EFFECT OF WORK ZONE LENGTH AND SPEED DIFFERENCE BETWEEN VEHICLE TYPES ON DELAY-BASED PASSENGER CAR EQUIVALENTS IN WORK ZONES

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ABSTRACT
This paper presents how Delay-based Passenger Car Equivalent (D-PCE) values of heavy vehicles in work zones vary with work zone length, speed difference between vehicle types, heavy vehicle type, traffic volume and heavy vehicle percentage. The D-PCE values increased with increasing volume, work zone length and speed difference between vehicle types. Speed difference had the most significant effect on D-PCE. They decreased with increasing heavy vehicle percentage. Depending on the work zone length, speed difference between vehicle types, volume and percentage heavy vehicles, the D-PCE values ranged from 1.01 to 21.18. Operation of two lane highways resemble one lane work zones more closely than basic freeway sections and the D-PCE values are comparable to the PCE values of heavy vehicles for two lane highways. D-PCE values for different combinations of the factors were developed in this paper.

INTRODUCTION
The growth in the vehicle-miles traveled far exceeds the lane-miles added to the highways. Extending the life of existing roads and utilizing the available capacity play a key role in meeting the mobility needs of the society. Consequently, work zones have become a necessary feature of the U.S. highway system. However work zones are the second largest contributor to non-recurring delay on freeways and principal arterials and are estimated to account for nearly 24 percent of all non-recurring delay (*1*). Work zones cause 10% of the delay experienced in the entire United States and 80-90% of delay experienced in rural areas (*2*). Accurate capacity analyses procedures are required to better manage traffic flow through work zones such that the delay and inconvenience is minimized. Trucks are a major part of highway traffic and their proportion is estimated to increase in the future. The concept of Passenger Car Equivalents (PCE) is used to convert the effects of truck to equivalent cars in capacity analysis procedures. Chitturi and Benekohal (*3*) proposed a methodology for computing delay-based PCE of heavy vehicles in work zones. However, they did not examine effects of work zone length and speed differences between cars and trucks. This paper examines effects of those and other factors on D-PCE. Conceptually, the ratio of delay caused by a heavy vehicle to the delay caused by a passenger car in an all passenger car traffic stream is defined as the D-PCE. Factors that can influence delay and thus D-PCE are discussed first. Following this a brief description of how VISSIM is used to compute the D-PCE values is presented. Then, the effect of work zone length, speed difference between vehicle types, heavy vehicle type, traffic volume, and heavy vehicle percentage are discussed. Finally application of D-PCE values is presented. Two examples are given to illustrate the error one could make if the HCM basic freeway section values are used for work zones.

FACTORS AFFECTING DELAY-BASED PCE
The major factors that affect delay and therefore delay-based PCE are discussed in this section.

Length of Work Zone
Travel time is directly proportional to the length of the travel section. Therefore, longer the work zone, longer would be the travel time and delay if any. It should be noted that the delay-based PCE is defined as the ratio of delay caused by the trucks to the delay

caused by the passenger cars in the only-passenger car case. Since both the delays would be a function of the length of work zone, one might think that the length of work zone would not affect delay-based PCE. It should be noted that this would be the case only when the all the vehicles go through the work zone unimpeded by slow-moving vehicles. When there are slow-moving vehicles in the work zone, the longer the work zone, the greater is the possibility of a faster vehicle catching up with the slow-moving vehicles. Therefore, the longer the work zone, the greater is the travel time, but it need not necessarily be linear. Hence it is expected that the length of work zone would be a significant factor affecting D-PCE.

Speed Difference between cars and heavy vehicles

Benekohal, Wang, Orloski, Kastel (*4*) studied the speed profiles of vehicles as they traversed a work zone on a rural interstate highway and found that the speeds of passenger cars were 4-7 mph higher than those of trucks. McCoy, Bonneson, and Kollbaum (*5*) studied the effects of placing speed monitoring displays with radar in work zones on interstate highways and found that mean speed of vehicles with 2 axles was higher than that of vehicles with more than 2 axles in both the before and after studies. Fontaine, Carlson and Hawkins (*6*) evaluated the effectiveness of trailer-mounted speed display with radar and reported that trucks generally experienced larger speed reductions than cars.

Benekohal and Shu (*7*) evaluated the speed reduction effects of displaying speed limit and information messages on a changeable message sign (CMS) placed inside the work activity area and found that a CMS reduced the car speeds immediately after passing it, but not at a point far from the CMS. On the contrary the trucks traveled at reduced speeds even after passing the CMS. Benekohal, Resende and Orloski (*8*) studied the effects of police presence on vehicular speeds in a work zone and found that trucks traveled at a reduced speed for at least one hour after the police departed from the work zone, but not cars.

Benekohal, Resende and Zhao (*9*) evaluated the effects of using 2 drone radar guns and their lasting effects in work zones. They found that in five out of six cases, trucks showed statistically significant net speed reductions. In the case of cars, the net reductions were significant only in two out of six cases. They also reported that the speed reduction effects of drone radar did not diminish on trucks over a time period of approximately three hours. Similarly, Ullman (*10*) studied the effect of radar transmissions at highway work zones and reported that generally, the radar transmissions had a more pronounced effect on trucks than on passenger cars.

Chitturi and Benekohal (*11*) studied the effect of narrow lane widths on speeds of vehicles in work zones. They reported that the speed reductions in work zones on interstate highways are significantly greater than the speed reductions recommended by the HCM for basic freeway sections. They also found evidence for speed reduction of trucks being greater than the speed reduction of cars in work zones.

In conclusion, all these studies indicate that in work zones trucks could be traveling at a significantly reduced speed than cars even on level terrain. Consequently the difference in the speeds of these two vehicle types is considered as a factor that affects the D_PCE in this research.

Traffic Volume

At a low traffic volume, the vehicles travel unimpeded and experience practically no delay. But as the traffic volume increases the interaction between the vehicles increases. This increased interaction between the vehicles could cause some vehicles to get stuck behind slow moving vehicles and thereby increasing the travel time and delay. Therefore, all the other factors remaining the same, as the traffic volume increases the travel time and delay increase. Therefore it is expected that traffic volume can have a significant impact on D-PCE and its effect on D-PCE is studied in this research.

Percentage heavy vehicles

On regular basic freeway sections on level terrain the speeds of heavy vehicles are similar to the speeds of passenger cars. However in work zones, even on level terrain, previous research (*4-11*) has unambiguously established that heavy vehicles travel at slower speeds than cars. Therefore greater the number of slow-moving heavy vehicles in a work greater would be the delay. The increase in delay is not linear because initially, as the number of trucks increases, the likelihood of a car getting stuck behind a truck increases. Beyond a certain truck percentage adding more heavy vehicles causes heavy vehicles to queue behind heavy vehicles rather than causing additional cars to queue behind heavy vehicles. Therefore it is expected that D-PCE would decrease beyond a certain truck percentage.

Number of lanes open in work zone

The number of lanes open determines the amount of opportunity to pass that is available to the drivers. Consider a work zone with one lane open. In this scenario, vehicles do not have any opportunity to pass and therefore once they are queued behind a slow-moving vehicle they have to travel at that slower speed till they exit the work zone. When there are multiple lanes in the work zone, vehicles have more opportunities to pass slow-moving vehicles and therefore additional delay due to slow-moving vehicles would be minimal. Therefore, in this research the D-PCE values for work zones with one lane open for traffic are presented.

Vehicle type

Delay-based PCE is dependant on the additional delay that the heavy vehicles cause to the traffic stream. If by changing the heavy vehicle type, a significant change in travel time does not result, then the delay-based PCE would not change significantly either. Therefore unless there is evidence that there is a significant difference in speed of different heavy vehicle types, it is not expected that heavy vehicle type would significantly affect D-PCE. This issue is addressed again by comparing the D-PCE values for single-unit trucks and tractor-semitrailers later in this paper.

Grade

On grades, the acceleration and deceleration characteristics of the vehicles become significant. Therefore, upgrades adversely affect the speeds of vehicles, more so heavy vehicles than passenger cars. Hence grades increase the delay and can consequently affect the delay-based PCE. It is not possible to collect field data and determine the delay-based PCE given that there are so many factors that are beyond our control in a

real-world situation. Therefore simulation is the only viable means by which one could quantify the effect of grade. However, to be able to accurately capture the effect of grades, a very accurate representation of the vehicle acceleration and deceleration characteristics is required in the simulation model. This would mean that data would have to be collected from real world to validate the acceleration and deceleration characteristics before getting any reasonable results from simulation. This has not been done for VISSIM. Therefore the task of accounting for grades in computing delay-based PCE is recommended for future research. However, before such research is performed, the users can determine what the speed drop from grades can be by using the curves provided in HCM for grades. This speed drop can be included in the difference in speeds between cars and trucks and use the D-PCE values developed for level terrain as an approximation.

COMPUTATION OF D-PCE USING VISSIM

Considering the large number of scenarios that arise from the combinations of various factors that can D-PCE, it is impossible to use field data to compute the D-PCE values. There are no analytical models which can realistically represent the work zone conditions. Consequently VISSIM, a microscopic simulation tool is used to compute the D-PCE values. The work zones of required characteristics are coded in VISSIM and the travel times of the vehicles are obtained under different scenarios. These travel times are used to compute the delays caused by the heavy vehicles and D-PCE values for the different scenarios. A complete description of the methodology used to compute the D-PCE values is presented in Chitturi and Benekohal (*3*).

DISCUSSION OF D-PCE VALUES

Using the procedure described in the previous section D-PCE values were computed for various scenarios. How the D-PCE values varied with five factors: traffic volume, heavy vehicle percentage, work zone length, speed difference between heavy vehicles and cars and heavy vehicle type are discussed in this section.

Effect of Truck Percentage and Traffic Volume

Figure 1a shows variation of D-PCE with traffic volume and truck percentage when the speed difference between cars and trucks is 15mph. Each line in Figure 1a 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. 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. Also 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.

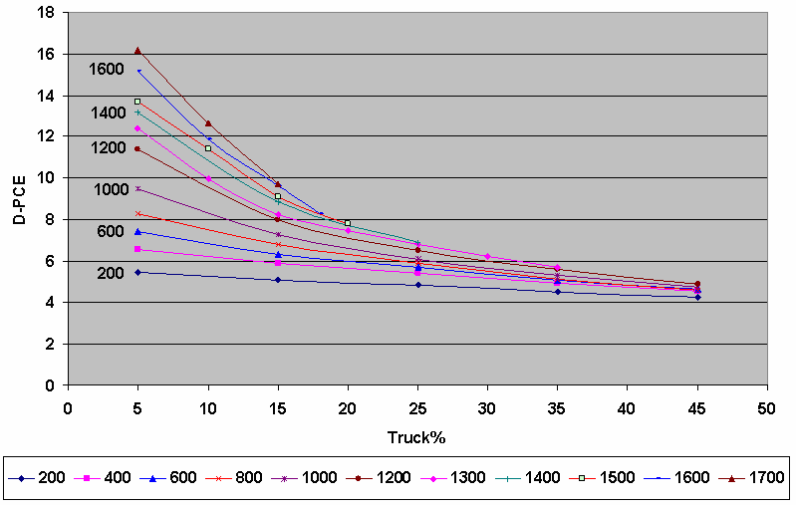
From Figure 1a it can also be noted that the D-PCE values are shown for truck percentages from 5% to 45% only up to a volume of 1200 vph. Beyond that volume, the

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 breaksdown much before reaching its 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.

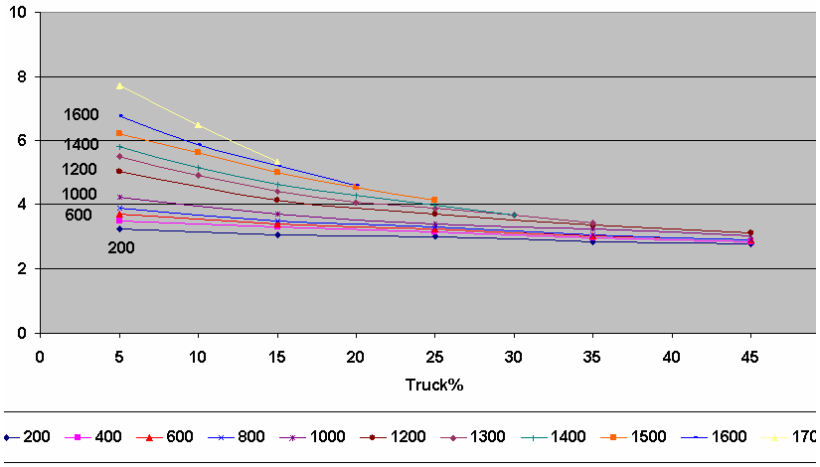
Figure 1b shows the variation of D-PCE with traffic volume and truck percentage for a one mile work zone with speed difference of 10 mph. It should be noted that the D-PCE trends of Figure 1b are qualitatively same as the trends in Figure 1a. In other words at every volume level, the D-PCE decreases as truck percentage increases and at any given truck percentage the D-PCE increases as the traffic volume increases. Also the breakdown begins to happen at a lower truck percentage as the traffic volume increases. One significant difference is that for any given volume level and truck percentage, the D-PCE is lower when the speed difference is 10 mph as opposed to 15 mph. As the speed difference between cars and trucks increases, greater number of cars would be impeded by the slower moving trucks. This is because the trucks would take longer to traverse the work zone. Consequently, when everything else remains the same, as the speed difference between cars and trucks increases, the D-PCE increases.

Figure 1c shows how the simulated D-PCE varies with traffic volume and truck percentage for a one mile work zone with speed difference of 5 mph. As expected the PCE decreases with truck percentage and increases with traffic volume. One significant difference between this scenario and the scenarios when the speed difference is 10 mph and 15 mph is that the D-PCE values up to volume level of about 1000 vph are constant for all practical purposes. This insensitivity of D-PCE to volume appears aberrant. However, it should be noted that the work zone is only one mile long. Therefore, under low volume conditions, the heavy vehicles are in the work zone for such a short duration that their actual delay-causing potential does not come into full effect. But as the length of the work zone is increased, even at lower volume levels, the trucks can cause significant delay to cars.

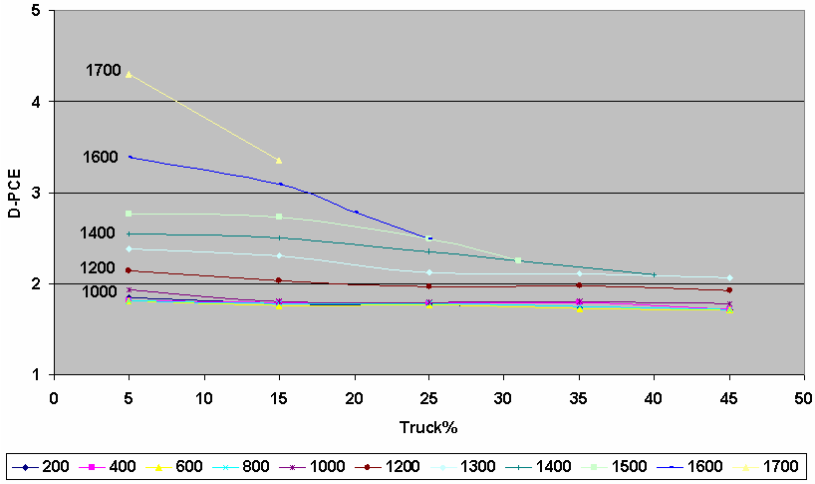
Figures 2 a-c show how the simulated D-PCE varies with traffic volume and truck percentage for a 5 mile work zone with 5, 10 and 15mph speed difference between cars and trucks. Similarly, Figures 3 a-c show the D-PCE results for a 10 mile work zone with speed differences of 5, 10 and 15 mph respectively. In all the cases the trends of decreasing PCE with increasing truck percentage and increasing PCE with increase in volume are observed. Although the trends are same it should be noted that the actual variation in the D-PCE values themselves is not same. How the work zone length and speed difference affect D-PCE is studied in the next section.



a) 15 mph speed difference

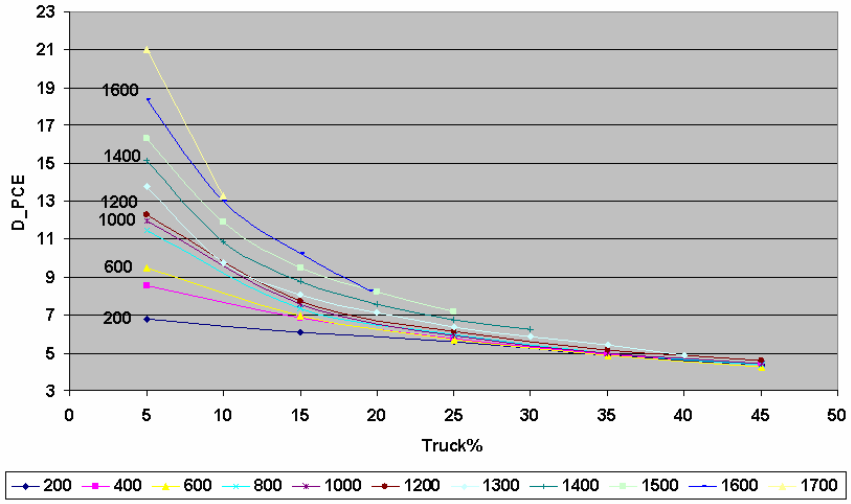


b) 10 mph speed difference

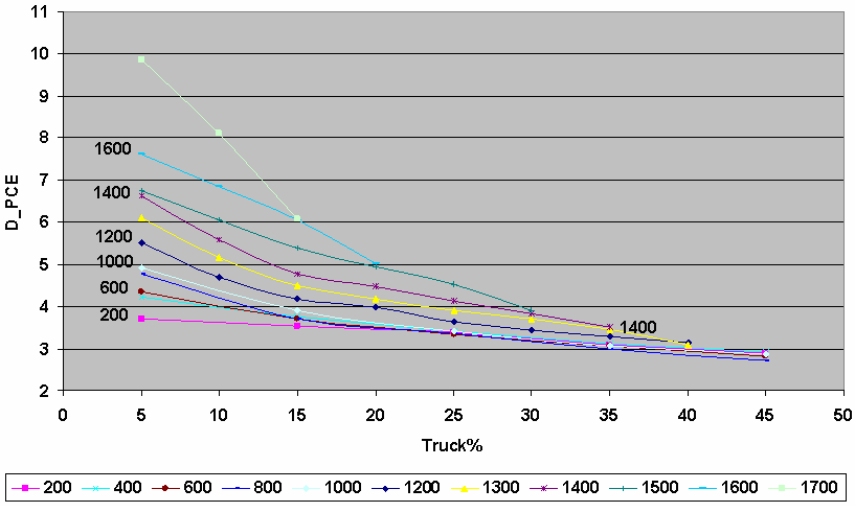


c) 5 mph speed difference

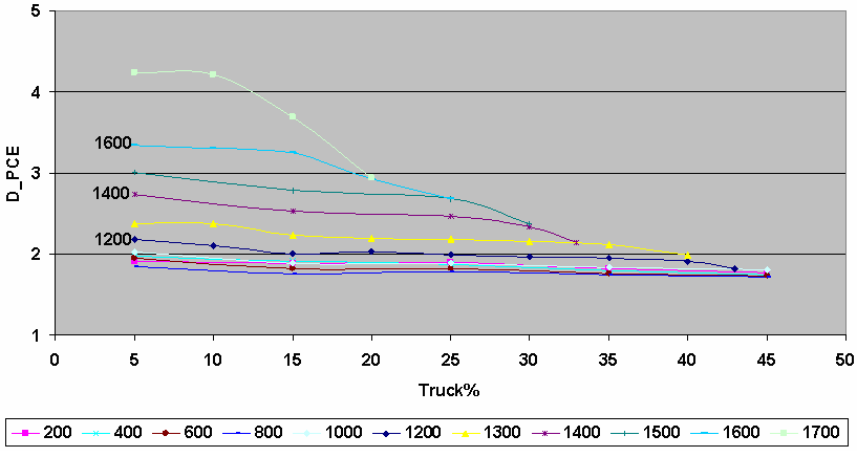
FIGURE 1 Variation of D-PCE for 1 mi WZ.



a) 15 mph speed difference

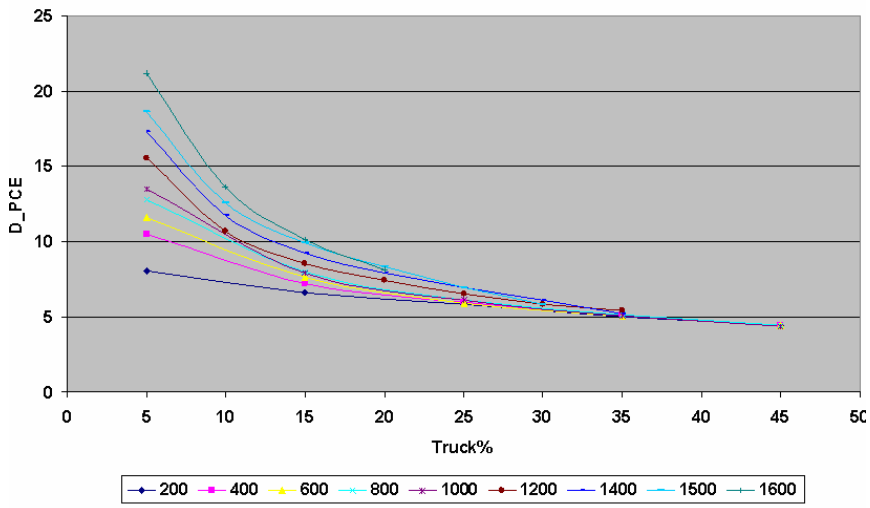


b) 10 mph speed difference

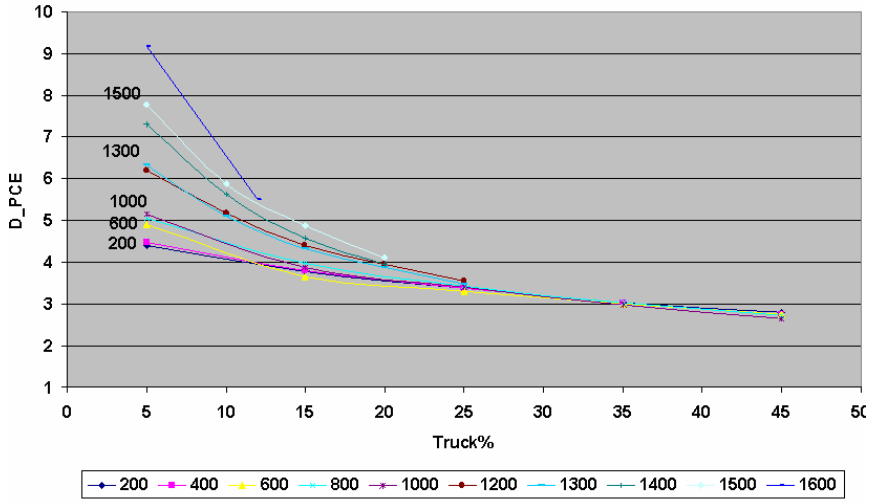


c) 5 mph speed difference

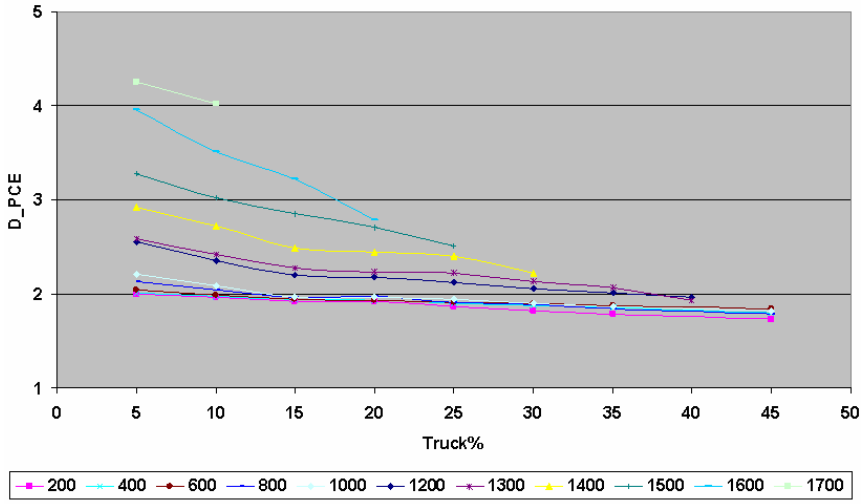
FIGURE 2 Variation of D-PCE for 5 mi WZ.



a) 15 mph speed difference



b) 10 mph speed difference



c) 5 mph speed difference

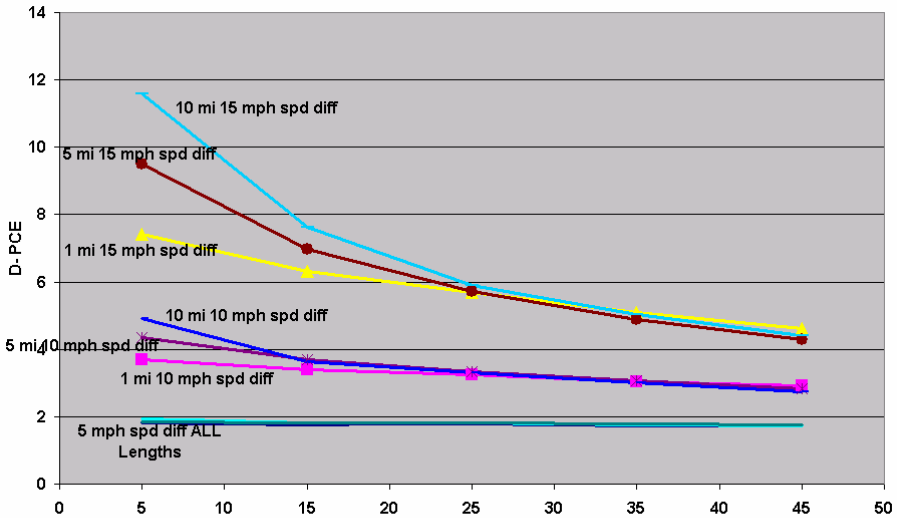
FIGURE 3 Variation of D-PCE for 10 mi WZ.

Effect of Work Zone Length and Speed difference

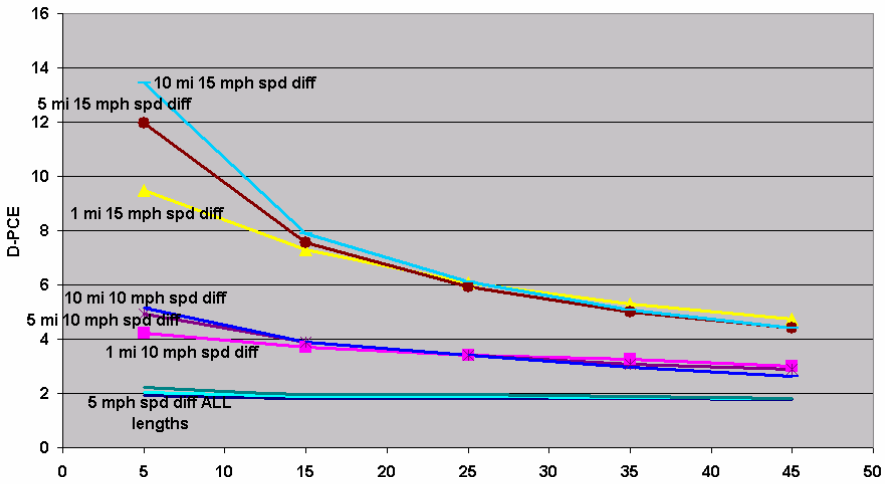
In order to study the effect of work zone length and the speed difference between cars and trucks, the variation of D-PCE with these factors is shown at three different volume levels in Figures 4 a-c. The volume levels are 600 vph, 1000 vph and 1400 vph.

From these figures it can be observed that the data segregates itself according to the speed difference. The D-PCE values are the lowest when the speed difference is least. As the speed difference increases the D-PCE increases for every truck percentage, length of work zone and volume level. It should also be noted that the magnitude of increase in D-PCE when the speed difference is increased from 5 to 10 mph is less than the increase when the speed difference is increased from 10 mph to 15 mph. This indicates that the D-PCE does not vary linearly with speed difference, but rather non-linearly. This is the expected trend, because the greater the speed difference between cars and trucks, the longer are the trucks going to be traveling in the work zone and delay more number of cars. The increase in duration of travel does increases nonlinearly with the speed difference, therefore the delay caused to the traffic stream also increases accordingly and so does the D-PCE.

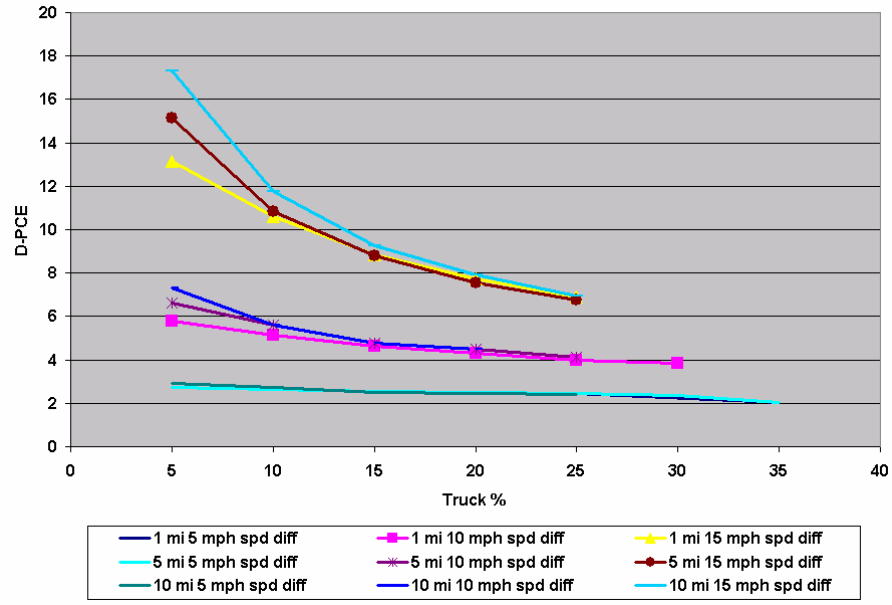
Also these figures clearly indicate that everything remaining same, the D-PCE increases with work zone length. The same explanation that was given for the increase in D-PCE with increase in speed difference hold true for the increase in D-PCE in this case. Therefore these results indicate that the D-PCE values obtained from the simulation are according to the expectations and therefore reasonable.



a) 600 vph



b) 1000 vph



c) 1400 vph

FIGURE 4 Variation of D-PCE with WZ length and speed difference.

CONCLUSIONS AND RECOMMENDATIONS

This paper examined the effect of five factors on delay-based PCE (D-PCE) for heavy vehicles in work zones. The factors are: work zone length, speed difference between vehicle types, heavy vehicle type, traffic volume and heavy vehicle percentage. VISSIM was used to obtain the travel times for different combinations of the above-mentioned four factors, using which the delay-based PCE values were computed. The D-PCE values increased with increasing volume, work zone length and speed difference between vehicle types. Speed difference had the most significant effect on D-PCE. Therefore it is recommended that in considering alternate traffic control/management plans those plans be chosen which have lower speed difference between cars and heavy vehicles. The PCE values decreased with increasing heavy vehicle percentage. When the speed difference was 5mph the D-PCE values practically did not vary with truck percentage upto 1000 vph volume for all the work zone lengths.

Depending on the work zone length, speed difference between vehicle types, volume and percentage heavy vehicles, the D-PCE values ranged from 1.01 to 21.18. 1.01 occurred for a volume of 200 vph and when there was no speed difference between vehicle types. The highest D-PCE occurred at a volume of 1600 vph with 15 mph speed difference between vehicle types in a 10 mile long work zone. These numbers are comparable to the PCE values of heavy vehicles on two lane highways. It is more reasonable to compare the D-PCE values to PCE values of two lane highways as they are closer in operation to one lane work zones than basic freeway sections.

D-PCE values for different combinations of the factors were developed and the values are given in this paper. Grade is an important factor that can have a significant effect on PCE and therefore further research is recommended to determine the effect of grade on D-PCE.

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