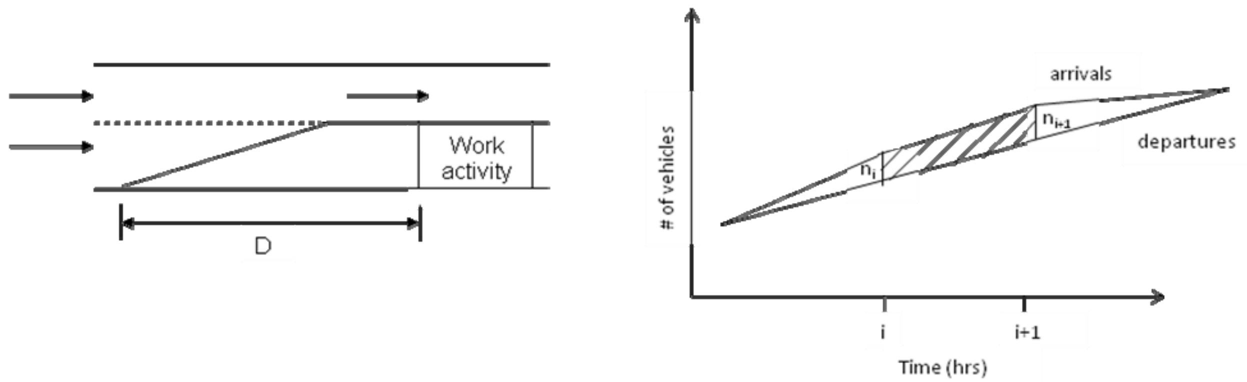
Calculate stacked queue length (Q_{Si}) using Equation 11.

$$Q_{Si} = n_i * l_{eff} \quad (11)$$

Where,

Q_{Si} = Stacked queue length at the end of i^{th} hour (m)
n_i = Number of vehicles in queue at the end of i^{th} hour
l_{eff} = Effective spacing between vehicles (m)

Determine the distance from the work activity area to the beginning of the transition taper (D) as depicted in Figure 3a.



a) Determining D in a work zone b) Average delay due to queuing

FIGURE 3 Queue and delay computation.

If D > Q_{Si} / N_{op}, queue will not extend outside of the work zone. Then queue length at the end of the i^{th} hour is computed using Equation 12.

$$Q_i = Q_{Si} / N_{op} \tag{12}$$

Where

Q_i = Queue length at the end of the i^{th} hour (m)
Q_{Si} = Stacked queue length at the end of i^{th} hour (m)
N_{op} = Number of lanes open in the work zone

If D < Q_{Si} / N_{op}, queue will extend outside of the work zone. Then queue length at the end of the i^{th} hour is computed using Equation 13.

$$Q_i = D + (Q_{Si} - D*N_{op}) / N_{nr} \tag{13}$$

Where,

Q_i = Queue length at the end of the i^{th} hour (m)
D = Distance from the work activity area to the beginning of the taper (m)
Q_{Si} = Stacked queue length at the end of i^{th} hour (m)
N_{op} = Number of lanes open in the work zone
N_{nr} = Number of lanes open before the work zone

It should be noted that the queue length is measured from the beginning of the work activity area.

8. Estimate the delay due to queuing using the Equation 14.

$$d_q = \sum_{i=0}^{t-1} \left(\frac{n_i + n_{i+1}}{2} \right) \tag{14}$$

Where,

d_q = Delay due to queuing (in veh-hours)
t = Number of hours of queuing
n_i = Number of vehicles in queue at the end of i^{th} hour
n_{i+1} = Number of vehicles in queue at the end of $(i+1)^{th}$ hour

The shaded area shown in Figure 3b is a trapezoid and the average delay experienced by the vehicles during hour *i*+1 is given by $d_{i+1} = (n_i + n_{i+1})/2$

If we had "*t*" hours of queuing, the total queuing delay summed over the hours is given by Equation 14.

9. Determine the Equal-delay volume (EDV) for the given conditions using equation 1 shown again below.

$$EDV = V * (1+P_{HV}(D\_PCE-1))$$

Where,

EDV = Equal-delay-volume (pc)
V = minimum of hourly volume and Capacity-at-operating-speed (vph)
P_{HV} = Percentage heavy vehicles expressed in decimal
D_PCE = delay-based PCE for the given work zone length, speed difference between cars and heavy vehicles, volume and heavy vehicle percentage. If the traffic volume is below capacity-at-operating-speed D_PCE corresponding to the traffic volume should be used otherwise find D_PCE corresponding to the capacity-at-operating-speed.

10. Estimate the moving delay in the work zone using Equation 15.

$$d_{moving} = \sum_i EDV_i \times L \times \left(\frac{1}{v_{des} - v_{red}} - \frac{1}{v_{ref}} \right) \qquad (15)$$

Where,

d_{moving} = Moving delay in work zone (veh-hours)
L = Length of the work zone (km)
EDV_i = Equal-delay-volume in hour i (pc)
v_{des} = average desired speed of cars (8km/h over the speed limit)
v_{red} = reduction in average desired speed of cars (from Table 1)
v_{ref} = reference speed or speed relative to which delay is computed.

11. Estimate the total delay using Equation 16.

$$d_{total} = d_{moving} + d_q \qquad (16)$$

Where,

d_{total} = Total delay experienced by the users (veh-hours)
d_{moving} = Moving delay (veh-hours)
d_q = Queue delay (veh-hours)

12. Compute users cost using equation 17.

$$UC = d_{total} ((P_T * C_T) + (P_C * C_C * N_{occ})) \qquad (17)$$

Where,

UC = Total user costs ($)
d_{total} = Total delay experienced by the users (in veh-hours)

P_T = Percentage of heavy vehicles in decimal
C_T = Hourly delay costs for trucks ($/hr)
P_C = Percentage of passenger cars in decimal
C_C = Hourly delay costs for each passenger in a car ($/hr/passenger)
N_{occ} = Average number of occupants in cars (passengers/car)

CONCLUSIONS AND RECOMMENDATIONS

This paper presented a methodology (that builds on methodology developed earlier by the authors) for computing user delays and user costs in work zones that accounts for the speed difference between cars and heavy vehicles as well as the variability in the desired speeds of the drivers. The methodology is illustrated by a step-by-step procedure for computing delay and queue length.

Conceptually the effect of all the work zone factors on the speeds of the vehicles is computed and the capacity-at-operating-speed is determined from speed-flow curve for work zones. Then the speed and capacity is used to compute delay and queue length. For uncongested conditions, the speed flow curves were developed using data from calibrated VISSIM. Delay is divided into queue delay and moving delay. Moving delay is computed using the delay-based PCE values. Queue delay and queue length are computed using input-output analyses with the capacity determined as discussed in this paper.

In this methodology it was assumed that vehicles will maintain the highway speed upstream of the lane closure area when there is no flow breakdown. When there is flow breakdown the delay in this section can be substantial because of the formation of queues and this delay is accounted for in queue delay. Therefore, under non-breakdown conditions this methodology might underestimate the delays to the travelers.

Further research is recommended to collect field data to quantify the speed difference between cars and heavy vehicles due to narrow lane widths, lateral clearances, speed enforcement, work intensity and other factors. Also it is recommended that speed flow curves be developed for work zones considering the effect of speed difference between vehicle types.

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