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**Calibrating Passenger Car Equivalent (PCE)
for Highway Work Zones using Speed and Percentage of Trucks**

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ABSTRACT

In the Highway Capacity Manual (HCM 2000), capacity is expressed as the unit passenger cars per hour per lane (pcphpl). The number of passenger cars a single vehicle is equivalent to is the passenger car equivalent (PCE). This paper studied PCEs within highway work zones that were based upon the speed and the percentage of trucks. The results indicated that PCEs designated for highway work zones have their own distinct characteristics. This study plotted 3 dimensional charts to display the change of PCEs with respect to the speed and percentage of trucks. Thus, a mountain chain of PCEs is formed on the speed-percentage (percentage of truck traffic) plane. The 3 dimensional charts help identify the PCE value as speed varies given the same percentage of truck traffic or as the percentage of truck traffic changes given the same speed. First, the multiple regression (the traditional method) was implemented to identify the relationship among PCEs, speed and percentage of truck traffic. Then, a new closed-loop approach was introduced in this paper to estimate PCEs using collected work zone data, which is totally different from traditional methods. It was also found that the closed-loop approach could help remove the error caused by a critical factor whose impact is usually ignored by traditional methods. Finally, more detailed PCE values for short-term and long-term work zones are tabulated in a compatible format similar to that used in the HCM (2000).

KEY WORKS

Passenger Car Equivalent (PCE), work zones, Closed Loop.

1. INTRODUCTION

Initially, the passenger-car equivalent (PCE) represents the number of passenger cars (basic vehicles) displaced by each truck in the traffic stream under specific conditions of flow. PCEs have been used extensively in the “Highway Capacity Manual (HCM 2000)” to establish the impact of trucks, buses, and recreational vehicles on traffic flow. Traditionally, PCEs have played an important role in freeway design and operations analysis. Since the concept of PCE was first formally introduced by the HCM (1965) to transportation engineers, there has been consistent study to improve and model this parameter.

The first modifications of the PCE started at the end of the 1970s. At that time, Werner et al first challenged the HCM (1965) (1). The 1980s was a decade referred to as the “Golden Time” of PCE development. In 1981, Hu introduced a unique method used to establish a general PCE model on multi-lane rural highways and urban freeways and on rural two-lane highways (2). In 1982, Huber proposed another model, generated from the impedance-flow relationship, that implements the use of a deterministic model of traffic flow (Greenshields' Method) (3). Later, based on the parameters of speed distribution, traffic volume and vehicle type, Cunagin and Messer developed PCE values for 14 different vehicle types on both two-lane and four-lane highways (4). Besides vehicle size and traffic volume, a study by Keller also accounted for signal timing (5). It was at this time the HCM (1965) required updating. The research by Roess and Messer (6) provided the "Interim Materials on Highway Capacity" in 1984, just a year before the new edition of the (HCM 1985) was published. TxDOT also played an important role in the development of PCEs along with the FHWA (Federal Highway Administration). With the sponsorship of these two organizations, Burke studied the detailed effects of larger trucks on passenger car equivalents (7). Krammes and Crowley recommended the PCE be expressed in terms of headway measurements (8). Then in 1987, just two years after the publication of the HCM (1985), drawbacks to computing the PCE were identified when using the new manual (9). This finding indicated the PCE was very difficult to measure. Molina et al., in their report (9) concluded the PCE value calculated by HCM (1985) as inadequate for the large 5-axle combination trucks. This was accomplished through an in-depth analysis of different data groups including: length of queue, classification of vehicles, and total travel time for each vehicle measured from start of green to the time the vehicle's rear axle crossed the stop line.

Although the general method in computing PCEs in the 1980's had been a comprehensive effort by many scientists and engineers, by the end of 1990's and the beginning of 2000, proposed models had developed their own new characteristics – simulative, international, and specialized. The first modification was due to insufficient field data and the difficulty involved with collecting it, resulting in an increase in the number of studies developing models with the aid and sometimes entire dependence on simulation data (10, 11, 12, 13, 14). A second catalyst was formed as the USA and UK recognized the importance of PC, and other countries, including China (Hong Kong) (15), China (Mainland) (16, 12), Denmark (17), Brazil (18), and Malaysia (19) also recognized but began to establish their own models

according to local traffic conditions. A third modification established was a refinement of the models for different applications and customers. Most focused on signal intersections (10, 16, 19, 20), and there were also other models concerning highway cost allocation (11), queues and congestion (21, 22).

With current widespread traffic growth, the need has presented itself for roadway improvements in most sectors of urban roadway systems. As the number of work zones increase, it is increasingly more important to accurately predict capacity within work zone segments. Consequently, this prescribed the need for a comprehensive model to compute PCE for work zones. The HCM (2000) valued the PCE as 1.5 at the level condition on the extended segment. But later, Al-Kaisy suggested enlarged values (generally over 2.0) under congested traffic condition. This is because the impact of a truck on other vehicles in high traffic density was underestimated (21, 22). The problem of PCE for work zones was made even more complicated when Zhou and Hall (23) found there existed differences in the congested part of the speed-flow curve in the area between normal and construction conditions.

This paper establishes a PCE table at the level condition, based on speed and the percentage of trucks. The scope of this research began with data collections and data reductions in Section 2. Developed in Section 3 was a model using closed loop calibrations. Following in Section 4 is the analysis of PCE under different speeds and percentage of truck conditions. Conclusions and recommendations are presented in Section 5 and Section 6.

2. DATA

The data collected in Illinois by Benekohal et al. (24, 26, 27) were used in this paper. These data collection sites were located on interstate highways in Illinois with only one lane open due to construction. These investigation sites consisted of 3 short-term and 8 long-term work zones. A short-term work zone was defined as a construction or maintenance site with work that lasted only a few days and the closed lane was configured using cones, barrels and barricades during the work zone activities. A long-term work zone was defined as a construction or maintenance site with work that continued for more than a few days and the closed lane is configured using concrete barriers. A video camera was used to capture the time point when a vehicle passed specific markers placed at a fixed distance apart. Based on 15-minute intervals, the collected data were reduced to data elements. To guarantee an adequate number of data, the rolling method was used to reduce data. In other words, we could obtain a data element every minute by averaging the speed and volume in the past 15 minutes. Therefore, more than 100 data elements could be derived from each work zone during a data collection time of about 2 hours. The total number of these elements was 1360, comprised of 391 for short-term work zone and 969 for long-term work zone. Every element has the necessary information, including the heavy vehicle percentage, the average speed and the average headway.

Referring to the PCE table on uniform upgrades in HCM (2000) (25), we decided to group data into different levels according to speed and percentage of trucks. Besides considering the total number of the data, we primarily evaluated the

importance of the above two variables when grouping data, with the help of the multiple regression method described in the following.

In this simple method, the ratio of the average time headway of a truck to that of a passenger car was used to express the PCE value. This is reasonable to calculate the capacity. The ratio indicates the number of passenger cars passing in the time a truck can pass (truck headway). Thus every data element had 3 variables: the PCE value, the speed, and the percentage of trucks. The multiple regression was implemented to identify the relationship among them.

(For short-term work zones)

$$E_t = -0.494 + 7.053P_t + 0.053S - 0.196P_t \cdot S \quad (1)$$

Where, E_t -- the PCE value;

S -- the speed;

P_t -- the percentage of trucks.

The mean of P_t is 0.260, standard deviation is 0.062, the Minimum is 0.123 and Maximum is 0.441. For S , the mean is 41.067, standard deviation is 6.258, Minimum is 26.6 and Maximum is 52.009.

$$\frac{\partial E_t}{\partial P_t} = 7.053 - 0.196S \quad \frac{\partial E_t}{\partial S} = 0.053 - 0.196P_t$$

To evaluate the effects of different variables, the means and standard deviations of the variables must be considered.

The effect of P_t :

$$(7.053 - 0.196M_s)Std_{P_t} = (7.053 - 0.196 * 41.067) * 0.062 = -0.062 \quad (2)$$

The effect of S :

$$(0.053 - 0.196M_{P_t})Std_S = (0.053 - 0.196 * 0.260) * 6.258 = 0.013 \quad (3)$$

Where, M_s -- the mean of the speed;

M_{P_t} -- the mean of the percentage of trucks;

Std_{P_t} -- the standard deviations of the speed;

Std_S -- the standard deviations of the percentage of trucks.

(For long-term work zones)

$$E_t = 1.763 + 1.691P_t - 0.006S - 4.665P_t \cdot S \quad (4)$$

For P_t , the mean is 0.211, the standard deviation is 0.122, the Minimum is 0.021, the Maximum is 0.500; for S , the mean is 41.591, the standard deviation is 12.123, the Minimum is 14.6663 and the Maximum is 61.343.

$$\frac{\partial E_t}{\partial P_t} = 1.691 - 4.665S \qquad \frac{\partial E_t}{\partial S} = -0.006 - 4.665P_t$$

The effect of P_t :

$$(1.691 - 4.665M_s)Std_{P_t} = (1.669 - 4.665 * 41.591) * 0.122 = -23.467 \quad (5)$$

The effect of S :

$$(-0.006 - 4.665M_p)Std_S = (-0.006 - 4.665 * 0.211) * 12.123 = -12.00 \quad (6)$$

The previous analysis for both short-term and long-term work zones indicated the percentage of trucks had a somewhat larger effect on the PCE than the speed. Thus, we classified the data into 5 grades according to the percentage of trucks (0~10%, 10~20%, 20~30%, 30~40%, above 40%), while 4 grades according to the speed (below 30mph, 30~40mph, 40~50mph, above 50mph). This was necessitated due to the fact that data from field studies wasn't as abundant as data from simulations. The number of data elements in each group was shown in Table 1.

TABLE 1 The Number of Data Elements for Each Group

Speed (mph)		Percentage of Heavy Vehicles (%)				
		0~10	10~20	20~30	30~40	above 40
Short-term work zones	Below 30	0	0	11	23	0
	30~40	0	7	28	29	0
	40~50	0	46	153	55	4
	Above 50	0	20	15	0	0
Long-term work zones	Below 30	132	92	0	0	0
	30~40	19	87	6	0	0
	40~50	33	157	26	68	40
	Above 50	0	54	71	128	56

3. METHODOLOGY

Although the results after regression could remove some noise, the simple method described by Eqn. (1) and (4) has been challenged in the past few decades. This challenge is due to the ignorance of the physical effect of trucks on the headways of passenger cars that are in close proximity to them, but this is only a statistical result. The traditional methods used to compare the volume at different percentage of trucks with that of pure passenger cars is shown in Eqn. (7). The step to conclude V_E , the

volume of pure passenger cars becomes a necessary element. This is accomplished by calculating the volume while the percentage of trucks is zero and all other conditions remain unchanged. The simulation and the regression were two familiar means.

$$E_t = \frac{1}{P_t} \left(\frac{V_E}{V_M} - 1 \right) + 1 \quad (7)$$

Where, P_t -- the percentage of trucks;

V_E -- the base volume (only including passenger cars);

V_M -- the mixed volume (including both passenger cars and trucks).

It couldn't be denied that the volume calculated by the regression method is not accurate. In fact, all the conclusions at the zero heavy vehicle percentage condition are not suitable for the calculation of the equivalents, even when implementing the most accurate simulations, because all the other conditions will also be changed including speed, density and volume, when the heavy vehicles are removed artificially. For example, a traffic flow with 10 percent of heavy vehicles is traveling at a speed 40 mile/hour (or at a density 30 vehicles/mile). But in the same environment, a traffic flow with pure passenger cars must be traveling at a different speed (or at a different density). In other words, when the percentage of heavy vehicles is changing, all the other parameters will change. Thus no critical parameter can be determined which is assumed to remain, to evaluate the passenger car equivalences. Therefore, a closed loop method could be established using the equivalent volume provided adequate data.

$$V_E = V_M (1 - P_t) + V_M * P_t * E_t \quad (8)$$

Eqn. (8) is the base formula to compute the equivalent volume, where P_t and V_M can be measured in each data element, while V_E and E_t are what we want to obtain. $V_M(1 - P_t) \rightarrow \beta_0$, $V_M * P_t \rightarrow \beta_1$, and $V_E \rightarrow -X_2$. Eqn. (8) is changed to be the following format:

$$\beta_0 + \beta_1 * X_1 + X_2 = 0 \quad (9)$$

To get the solutions of X_1 and X_2 , the equation group must include at least two equations with the format of Eqn. (9), and the determinant of its coefficient matrix shouldn't be zero (Eqn. (10)).

$$\det(\boldsymbol{\beta}) = \begin{vmatrix} \beta_{11} & 1 \\ \beta_{21} & 1 \end{vmatrix} \neq 0 \quad (10)$$

To form the wanted equation group, all the data elements would be sorted in ascending order by V_E . V_E and E_t are assumed to be equal in the 2 data elements close to each other. This assumption is reasonable when the number of the data element is larger than the range of V_E . If one data element and its neighbor make up an equation group whose determinant of the coefficient matrix is zero, this data element should be fitted together with the next one in sequence. In the following, the new V_E' and E_t' can be calculated from the equation groups. Then, a comparison is made of the ranks of V_E and V_E' for each element. When the total difference of the ranks in the whole data base reaches a minimum, the value E_t is what is desired. Eqn. (11) can be used to evaluate the degree of the total difference.

$$D = \frac{\sum_{i=1}^n |R_i' - R_i|}{n} \quad (11)$$

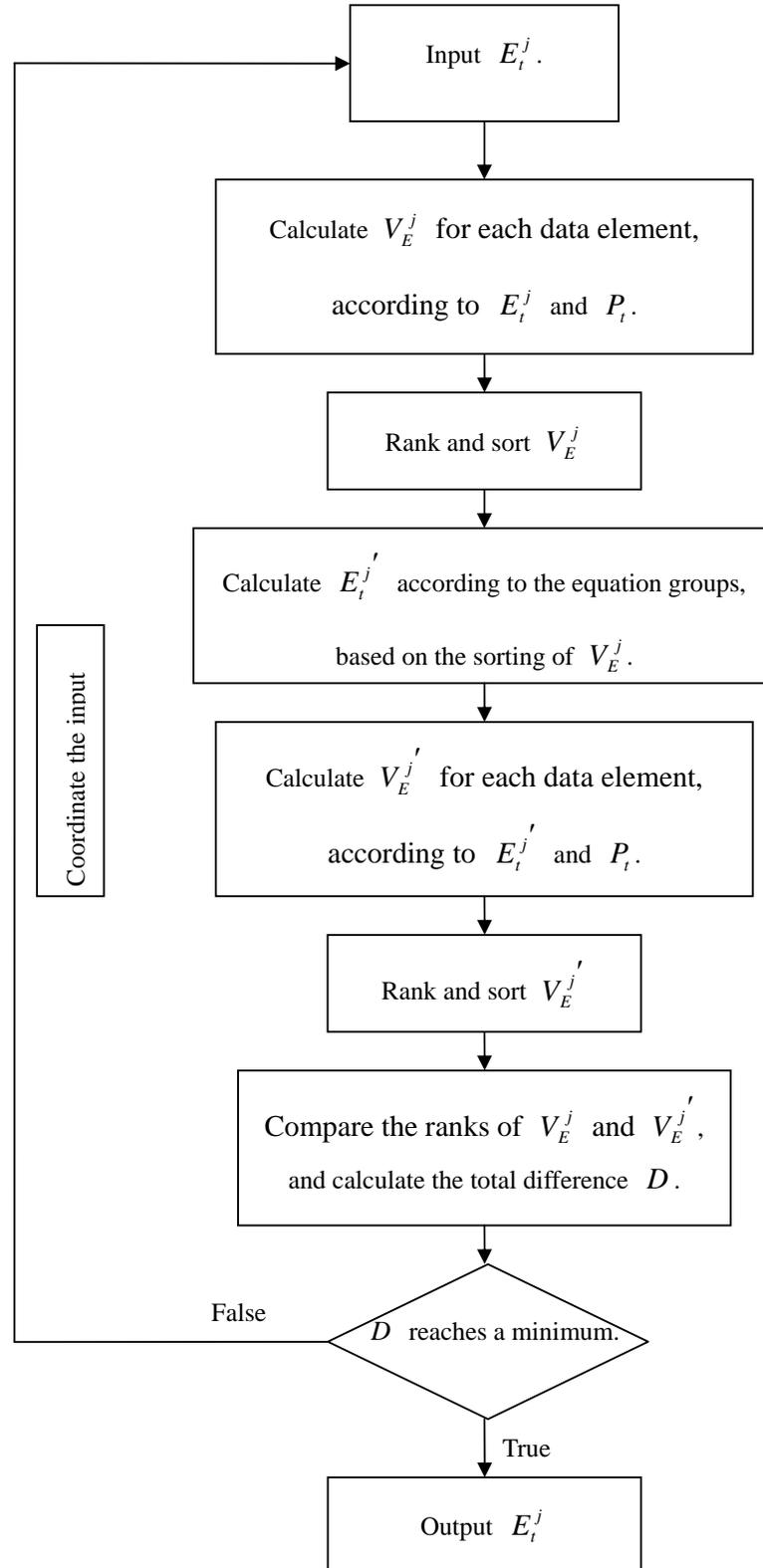
Where, R_i -- the rank of V_E for the i th data element;

R_i' -- the rank of V_E' for the i th data element;

n -- the number of data elements.

In the ideal situation, the total difference should be zero, and E_t would be equal to E_t' for each data elements. Fig. 1 described the process of this closed loop calibration.

FIGURE 1 Flow Chart of a Closed-Loop Calibration at the j th Step



For the ideal data base, we could use iterations to calculate the output E_t^j . It is in fact an optimization problem. The output tends to be optimum through coordinating as following:

$$E_t^{j+1} = \alpha E_t^j + (1 - \alpha) E_t^{j'} \quad (12)$$

Where, α is the coordination factor, whose domain is [0, 1].

For the given data base, we can only choose an optimum solution from options because of the limited data elements in some groups (Table 1). The options are eleven numbers with one decimal place, whose median is the result from the simple method, i.e. the ratio of the average time headways. Taking the group with the speed of 40~50 mph and the percent of 20~30% for short-term work zones as an example, the ratio of average time headways is 1.5, and the options should be the 11 numbers from 1.0, 1.1 ... until 2.0. Generally speaking, the more the data elements in the group, the more reasonable the assumption, the more accurate the result, and the more distinct the fluctuation of the total difference of the ranks D , as PCE option increases. When a group has less than 10 data elements, the closed loop calibration ceases to work. Fig. 2 supported this conclusion. And Table 2 summarized the results of the PCEs after closed loop calibrations.

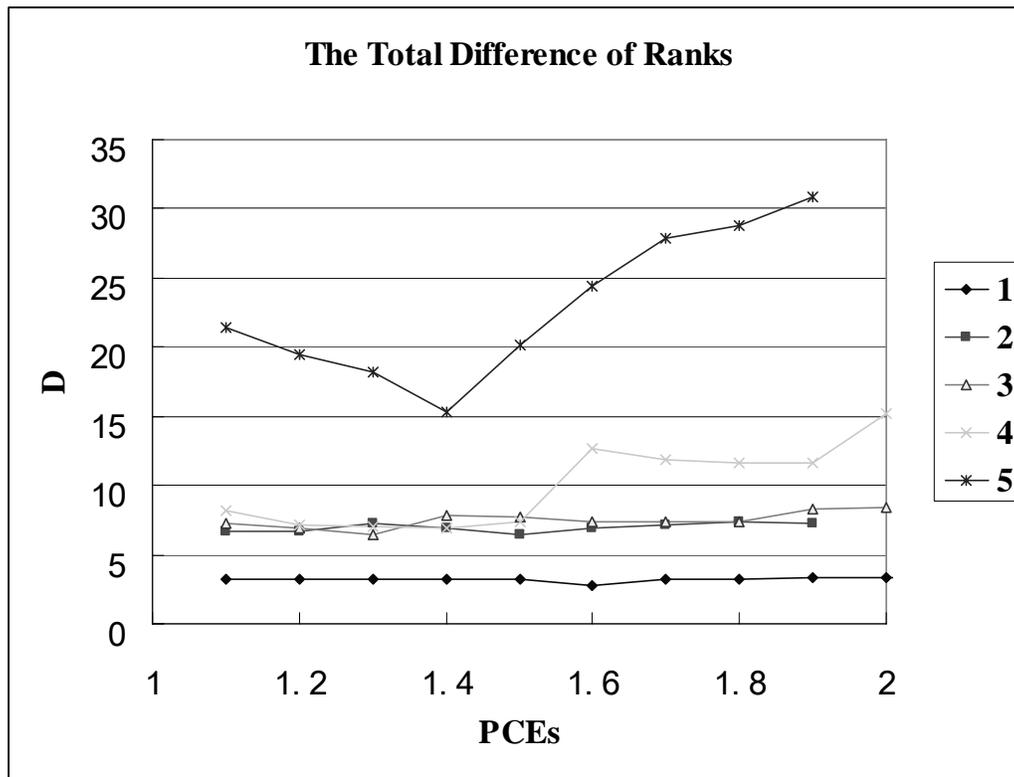
TABLE 2 The PCE for Each Group

Speed (mph)		Percentage of Heavy Vehicles (%)				
		0~10	10~20	20~30	30~40	above 40
Short-term work zones	Below 30	/	/	1.6	1.5	/
	30~40	/	*	1.3	1.3	/
	40~50	/	1.5	1.4	1.3	*
	Above 50	/	1.6	1.4	/	/
Long-term work zones	Below 30	1.6	1.7	/	/	/
	30~40	1.7	1.9	*	/	/
	40~50	1.7	1.6	1.5	1.5	1.4
	Above 50	/	1.6	1.5	1.4	1.4

Where, “/” – no data;

“*” – not enough data to conduct a closed loop calibration.

FIGURE 2 The D-PCE Curves as the Number of Data Elements in a Group Increases



Where,

Curves	Work Zone Type	Speed (mph)	Percentage of Trucks	Number of Data Elements
1	Short-Term	Below 30	20~30	11
2	Short-Term	Below 30	30~40	23
3	Short-Term	30~40	30~40	29
4	Short-Term	40~50	10~20	46
5	Short-Term	40~50	20~30	153

4. THE ANALYSIS OF PCE

Based on the Fig. 3 and 4, the PCE for both short-term and long-term work zones ranged from 1.3 to 1.9.

The PCE for work zones has some characteristics: (a) the PCE calculated by the simple method (the ratio of the headways) is usually underestimated; (b) at same speed, the PCE will be fluctuating as the percentage of trucks goes up. It increases at first and then decreases; (c) as the speed increases, the intensity of these fluctuations turns to be high at first and then low, which may cause the maximum PCE value to come out not on the boundary of the Speed-Percentage plane, but in the middle of the plane; (d) as the speed increases, the peaks of the fluctuations move forward to the low percentage of trucks. Following are the detailed discussions of these four characteristics:

FIGURE 3 The PCE for Short-term Work Zones after Calibrations

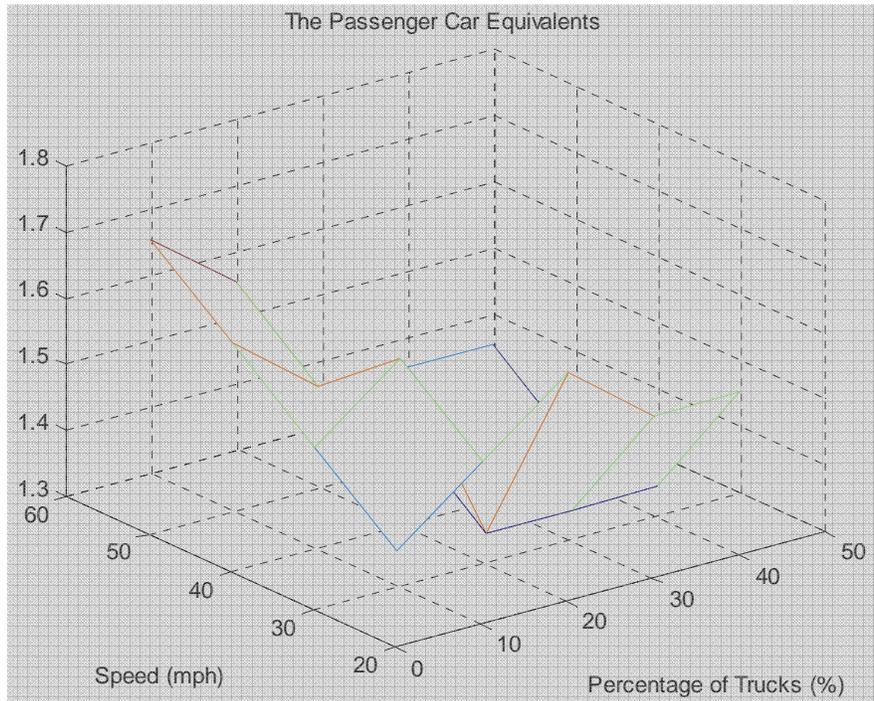
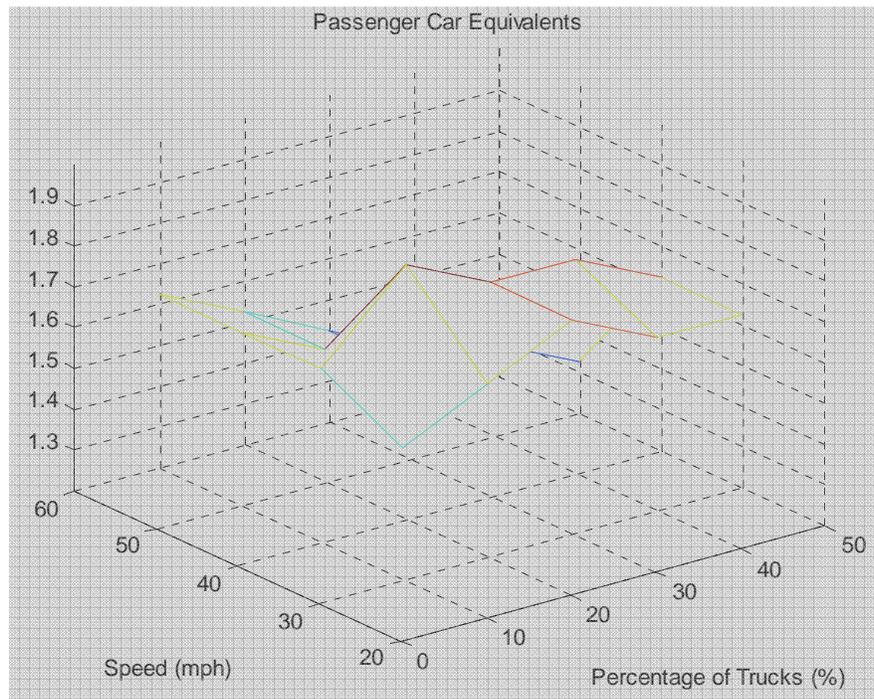


FIGURE 4 The PCE for Long-Term Work Zone after Calibrations



- (a) The PCE values should be larger than the ratio of headways, but smaller than those calculated using the method under normal congested traffic conditions. For one thing, trucks also increase the headways of the passenger cars closest to them, which makes the ratio *truck headway/car headway* smaller than the actual value. For another, the gaps increased between the vehicles under work zone conditions resulting in the difference between the normal congested conditions and work zone conditions. According to Eqn. (13), as the gaps increase, the actual PCE values decrease.

$$PCE \propto \frac{L_T + G_T}{L_C + G_C} \quad (13)$$

Where,

L_T -- the average physical length of trucks;

G_T -- the average gap of trucks;

L_C -- the average physical length of cars;

G_C -- the average gap of cars;

\propto doesn't describes a strict relationship of the direct proportion, but represents the two sides of the equation that have a similar trend to increase or decrease.

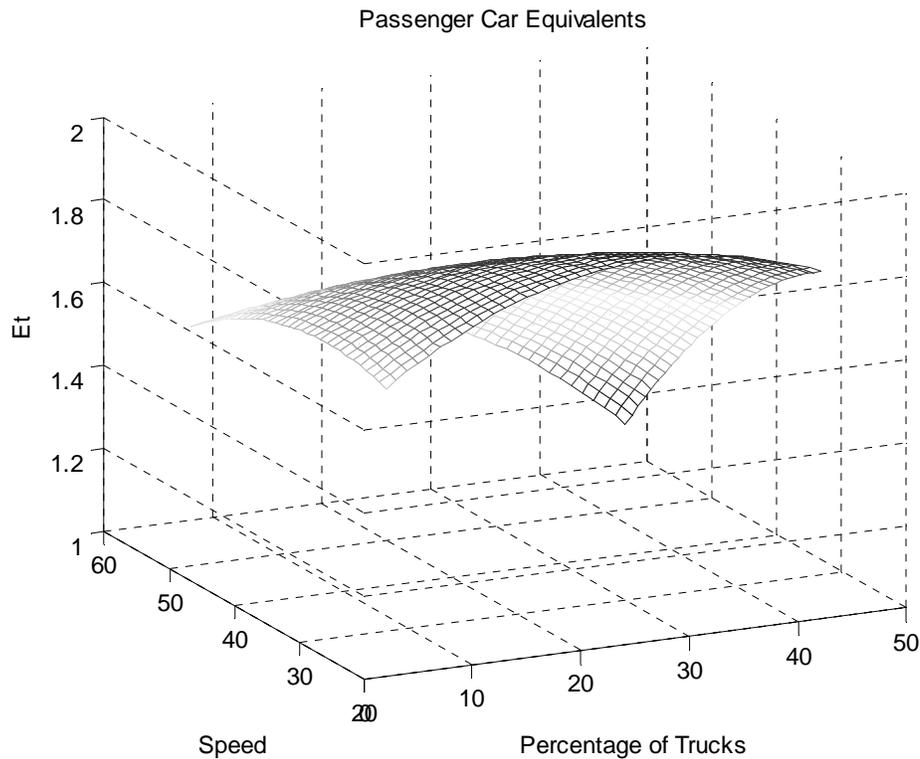
- (b) At the same speed, the work zone PCE will fluctuate as the percentage of trucks increases. The PCE will increase at first and then decrease. This fluctuation of the PCE mainly results from driver psychologies. Under certain speed conditions, the more trucks that drivers see, the larger gap they keep, which causes the PCE to increase at first; but it is found that truckers keep a shorter gap when they follow another truck, as opposed to a passenger car, which causes the PCE to decrease later, according to Eqn. (13). The more the speed, the more obvious these psychologies. For example, at the speed of 50 mph, a driver maintains a larger gap between his/her car and the previous one when he/she perceives a truck, but at the speed of 20 mph, he/she doesn't resort to this larger gap until he/she sees at least 3 trucks. So, the PCE values reach the maximum when the percentage of trucks is very low and the speed is over 50 miles/hour. Accordingly, the peak (maximum PCE value) of the fluctuation caused by driver psychologies moves in the negative direction along the axis of the percentage of trucks, as the speed increases.
- (c) As the speed increases, the intensity of these fluctuations turns out to be high at first and then low. At low speed regions, the effects of trucks are mainly physical characteristics – the length and the capability to accelerate and decelerate, so the intensity of fluctuations is low; in median speed regions, the effects of trucks are combinations of both physical and psychological characteristics – the driver near a

truck will control a larger gap consciously or unconsciously. In high speed regions, the PCE depends more on the density and flow rate upstream, so it doesn't change much as the percentage of trucks change, and the intensity of the fluctuation recovers to a lower level. This change of the fluctuation intensity may cause the maximum PCE value to be evaluated not on the boundary of the speed-percentage (percentage of trucks) plane, but in the middle of the plane. For example, there was the maximum PCE of 1.9 at the speed of 10~20 mph and at the truck percentage of 30~40% derived from our long-term work zone data.

- (d) The fluctuation of PCE is like a mountain chain on the speed-percentage (percentage of trucks) plane (Fig.3 and Fig. 4). The mountain chain for short term work zones was more disordered than that for long-term work zones in this study. There may be three reasons: First, there was less data for short-term work zones, which made the result for short-term work zones not as accurate. Second, there were lower speed limits during the short-term work zones. The speeding always happens when the density of the traffic flow is very low. Therefore, when the speed exceeds the speed limit (45 mph), the interactions of vehicles for short-term work zones is very low, too. Third, drivers tend to be more familiar with long-term work zones.

5. CONCLUSIONS

There forms a mountain chain of PCE on the speed-percentage (percentage of trucks) plane. The direction of a mountain chain is from low-speed and high percentage to the high-speed and the low percentage (Fig.5). The PCE calculated by the simple method (the ratio of the headways) were usually underestimated, while those derived from the normal congested traffic conditions were overestimated. At the same speed, the PCE will fluctuate as the percentage of trucks increase. The PCE will increase at first and then decrease. As the speed increases, the peaks of the fluctuations move in the negative direction along the axis of the percentage of trucks. Moreover, as the speed increases, the intensity of these fluctuations turns out to be high at first and then low, which may cause the maximum PCE value to be determined not on the boundary of the speed-percentage plane, but in the middle of the plane. This new finding is very useful to the traffic operation in work zones. It is no longer adequate to purely control the number of trucks or average the trucks in different lanes or different roads to reduce the effect of trucks. On the contrary, a lane or road which only permits trucks should be established to avoid the maximum PCE values according to our study. The truck only lane or road will result in a very high percentage of trucks on these segments, and very low percentages on the other segments, which would make the PCE a smaller value in both situations (Fig. 5).

FIGURE 5 The PCE for Work Zone Conditions after Interpolations

When employing different methods, different PCEs can be calculated. The previous studies only focus on the functions of PCE, regardless of the criteria (speed, density, or volume) they were based on. No feedbacks of those models were concerned. Although some functions were comprehensive enough, the whole processes to develop the model seemed to be very simple. An obvious drawback is that it is difficult to evaluate performance of different PCE values. For example, the traditional method can't assert that 1.7 is better than 1.5 as the PCE value at the speed below 30 mph under short-term work zone conditions when the percentage of trucks is 20~30%. In this paper, a new method is developed with closed loop calibrations to compute the PCE. The differences of ranks are used to evaluate different PCEs. Moreover, this new model is based totally on the meaning of PCE, not referencing to any critical parameter (speed, density, or volume). This is necessary because the other parameters (speed, density, or volume) are also changing as the percentage of trucks change. In other words, under the same road condition, the speed, density, or volume will change, too, when the trucks are removed from the road sector. Thus, the traditional method, to some degree, is inaccurate when base volume (only passenger cars) is used to calculate the PCE. We will improve this model using simulation data and generalize it to different kinds of road conditions in future studies.

6. RECOMMENDATIONS

The new model proposed in this paper also has a limitation. It needs an assumption that the volumes (pcphpl) of the sequent two data elements after sorting have a minimal difference. The assumption reduces the use of the new method. For example, the ideal situation is that there be at least 10 data during a range of every 10 volumes (pcphpl). Because, if the data are not enough in a small region, the model can't be used to calculate the PCE, but only to calibrate the model. The assumption doesn't come into existence, resulting in large errors in the calculations. The first recommendation is to establish a comprehensive data base using simulations. Simulation data can overcome the shortcoming of the number and the range of data.

The complicated configurations of work zones decide their special characteristics of PCE. So far, the PCEs derived from real data are better than those from simulation data to further estimate the capacity, delay, cost, and so on. In the future, the simulations to calculate PCEs should consider not only the congested traffic flow, but also the merging behavior and the driver psychologies when encountering large trucks. A second recommendation is to evaluate PCEs at different grades and grade length conditions.

The third recommendation is to build up a micro-model to study the essence of the PCE, unlike the macro-model proposed in this paper. For example, Benekohal et al have been analyzing the impact of a truck on the vehicles next to it through a micro-model (20). Sun et al also focused on the small differences between different vehicle-following patterns (23). An accurate macro-model is good for estimation, while an accurate micro-model is good for operations. According to macro-model, the regulations, such as the speed limit and the specific lane or road, can be made to avoid a higher PCE and further to increase the capacity as much as possible. Besides that, the reduction of delay and cost, and even the improvement of safety will be part of the benefit of the micro-analyses through optimizing the configuration of the work zone, including the speed limit, the merge control, the lane closures, and even the barrier types. Therefore, the combinations of macro- and micro- models will be the direction of this study in the future.

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