TRAFFIC DELAY AT A FREEWAY WORK ZONE

Ruey Long CHEU
Assistant Professor
Department of Civil Engineering
National University of Singapore
10 Kent Ridge Crescent
Singapore 119260, Singapore
Fax: +65-779-1635
E-mail: cvecrl@nus.edu.sg

Tien Fang FWA
Associate Professor
Department of Civil Engineering
National University of Singapore
10 Kent Ridge Crescent
Singapore 119260, Singapore
Fax: +65-779-1635
E-mail: cvefwatf@nus.edu.sg

Abstract: This paper presents the development of a delay estimation model due to closure of fast lane in a three-lane freeway, without queue formation. The proposed model estimates average work zone delay which is the sum of (i) transition delay due to lane changing and merging, and (ii) maintenance delay due to speed reduction in the maintenance zone. Equations for transition and maintenance delays have been developed for passenger cars/light vehicles as well as for heavy vehicles, based on field data. The average work zone delay for each of the two vehicle types can be calculated separately, and then weighted by the vehicle composition to form the overall average work zone delay. The maintenance delay component is found to be slightly lower, but closely match with an existing model based on the U. S. Highway Capacity Manual.

1. INTRODUCTION

Highway maintenance activities often involve closure of traffic lanes. The delays caused by highway maintenance activities are a major concern to transportation engineers. Careful scheduling of maintenance activities can help to reduce delays, and lead to considerable savings in travel time and reduction of economic loss in the case of urban road networks. Delay models capable of providing good estimates are therefore essential in the planning of maintenance activities.

Work zone delay may be divided into congestion or queuing delay and speed-reduction delay (Cassidy and Han, 1993; Martinelli and Xu, 1996; Davis *et al*., 1981). Congestion or queuing delay is due to traffic demand in excess of the reduced capacity of the work zone. Speed-reduction delay may be defined as the delay due to reduction in speed as vehicles pass the section under maintenance. Most highway agencies rely on a set of rules and engineers' judgment in scheduling maintenance activities to minimize the overall work zone delay. Very often, maintenance works in urban areas are carried out at off-peak period. Because of the relatively low traffic demand, the closure of one lane in a multilane freeway does not result in the formation of queue at upstream of the maintenance section. However, significant speed-reduction delay may still be imposed on motorists when they have to reduce speed while changing lane and travel pass the section under maintenance. While much attention has been devoted to, and mathematical solutions are available for congestion or queuing delay (for example, see Cassidy and Han (1993), Martinelli and Xu, (1996), and Davis *et al*. (1981)), little research effort has been focused on delay due to merging and lane changing, as well as speed-reduction in the maintenance zone, without queue formation.

This paper presents the analysis of field data collected at a freeway work zone involving the closure of one out of three lanes, but without queue formation. The impact of lane closure on delay due to (i) lane changing and merging, and (ii) speed-reduction in the maintenance zone were analyzed with respect to length of maintenance section and traffic volume. The results have led to the construction of a new work zone delay model. The proposed model has also been compared with an available model reported in Martinelli and Xu (1996) which is based on the level of service concept in the U. S. Highway Capacity Manual (TRB, 1985).

2. PROBLEM FORMULATION

Our delay model is based on a freeway work zone that has a total length of L_{wz}. The length of work zone includes L_m, the maintenance zone or length of section under maintenance, plus the portions upstream of the maintenance zone where vehicle speed starts to decelerate, and downstream of the maintenance section where vehicles accelerate back to the approach speed.

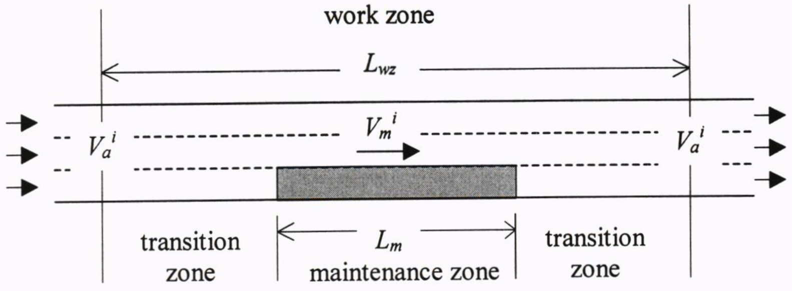

Figure 1. Schematic layout of site

Consider the behavior of vehicle i entering the upstream end of the study site. This vehicle initially travels with a constant approach speed of V_a^i. Upon seeing the maintenance activity, it decelerates until reaching a constant speed of V_m^i while entering the maintenance zone. The vehicle is assumed to travel pass the maintenance zone with a constant speed of V_m^i. It is obvious that $V_a^i \geq V_m^i$. After leaving the maintenance zone, it accelerates back to the original approach speed of V_a^i. The total time a vehicle spent travelling pass the work zone can be measured by license plate survey, and is denoted by T_{wz}^i. The approach and maintenance speeds (V_a^i and V_m^i respectively) can be measured by spot speed devices such as radar or laser guns. For this vehicle, the *work zone delay* can be computed from

$$D_{wz}^i = T_{wz}^i - \frac{L_{wz}}{V_a^i} \qquad [1]$$

in which the second term in the right-hand-size of the equation is the travel time without delay, assuming this vehicle will travel with V_a^i throughout. Applying the same assumption, the delay in the maintenance zone (hereafter referred to as *maintenance delay*) is then

$$D_m^i = L_m \left[\frac{1}{V_m^i} - \frac{1}{V_a^i} \right] \qquad [2]$$

There is also delay caused by the vehicle decelerating from V_a^i to V_m^i, and accelerating from V_m^i back to V_a^i. This is termed *transition delay*, and can be computed by taking the difference between the work zone delay and maintenance delay:

$$D_t^i = D_{wz}^i - D_m^i \qquad [3]$$

Different vehicles are expected to have different approach and maintenance speeds, and hence different delays. For the estimation of overall traffic delay due to pavement maintenance activities, the average work zone, maintenance and transition delays are of interest. These can be computed by taking the average delays obtained from n vehicles, and hence dropping the superscript i in the notations. Thus

$$D_{wz} = \frac{1}{n}\sum_{i=1}^{n} T_{wz}^i - \frac{L_{wz}}{n}\sum_{i=1}^{n}\frac{1}{V_a^i}$$

$$= T_{wz} - \frac{L_{wz}}{V_a} \qquad [3]$$

$$D_m = \frac{L_m}{n}\left[\sum_{i=1}^{n}\frac{1}{V_m^i} - \sum_{i=1}^{n}\frac{1}{V_a^i} \right]$$

$$= L_m \left[\frac{1}{V_m} - \frac{1}{V_a} \right] \qquad [4]$$

$$D_t = D_{wz} - D_m \qquad [5]$$

Note that, the average approach speed (V_a) and average maintenance speed (V_m) are the harmonic means of their respective individual speeds. The analysis and models reported in this paper are based on the aggregated measures.

3. DATA COLLECTION

This paper presents the results of our study based on data collected at a site at the Pan Island Expressway (PIE) in Singapore. The site is located at approximately 4.0 km mark at the eastern end of the Singapore island. Nine weekdays of data were obtained from December 10, 1997 to February 5, 1998, excluding the week from December 24, 1997 to January 2 1998, and other public holiday. Data from both the eastbound and westbound directions are taken in different days. Each of the directions has 3 lanes, and only the fast lane was blocked for maintenance activity at any time. The maintenance work involved repairing and replacement of guardrails. Due to the nature of work, the length of maintenance zone varied from 330 m to 1100 m from day to day. The 9 days of data consisted of L_m=330, 380, 510, 580, 850, 980 and 1100 m. The data collection time ranged from 11:00 a.m. to 4:00 p.m., mainly due to the restriction of maintenance work hour during the off-peak traffic. Each data collection session lasted for approximately 3 hours, with periodic rest in between to avoid human fatigue. The traffic volume was in the range of approximately 2100 to 3200 vph (all lanes in one direction combined). There was no queue forming at the upstream end of the work zone.

During data collection, license plate observers were positioned at the upstream and downstream ends of the work zone in order to capture the average actual travel time (T_{wz}) of vehicles. The average approach speed (V_a) and maintenance speed (V_m) were measured at the upstream end of the work zone and in the center of the maintenance zone by two separate laser guns (Laser Technology, 1994). It was not possible to capture all vehicles in the traffic stream during the license plate survey and spot speed measurement. Random samplings were made for the measurements of T_{wz}, V_a, and V_m. It should be noted that each of the above samples may consist of different vehicles within the same data collection interval. The length of work zone (L_{wz}) and maintenance zone (L_m) were measured by a pecimeter. In addition, a video camera was positioned at the upstream end of the work zone that pointed towards the maintenance zone to record the traffic conditions. The traffic volume and vehicle compositions were extracted from the video recordings in the laboratory.

In Singapore, heavy vehicles have a lower legal speed limit of 50 km/h in expressways compared to 80 km/h for passenger cars and other light vehicles. In our preliminary site observation, it was found that heavy vehicles, due to their speed limit and vehicle performance, behaved differently compared to passenger cars. The data collection session was therefore divided in to alternate intervals of 15 minutes each. In each interval, only a vehicle type (i.e., either passenger cars/light vehicles or heavy vehicles) was observed. At the prevailing traffic volume, the 15-minute interval was adequate to provide sample size of at least 40, which was large enough for the computation of T_{wz}, V_a, and V_m respectively.

4. CONSTRUCTION OF DELAY MODELS

The computation of work zone, transition and maintenance delays based on collected data have been explained in the previous sections. In this paper, the model of interest are average work zone delay (D_{wz}), transition delay (D_t) and maintenance delay (D_m) with respect to prevailing traffic volume (q) and length of maintenance zone (L_m). Since different days of data involved maintenance zones of different lengths, it is sometimes necessary to express delay in terms of per unit length of maintenance zone.

The model development started by assuming that the average work zone delay is the sum of average transition delay and average maintenance delay, i.e.

$$D_{wz} = D_t + D_m \qquad [6]$$

D_m was assumed to be a linear function of L_m, and perhaps volume q, while D_t was assumed to be a function of q with the physical capacity reduction being kept constant. Note that D_t was believed to be directly proportional to q because of the increase in vehicle interaction during lane changing and merging events as they enter the work zone.

Figure 2 plots the D_m versus L_m. The average maintenance delay for passenger cars/light vehicles are higher than that for heavy vehicles. This is expected as passenger cars and light vehicles have higher average approach speed compared to heavy vehicles. Two regression lines, each passing the origin of the graph were fitted to the data points. The slopes of the regression lines indicate that (i) for passenger cars/light vehicles, the average maintenance delay is 0.0067 sec/m; and (ii) for heavy vehicles, the average maintenance delay is 0.0047 sec/m.

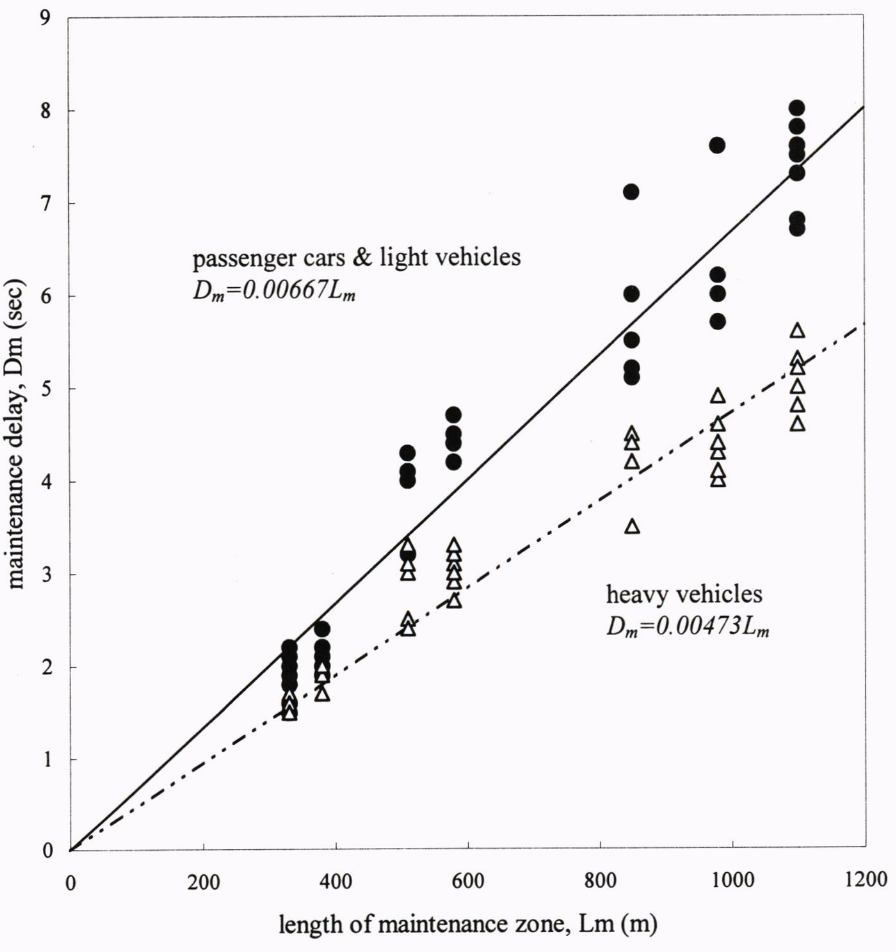

Figure 2. Plot of maintenance delay versus of length of maintenance zone

The average work zone delay per unit length of maintenance zone (i.e., $D'_{wz}=D_{wz}/L_m$, in sec/m/veh) was next plotted against q in Figure 3. The data points were found to scatter into 4 different regions according to vehicle classification (either passenger cars/light vehicles or heavy vehicles) and range of L_m. Due to car-following effect, it is reasonable to expect that D'_{wz} increases with q. It appears that the length of work zone also has significant impact on the model. Vehicles encounter $L_m \geq 850$ m experienced lower D'_{wz} compared to the sites where $L_m \leq 580$ m. There is no data for 580 m<L_m<850 m.

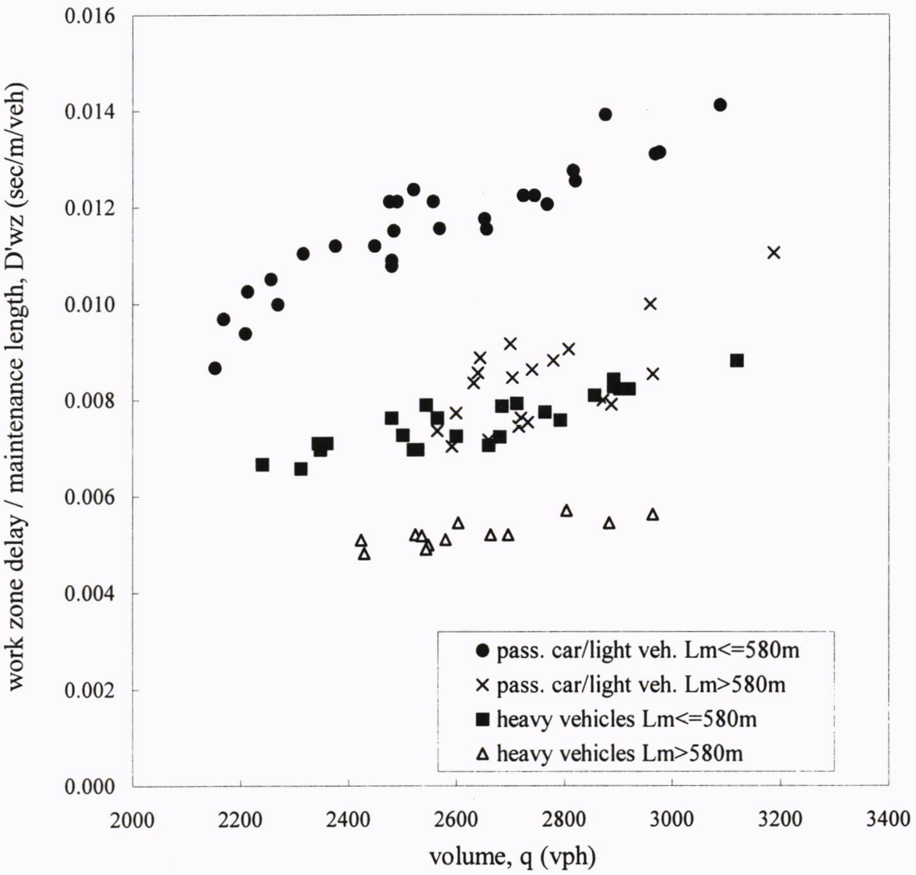

Figure 3. Plot of work zone delay per unit length of maintenance zone versus volume

Since we have divided D_{wz} into 2 components: D_m and D_t, effort was next devoted into finding the characteristics of D_m and D_t that lead to the segregation of D'_{wz} data points based on L_m. The maintenance delay per unit length of L_m (i.e., $D'_m=D_m/L_m$) was plotted against q in Figure 4. The data points for passenger cars/light vehicles and heavy vehicles each form a linear cluster. There was no distinct group based on different ranges of L_m.

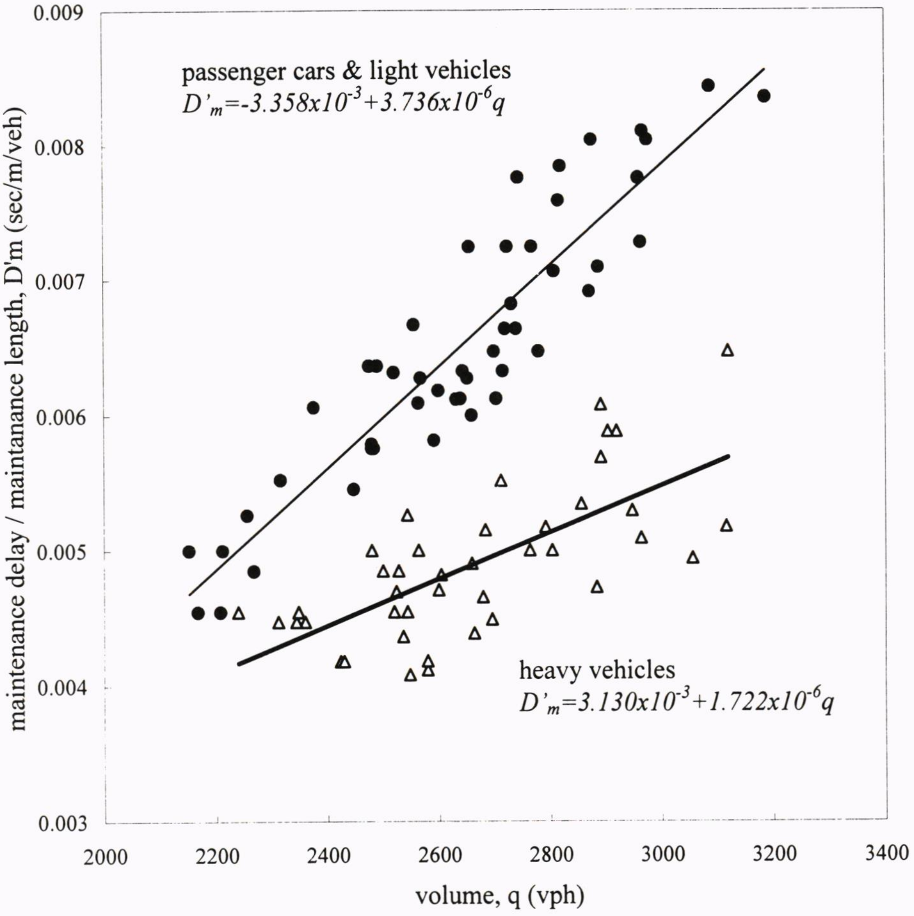

Figure 4. Plot of maintenance delay per unit length of maintenance zone versus volume

The transition delay per unit length of L_m (i.e., $D'_t = D_t / L_m$ was next plotted against q in Figure 5. The spread of data points shows that the effect of L_m is embeded in D_t, and the clustering of D'_{wz} is caused by the transition delay. It was initially surprising to see that D_t is not dependent on q. Rather, depending on the vehicle type and range of L_m, D'_t remains approximately constant. The average value of D'_t for the two categories of vehicles and ranges of L_m are listed in Table 1.

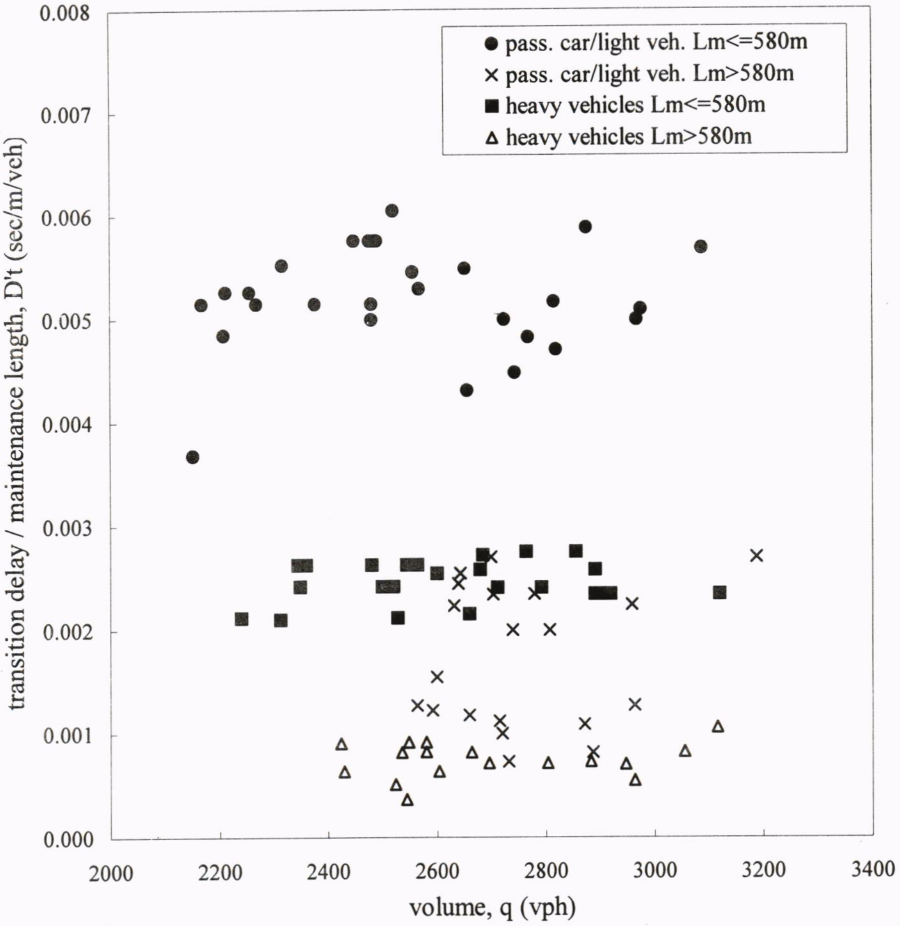

Figure 5. Plot of transition delay per unit length of maintenance zone versus volume

Table 1. Average value of transition delay per unit length of maintenance zone

D'_t (sec/m/veh)	vehicle type	
	Passenger cars/light vehicles	Heavy vehicles
$L_m \leq 580$ m	0.005203	0.002464
$L_m \geq 850$ m	0.001742	0.000744

Given the same length of maintenance zone, the average D_t' for passenger cars/light vehicles are higher than that for heavy vehicles. This is because in our site, only the fast lane was blocked. Passenger cars and light vehicles have to slow down and change from the fast lane to two other lanes in order to enter the maintenance zone. On the contrary, heavy vehicles normally travel on the slow lane. In Singapore, the legal speed limit for heavy vehicles is 50 km/h, as compared to 80 km/h for other vehicles in expressway. The impact of work zone on the slow lane and vehicles with a lower speed limit is not as severe.

In the Problem Formulation section, it has been assumed that transition delay is due to deceleration upstream of the maintenance zone, and acceleration downstream of the maintenance zone. The model is simplified in view of manpower and equipment constraints during data collection. For same type of vehicle, work zones with $L_m \geq 850$ m experienced a lower average D_t' than those with $L_m \leq 580$ m. This may be due to the fact that for a maintenance zone longer than 850 m, vehicles tend to accelerate to closer to the approach speed once they have traveled for a distance inside the zone. Thus, the D_t component at downstream of the maintenance zone has been reduced. This is unlikely for shorter maintenance zone, in which vehicles are still travel with rather constant and slow speed, carry on with the momentum after deceleration and merging. However, this deduction can only be confirmed with more extensive field instrumentation and data measurement, such as the one employed by Ceder (1993), which is not available at the time of writing.

5. THE PROPOSED DELAY MODEL

With the current findings, the proposed model for average work zone delay (in sec/veh) is therefore

$$D_{wz} = L_m\left[\left(D'_{t,lv} + D'_{m,lv}\right)\left(1 - HV\right) + \left(D'_{t,hv} + D'_{m,hv}\right)HV\right] \qquad [7]$$

where HV denotes fraction of heavy vehicles in the traffic stream;
lv is the subscript that denotes passenger cars/light vehicles; and
hv is the subscript that denotes heavy vehicles.

$D'_{t,lv}$ and $D'_{t,hv}$, the average transition delays per unit length of maintenance zone for passenger cars/light vehicles and heavy vehicles respectively, can be read from Table 1. $D'_{m,lv}$ and $D'_{m,hv}$, the average maintenance delays per unit length of maintenance zone for passenger cars/light vehicles and heavy vehicles respectively, can be approximated by the regression lines fitted to the data points in Figure 4:

$$D'_{m,lv} = -3.358\text{x}10^{-3} + 3.736\text{x}10^{-6}q \qquad [8]$$

$$D'_{m,hv} = 3.130\text{x}10^{-3} + 1.722\text{x}10^{-6}q \qquad [9]$$

where $D'_{m,lv}$ and $D'_{m,hv}$ are in sec/m/veh and q is in vph.

6. COMPARISON WITH AN EXISTING MODEL

This section of the paper illustrates the application of the proposed work zone delay model, and the comparison between the proposed model with the one by Martinelli and Xu (1996). The calculations are based on 2 separate L_m of 500 m and 1000 m respectively. The traffic volume is assumed to vary from 2200 vph to 3000 vph, and 30% of which are heavy vehicles.

For our proposed model, the average work zone delays at various traffic volume for the 2 scenarios of different L_m are plotted in Figure 6. Their average maintenance delays are also plotted in Figure 6. The maintenance delay is higher than the transition delay. It is obvious that the maintenance delay increases with L_m, and q. The transition delay component is independent of q. The work zone and maintenance delays for L_m=1000 m increase at faster rates with respect to q compared to L_m=500 m because of the L_m term in Equation [7].

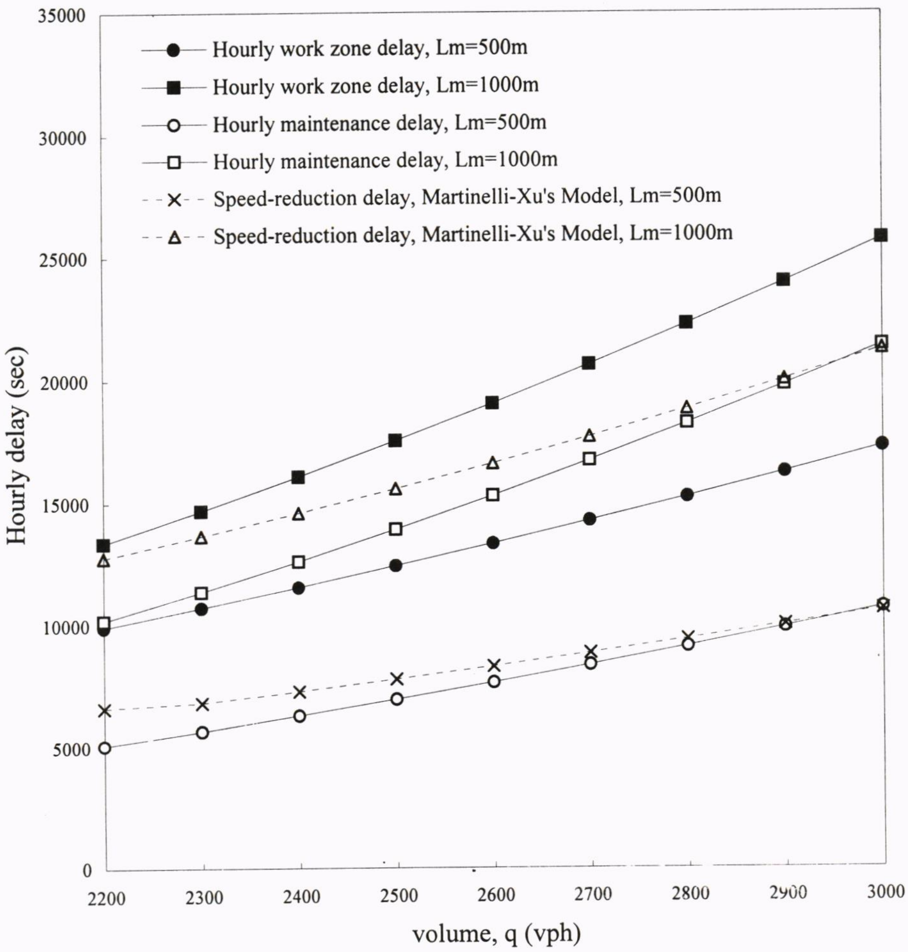

Figure 6. Comparison of hourly work zone and maintenance delays at various volume

The Martinelli-Xu's Model divides the work zone delay at a 4-lane freeway into (i) congestion delay due to queuing and (ii) speed-reduction delay while passing the maintenance zone. In this paper, the speed-reduction delay in the Martinelli-Xu's Model is taken as equivalent to maintenance delay, as its main equation follows the same form as Equation [2]. This speed-reduction model gives a set of equations that makes use of the level of service concept in the U. S. Highway Capacity Manual (TRB, 1985). The following values were used in the computation:

- Freeway capacity under ideal conditions = 2400 vphpl
- Lane width and lateral clearance factor = 0.97, based on lane width of 3.4 m in Singapore expressways
- Driver population factor = 1.0
- Passenger car equivalent for heavy vehicles = 1.75, using the average of 1.5 for light goods vehicles and 2.0 for heavy goods vehicles
- Heavy vehicle factor = 0.82

The total hourly delays are plotted against volume in Figure 6. For L_m=500 m, the speed-reduction delays given by the Martinelli-Xu's Model are slightly higher but very close to our maintenance delays. The two curves converge as q approaches 3000 vph. As for L_m=1000 m, the differences are larger for q less than 2500 vph, but the 2 curves match very closely at higher value of q. Even at the smallest volume where the highest disparities occurs (i.e., q=2200 vph), the differences are only 0.70 and 1.17 seconds per vehicle, for L_m=500 m and L_m=1000 m respectively. The small differences in maintenance delay are very encouraging. It should be noted that the Martinelli-Xu's Model is developed for 4-lane freeway in each direction. Although the number of lanes has been factored into the volume/capacity ratio during calculations, it may not have tested against a 3-lane freeway. Furthermore, the Martinelli-Xu's Model is for U.S. freeway that has a speed limit of at least 88 km/h (55 mph). Whereas the speed limits for expressways in our Singapore site are 80 km/h for passenger cars and light vehicles, and 50 km/h for heavy vehicles. Using a higher approach speed in the calculation would result in higher delay. The may explain why at lower traffic volume, the Martinelli-Xu's Model gives higher maintenance delays. Another possible difference may lie in the maintenance activity. Our data is based on fast lane closure for guardrail repair and replacement. Other pavement maintenance activities, such as surfacing and overlaying, may involve heavy machinery that cause vehicles to slow down further in the maintenance zone. Despite all these minor differences, the maintenance delay predicted by our proposed model matches very closely with the speed-reduction delay from the Martinelli-Xu's Model.

7. CONCLUSIONS

A model to estimate the traffic delay while passing a freeway work zone involving lane closure has been proposed. This model formulation is applicable to the condition when the upstream traffic demand is less than the freeway capacity of the remaining lanes (i.e., no queue formation). This model considers the work zone delay as the sum of transition and maintenance delays. The transition delay accounts for the transition between the normal travel speed (approach speed) and the reduced speed while inside the maintenance zone. This occurs at upstream as well as downstream of the maintenance zone. The maintenance delay is due to the difference between the normal travel speed and the reduced speed in the maintenance zone.

Field data has been collected at an expressway site in Singapore during the model development. The data covers the condition of traffic volume between 2100 to 3200 vph, in which approximately 30% of the traffic is heavy vehicle. The length of maintenance zone varied from 330 to 1100 m. Only the fast lane out of the 3 travel lanes was closed for guardrail repair and replacement.

The data shows that maintenance delay per unit length of maintenance zone is a linear function of traffic volume. Two linear functions, one for passenger cars/light vehicles and another one for heavy vehicles, have been calibrated. The transition delay per unit length of maintenance zone, however, can be approximated by a constant value depending on the length of maintenance zone and vehicle type. Given a site with a fixed maintenance zone length and traffic volume, the transition and maintenance delays for passenger cars/light vehicles and heavy vehicles can be computed separately. The respectively delays are then weighted by the vehicle composition to form the overall average work zone delay.

The maintenance delay estimated by our proposed model has also been compared with the speed-reduction delay model proposed by Martinelli and Xu (1996). The delay estimations from the two different approaches match very closely.

The results reported in this paper is based on a model with a simplified speed profile, and applied to one freeway site. These initial findings are very encouraging. Work is currently underway to validate the model's speed profile at another test site. In future, when data from more sites are available, more general models for maintenance delay, transition delay and total delay can be established. Other factors, such as types of maintenance activity and road width, can then be incorporated into the model.

REFERENCES

Cassidy, M.J. and Han, L.D. (1993) Proposed Model for Predicting Motorist Delays at Two-Lane Highway Work Zones. **Journal of Transportation Engineering**, 119(1), 27-42.

Cedar, A. (1993) Traffic Behavior During Lane Closure Periods of a Two-Lane Road. In C.F. Daganzo (ed.), **Transportation and Traffic Theory**, Elsevier Science, 553-574.

Davis, R.F., Vincent, J.F. and Jacoby, R.G. (1981) A Method of Assessment of Delays Caused by Roadworks. **Traffic Engineering and Control**, 22(1), 9-13.

Laser Technology (1994) **Marksman LTI 2020 Laser Speed Detection System Operator's Manual**, Laser Technology Inc., Engelwood, Colorado.

Martinelli, D.R. and Xu, D. (1996) Delay Estimation and Optimal Length for Four-Lane Divided Freeway Workzones. **Journal of Transportation Engineering**, 122(2), 114-122.

TRB (1985) **Highway Capacity Manual**. Special Report 209, Transportation Research Board.