PASSENGER CAR EQUIVALENTS FOR HEAVY VEHICLES IN WORK ZONES

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ABSTRACT

There are no PCE values developed for work zones. Consequently the PCE values of basic freeway section are borrowed despite the reservations about their applicability to WZ. This paper extended the delay-based methodology that was developed for intersections to work zones, and developed PCE values for heavy vehicles in work zones. Delay is used for defining the equivalence because it captures the effects of the heavy vehicles better than headway. Simulation was used to quantify the delays caused by the heavy vehicles so PCE values can be determined. Delay and consequently delay-based PCE (D-PCE) values are affected by the length of the work zone, the speed difference between cars and heavy vehicles, traffic volume, percentage trucks and other work zone factors. The D-PCE values computed when there is a 10 mph speed difference between cars and heavy vehicles ranged from 2.8 to 7.7. The D-PCE values decreased with increasing heavy vehicle percentage and increased with volume.

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)*. Work zones are a major contributor to the delay experienced by the motorists and are estimated to account for 889 million vehicle hours of delay which is nearly 24 percent of all non-recurring delay *(2)*. Another study *(3)* found that work zones contribute to 10% of the delay experienced in the entire United States and to 80 to 90% delay experienced in rural areas. Consequently managing traffic through work zones in a safe and efficient manner is a critical task that requires reliable and accurate information. Two important pieces of information for this task are the estimated values for capacity and delay. One of the key factors in capacity estimation is the passenger car equivalent (PCE) values used to convert heavy vehicles to equivalent number of cars. Heavy vehicles have adverse effects on work zone traffic flow and proper conversion of them to equivalent number of cars is a very important step in capacity calculation. It is estimated that about 36% of the rural interstate and 63% of urban interstate highway segments would carry more than 10,000 trucks per day by the year 2020 *(3)*. Consequently, accounting for the effects of heavy vehicles accurately becomes even more crucial.

There has been no published work on PCE of heavy vehicles in work zones. Due to this paucity of data, researchers *(4)* had to use the PCE values in Highway Capacity Manual 2000 *(5)* for basic freeway section despite being concerned about their applicability to WZ. Traffic flow in work zones is fundamentally different from basic freeway sections because of the influence of factors such as work activity, traffic control devices, speed control strategies, less than ideal geometric characteristics, fewer lanes for travel, speed difference between vehicle types, etc. All these can affect the speed and flow characteristics in WZ thus requiring developing capacity estimation techniques that are more appropriate for work zones.

In this paper we extended the delay-based methodology that was developed by Benekohal and Zhao *(6)* for intersections to work zones, and developed PCE values of heavy vehicles in work zones. First the approaches that were used to compute PCE in the past are summarized, followed by a discussion on which approach should be used. Following this the delay-based PCE methodology is presented and how it is used to compute the D-PCE values. This is followed by a discussion of how the D-PCE values are affected by traffic volume and truck percentage and how these values compare with the HCM values.

PAST APPROACHES TO COMPUTING PCE

The 1965 Highway Capacity Manual *(7)* first introduced the concept of Passenger Car Equivalent (PCE) and defined it as "The number of passenger cars displaced in traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions." Since then several studies using different approaches have been performed to estimate PCE. In this section a brief summary of the prominent studies using the different approaches is presented.

Headways

The headway ratio method was pioneered by Greenshields *(8)*. The concept behind using the headways (time or space) is that headway is a measure of the space occupied by a vehicle. PCE is defined as the ratio of average. This is the most commonly used method for measuring PCE at signalized intersections. This method has also been used for basic freeway sections and rural highways *(9,10)* but by considering the space headways instead of time headways. When the headway approach is used, the effect of the heavy vehicle on only the vehicle that is immediately following it is being considered. Therefore, major deficiency of headway approach is that it does not take into account the additional delay caused to the entire traffic stream due to heavy vehicles in work zones. Molina *(11)* proposed a modified headway approach to computing PCE at signalized intersections. Unlike the headway approaches discussed above, this approach considers the increased headways of the vehicles queued behind the truck at the signalized intersection but does not consider the additional delays experienced by the queued vehicles.

Speed

Speed has been used as the measure of performance primarily for two-lane and multilane highways. For two-lane highways St.John *(12)* and St.John and Kobett *(13)* developed a nonlinear relationship for deriving PCE using mean speed as the measure of equivalence. Linzer et al *(14)* used operating speed as the parameter for multilane highways. Messer *(15)* used simulation to compute PCE on two-lane highways. TWOWAF, a simulation model was used for this study. Van Aerde and Yagar *(16)* developed PCE for two-lane highways based on the speed reduction potentials of different vehicle classes.

Density

Webster and Elefteriadou *(17)* used density for computing the PCE of trucks on basic freeway sections. FRESIM was used to generate the density data for the different scenarios. The method used to determine the PCE is based on a method developed by Sumner et al *(18)*.

Travel Time or Delay

Keller and Saklas *(19)* derived PCE for urban arterials using total travel time of the traffic stream as the parameter. PCE was defined as the ratio of total travel time of heavy vehicles to the travel time of passenger cars traveling through an urban network. Cunagin and Messer *(20)* used delay to compute the PCE for trucks on two-lane highways. Craus, Polus and Grinberg *(21)* also proposed a method to compute PCE for two-lane highways based on delay. They also considered the delay due to the opposing traffic stream. However, these formulations for PCE do not ensure that the mixed and the passenger car-only traffic stream have the same total delay. Benekohal and Zhao *(6)* presented a methodology for computing PCE at signalized intersections based on delay. The underlying concept is that both the mixed and equivalent passenger car-only stream have the same total delay. Before this work the PCE for intersections was primarily based on headways. Although all the approaches discussed in this section use delay in computing PCE, only Benekohal and Zhao's approach results in same total delay for both the mixed stream and the equivalent passenger car only stream.

It should be noted that in work zones delay captures the effects of heavy vehicles better than any other factor. For example headway considers the effect of heavy vehicle only on the adjacent vehicle and not on all the vehicles that may be delayed if the heavy vehicle is traveling at a slower speed than cars. However when delay is considered the effect of heavy vehicle on all the cars is considered. Therefore a delay-based approach has been used to compute the PCE of heavy vehicles in work zones.

DELAY-BASED PASSENGER CAR EQUIVALENT (D-PCE) METHODOLOGY

The delay-based PCE used in this paper was first introduced by Benekohal and Zhao *(6)* for developing PCE for heavy vehicles at signalized intersections. In this research this concept is extended to the work zones. Delay-based PCE (D-PCE) is based on the concept that the additional delay caused by the presence of heavy vehicles is directly related to the capacity-reducing effect of the heavy vehicles in a work zone. The ratio of delay caused by a heavy vehicle to the delay of a car in an all passenger car traffic stream is defined as D-PCE. Mathematically D-PCE can be expressed as in equation (1)

$$D\_PCE_i = 1 + \frac{\Delta d_i}{d_0} \tag{1}$$

Where
$D\text{-}PCE_i$: delay based PCE for a heavy vehicle type *i*,
Δd_i : the additional delay caused by a heavy vehicle of type *i*
d_0 : the average vehicle delay when the traffic is composed of all-passenger cars.

Since delay is the parameter of concern in work zones, Delay-based PCE ensures that the mixed traffic stream and the equivalent passenger car only stream have the same total delay. For example, if a caravan of 10 cars experiences a delay of 50 seconds the average delay experienced (d_0) is 5 sec/veh. However if a caravan consisted of 2 trucks and eight cars and the total delay experienced was 70 seconds, the average additional delay due to each truck is Δd = (70-50)/2 = 10 sec/truck. Thus the D-PCE computed is 1+10/5 = 3. In other words, if each of the trucks were to be replaced by 3 cars to make a total of 14 cars the total delay would be 14*5 = 70 sec for the traffic stream. This is the difference between D-PCE approach and other approaches which used delay to compute PCE in the past.

There are several factors that can influence delay in work zones and thus D-PCE values. The main influential factors are: traffic volume, truck percentage, length of work zones, speed difference between vehicle types, grade and length of grade, lane and shoulder widths, speed control strategies, number of travel lanes in work zone.
Considering the huge number of combinations that can arise from changing these factors, it is not possible to collect field data for all these conditions. Even if there were time and resources to collect the field data it is impossible to control in the field the variation of each factor in the combinations. Thus, practically it is impossible to collect a complete set of field data to develop D-PCE values.

Therefore simulation is used to compute the D-PCE values for heavy vehicles in work zones. VISSIM was validated using field data from work zones by the authors. The default VISSIM was found to result in a capacity of about 2000 pcphpl, which is reasonable and comparable to the capacities of work zones found in earlier research. Therefore VISSIM with default values of the car following parameters is used to generate the D-PCE values. How VISSIM was used to do this is discussed in the following section.

COMPUTING D-PCE USING VISSIM

Concept

In VISSIM *(31),* input files are created according to the values of the different parameters. The general structure of the network created in VISSIM is that there are four links:

1. Upstream link: This link represents the regular basic freeway section.
2. Transition link: This link represents the stretch of freeway where the lane closure has not begun, but the speed limit is reduced to the work zone speed limit. This also includes the taper area.
3. Lane closure area: This link represents the actual lane closure area.
4. Exit link: This link represents the exit area where the drivers are back to the basic freeway section.

Vehicles are generated from the desired traffic volume and composition and fed to the upstream link. This link is sufficiently long (about 3 miles) to give the drivers the travel distance to adjust their car-following and speeds before they reach the transition link. It was also ensured that under high volume conditions the link can handle any queues that can propagate upstream of the lane closure. The desired speed distribution for all the vehicles is the same on the basic freeway section. A normal distribution with mean speed 5 mph over the speed limit (65 mph is used in this research) and a standard deviation of 5 mph is used for assigning the desired speeds of the drivers at entry in to the network.

For passenger cars, the desired speed distribution in the transition link and lane closure area is assumed to be normal distribution with mean 5 mph over the speed limit (55 mph speed limit in the work zone) and standard deviation of 5 mph. For the heavy vehicles also, normal distribution is used but with a mean speed that is less than the mean speed of cars. The difference in speeds between cars and trucks is one of the input parameters. It should be noted that, in all the scenarios, the heavy vehicle type used was tractor-trailer and work zone has only one lane open. Also in the basecase (only-passenger car) the capacity of the work zone was approximately 2000 pcphpl .

In order to determine the delay, first the travel times for different scenarios need to be estimated. Therefore, Travel Time sections feature of VISSIM was used to obtain the travel times of each vehicle. For each scenario 30 runs were performed and the average travel times of cars and trucks through the work zone were determined. It is also required to ensure that the error in the estimate of travel time is not significant. Otherwise the reliability of estimates of the D-PCE would be diminished. Therefore, the variance of travel times of both passenger cars and trucks is monitored to ensure that the error in travel time is less than 5%. It was observed that in none of the cases the error exceeded 1.5s. Therefore 30 runs were deemed to be sufficient. Having limited the error to 5% and determining the average travel times for cars and trucks in each scenario, D-PCE is computed using equation 1.

The travel time on the regular freeway is computed by using 70 mph as the average speed (5 mph over the speed limit). It should be noted that, the highest volume considered in this research is 2000 vph for one lane of work zone. On the regular freeway this translates to 1000 vphpl. According to HCM *(5)* the speeds on basic freeway section are unaffected by volume upto a level of about 1300 vphpl. Therefore this assumption of an average speed of 70 mph on the regular freeway is reasonable. This procedure is used to compute the D-PCE values for all the scenarios in this research.

D-PCE VALUES

Effect of Traffic Volume

Using the procedure described in the previous section D-PCE values were computed for various volume levels and truck percentage combinations for a given work zone length and speed difference between cars and trucks. Figure 2 shows variation of D-PCE with traffic volume and truck percentage when the speed difference between cars and trucks is 10mph. Each line in Figure 2 corresponds to a volume level ranging from 200vph to 1200 vph in increments of 200 vph and in increments of 100 vph from 1200 vph to 1700 vph. At every truck percentage, it can be seen that the D-PCE increases as the traffic volume increases. For a given truck percentage, as the traffic volume increases the probability of a car getting queued behind a truck increases. Therefore, it is expected that the D-PCE would increase as the volume increases.

Effect of Truck Percentage

It should be noted that at every volume level, as the truck percentage increases, the D-PCE decreases. When trucks are introduced in the traffic stream, they increase the delay experienced by the vehicles. Beyond a certain threshold, adding more trucks causes trucks to queue behind trucks and not so much the cars. Therefore, the marginal increase in delay to the traffic stream due to the addition of the trucks decreases. Consequently D-PCE decreases. These trends of D-PCE are in agreement with trends reported by previous research *(5,17)*.

From Figure 2 it can also be noted that the D-PCE values are shown for truck percentages from 5% to 45% up to a volume of 1200 vph only. Beyond that volume, the D-PCE values are shown only for a subset of the truck percentages. This is because at the high volume levels, when trucks are introduced into the traffic stream, the flow breaks down much before reaching the numerical value for the basecase capacity. In this case, it should be recalled that the basecase capacity is 2000 pcphpl. In other words, with the introduction of trucks traffic breakdown occurs at a lower volume level than 2000 vehicle per hour.

In the case of 1300 vph, the traffic breaks down at a truck percentage of about 35%. Beyond this point, there is congestion. D-PCE is not defined for cases which exceed the capacity of the work zone. This is because, it is not physically possible to process so many vehicles through the work zone and consequently there is no need to find a D-PCE for those cases. It is expected that as the traffic volume increases, the traffic flow breakdown would occur at lower truck percentages. This is also depicted in Figure 2. Beyond the volume increases beyond 1300 vph, the D-PCE values are shown for fewer truck percentages. In the case of 1800 vph, the breakdown happens at 5% trucks. Therefore, the D-PCE values corresponding to these volume levels are not defined.

Discussion on D-PCE Values

The D-PCE values for a 1 mile work zone with 10 mph speed difference ranged from 2.8 to 7.7. These values of D-PCE might seem to be unreasonably high for a work zone in a level terrain. It should be noted that the speed difference between cars and trucks has a significant effect on delay and consequently on D-PCE resulting in these higher D-PCE values. These numbers are not unprecedented. It should be recalled that the work zone had only one lane open. Therefore, these D-PCE values would not be comparable with the HCM *(5)* PCE values for basic freeway sections, but the PCE values for estimating average speeds on two-lane highways with no passing may be used as a point of reference to illustrate the variation of PCE. The HCM PCE values for estimating average speeds on specific upgrades (Exhibit 20-15 from HCM) varies from 1.5 to 15.2 depending on grade, length of grade and volume. Although freeway work zone traffic and two lane highway traffic are not necessarily comparable, the range of 2.8 to 7.7 is well within the range of HCM values for two lane highways.

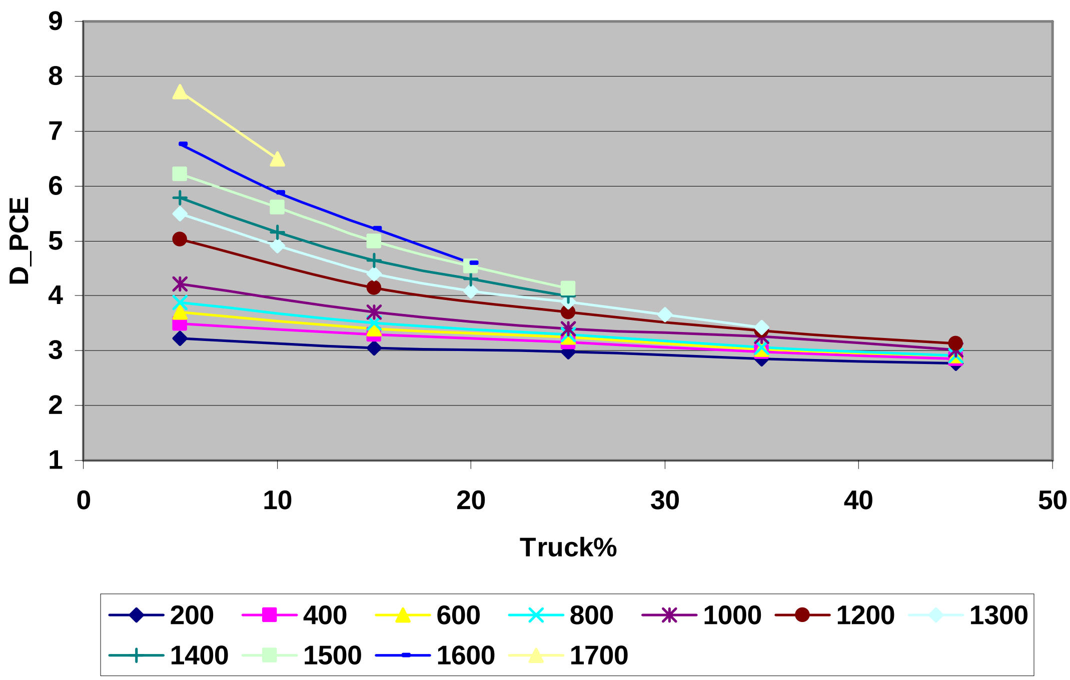

FIGURE 1 Simulated D-PCE for a 1 mile WZ with 10 mph speed difference at different volumes.

CONCLUSIONS AND RECOMMENDATIONS

This paper extended the delay-based methodology that was developed for intersections to work zones, and developed PCE values for heavy vehicles in work zones. The methodology for computing delay-based PCE of heavy vehicles in the work zones is presented. The equivalence is based on delay because delay captures the adverse effects of trucks in work zone traffic better than headway. Simulation was used to quantify the delays caused by the heavy vehicles so PCE values can be determined. Delay and consequently delay-based PCE (D-PCE) values are affected by the length of the work zone, the speed difference between cars and heavy vehicles, traffic volume, percentage trucks and other work zone factors. The D-PCE values for a 1 mile work zone with 10 mph speed difference between cars and heavy vehicles ranged from 2.8 to 7.7. The

D-PCE values decreased with increasing truck percentage and increased with increasing traffic volume. The D-PCE when there is speed difference are well within the range of PCE values of truck for estimating the average speed on two lane highways which are more similar to a one lane work zone than a basic freeway section. Further research is recommended to develop D-PCE values considering different work zone lengths and speed differences between cars and heavy vehicles. The PCE values computed in this research are for a partial closure work zone with one lane open for traffic. The methodology presented in this research can be used to compute the D-PCE values for multiple lanes of traffic and crossover work zones.

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