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Delay functions in trip assignment for transport planning process

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Delay Functions in Trip Assignment for Transport Planning Process

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Abstract. In transportation planning process, volume-delay and turn-penalty functions are the functions needed in traffic assignment to determine travel time on road network links. Volume-delay function is the delay function describing speed-flow relationship while turn-penalty function is the delay function associated to making a turn at intersection. The volume-delay function used in this study is the revised Bureau of Public Roads (BPR) function with the constant parameters, α and β values of 0.8298 and 3.361 while the turn-penalty functions for signalized intersection were developed based on uniform, random and overflow delay models. Parameters such as green time, cycle time and saturation flow were used in the development of turn-penalty functions. In order to assess the accuracy of the delay functions, road network in areas of Nibong Tebal, Penang and Parit Buntar, Perak was developed and modelled using transportation demand forecasting software. In order to calibrate the models, phase times and traffic volumes at fourteen signalised intersections within the study area were collected during morning and evening peak hours. The prediction of assigned volumes using the revised BPR function and the developed turn-penalty functions show close agreement to actual recorded traffic volume with the lowest percentage of accuracy, 80.08% and the highest, 93.04% for the morning peak model. As for the evening peak model, they were 75.59% and 95.33% respectively for lowest and highest percentage of accuracy. As for the yield left-turn lanes, the lowest percentage of accuracy obtained for the morning and evening peak models were 60.94% and 69.74% respectively while the highest percentage of accuracy obtained for both models were 100%. Therefore, can be concluded that the development and utilisation of delay functions based on local road conditions are important as localised delay functions can produce better estimate of link travel times and hence better planning for future scenarios.

INTRODUCTION

Four stage demand model is the most popular travel demand forecasting model used extensively by transportation engineers. The four stage demand models are trip generation, trip distribution, modal split, and trip assignment. Each of the steps in travel demand model plays difference roles in tracking traffic volume. Traffic assignment is the process to assign the traffic demand to the links of network and driver will choose the path based on the traffic condition and costs. The fundamental aim of the traffic assignment is to observe the pattern of vehicular movements on the road network where the travel demand is represented by the origin-destination matrix. In traffic assignment model, the travel time is equivalent to the travel cost. The shortest path could be identify based on travel time when traffic volume is being assigned on different routes. Therefore, travel time is taken as one of the most important factor in decision making regarding destinations, routes and transport modes.

Delay is total lost time that results in increment of the time travel of road users. Link delay and turn delay are the common delays encountered in a road network. Link delay is the delay function used to describe the speed-flow relationship in a travel demand network in which with the increasing number of vehicles, the time travelled also increases due to the heavy traffic flow along the link. When the road is congested, the speed of link will become lower and the link travel time will be higher than the free flow conditions. However, there are no standard link delay functions for expressways, major highways, and arterial roads that were being utilized by road network planners or designers in Malaysia. The primary link impedance is travel time, which increases with an increasing degree of saturation [1]. As such, volume-delay function is used to express travel times of a road link as a function of traffic volume. Usually these

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functions are expressed as the product of the free flow time multiplied by a normalized congestion function such as road capacity. Free-flow speed can be measured directly, while capacity is not easy to measure due to its stochastic nature and large variations. Some of the earlier developed volume-delay functions were by Overgaard in which he has proposed an exponential function while Mosher suggested logarithmic and hyperbolic functions (as cited by Branston [2]). However, one of the best known and the most widely-used volume-delay function is the function known as BPR function which was developed by U.S. Bureau of Public Roads (BPR) in 1964 [3]. But according to Singh [4], the problems with the BPR function is that it overestimates speeds when volume over capacity ratio is more than 1 and underestimates speeds when volume over capacity ratio is 1. Spiess [5] also has discovered some inherent shortcomings in the BPR function and therefore, has developed the conical functions. However, the parameters used to characterize the specific congestion behavior of a road link, such as capacity and steepness, is the same for both BPR and conical function and therefore, the difference between a BPR function and a conical function with the same parameter is very small, which then makes the transition from BPR function to conical function particularly simple. However, he commented that further research is needed to develop statistical methods for directly estimating the parameters of the conical functions using observed speeds and volumes. However, in a more recent study conducted by Kucharski and Drabicki [6], a new method to estimate volume-delay function using density was developed and they have managed to improve the goodness-of-fit from 27% to 72%, which indicated that their findings were much more consistent with field data.

Apart from link, intersections are the important nodes within a road network system where its performance is to be evaluated and measured. Similarly with volume-delay at link, turn delay is the critical index, which is used for evaluation service level and operational efficiencies especially at signalized intersections. It reflects the extra time users spent when passing it and also the operation state of signalized intersections in urban cities. If the state of operation is well, delay is short. Measuring delay at signalized intersection is a complex process due to the fact that different observers may make judgments that yield various different results. Estimation of delay is complicated due to the random arrival of vehicles, time loss when vehicles stop, or even over saturated flow scenarios and others. Besides, delay is about time difference between the passing time when vehicles don't need to stop and the actual time needed at intersections. Moreover, it has to do with signal cycle, timing plan, traffic flow, random factor and others. Intersection delays can be divided into two different types, namely static and dynamic delays [7]. The static intersection delay which is supported by many transportation modeling packages, represents the predicted delays at each approach of intersection which is not dependent to flows at intersections. As for the dynamic intersection delay it computes the volume-based delays at intersections.

Theoretically, delay models can be developed based on uniform delay, random delay and overflow delay models. Uniform delay is the delay with the assumption of uniform arrivals and stable flow without the individual cycle failures which means that no vehicles have to wait for more than one cycle to be discharged. Next, the random delay is defined as the delay where the vehicle flow is randomly distributed rather than uniformly at the intersection. As for the overflow delay, it is the additional delay that occurred when the capacity of an individual phase is less than traffic demand. Overflow delay happened when traffic flow is not able to fully discharge during green time which will then increase the number of queuing vehicles. In a study conducted in Tehran, Iran to investigate the delays at signalized intersections, four types of data, namely: traffic volumes, delay, signal timing for each intersection movement, and the intersection geometry were collected [8]. To calculate vehicle delay times, free-flow travel time of each intersection movement was then reduced from travel times recoded in that movement. The free-flow travel times were calculated based on the free-flow speeds of 60, 50, and 40 km/h. The average delay in each movement in different 5-min time intervals was then computed considering the delay of vehicles arriving within each 5-min interval. Finally using a weighting average on the movement delays of each approach with the weights equal to the traffic volumes of those movements in different 5-min intervals, delay values were obtained for each intersection approach. The traffic signals at the intersections were pre-timed, and over the period of data collection the green times and the cycle times were constant. In another study conducted in Harbin, theoretical delay values were compared with actual values measured [9]. It is said that the affecting elements on delay are complex however some elements overlap others, hence four mainly affecting elements: cycle length, saturation, split, and the ratio of the number of arriving vehicles at green light and that of arriving vehicles during the whole cycle length is chosen.

Hence, having a predictive model to estimate delay is more convenient and appropriate to investigate the effects of turn delay on travel time. Further knowledge regarding turn delay could definitely increase the preciseness of the delay calculations or functions. However, the development of signalized intersection delay function for estimating delays at signalized intersection have to be a balance between simplicity and accuracy and also its applicability based on the data requirements and algorithms. Therefore, in this study, delay associated with link volume and delay due to turning movements at signalized intersections were investigated.

STUDY METHODOLOGY

Road Network Model

In this study, road network in areas of Nibong Tebal, Penang and Parit Buntar, Perak were modeled. The traffic zoning system in this study is determined by the district boundary and distribution of land uses in the vicinity of the study area. A total of twenty-one traffic analysis zones were created for the study area in which twelve of them were external zones representing various inter-urban roads leading to external regions. In the road network model developed in the transport demand forecasting software, these zones are identified as centroids which will be connected to nodes and then to links. Link should be defined as either one-way or two-way links and they were divided into segments based on topography and conditions of the road terrain. Length of each link represent length of the road segment and they were measured using Google Earth. The number of lanes on each links were then defined. In this study area, fourteen signalized intersections were identified and they were created in the road network. In the model calibration process, the turn-penalty functions were identified with either 0 for prohibited turn or -1 for allowed turn and traffic assignment is achieved based upon the estimated peak hour demand matrices, which is based on passenger car unit.

Volume-delay function

The developed road network is first analyzed by applying assumed volume-delay functions. In Malaysia, traffic consultants and transport modelers often adopt volume-delay functions developed from other countries but calibrated them manually based on much localized traffic conditions. Different traffic consultants in Malaysia adopt different volume-delay functions. However, in this study, the most widely-used volume-delay function which is the BPR function shown in Eq. (1) is adopted.

$$T = T_o\left[1 + \alpha\left(v / v\right)^{\beta}\right] \tag{1}$$

where T is the travel time in minutes, T_o is the free-flow travel time in minutes, v is traffic volume in passenger car unit/hour, c is the capacity in passenger car unit/hour and $\alpha = 0.15$ and $\beta = 4$.

In this study, speed limit is used instead of free-flow speed due to the reason that speed limit is more practical and can be determined easily from site observations. Also, based on a study conducted by Deardoff *et al.* [10] to estimate free-flow speed from posted speed limit signs at ten sites in South Dakota, they found out that the average free-flow speeds were strongly associated with posted speed limits with correlation coefficients of +0.99, +1.00, and +1.00 for urban streets, multilane highways and freeways respectively. The ranges of vehicle speed limit defined for the road network in this study area were between 20 km/h to 90 km/h. Lower speed limit is assigned to smaller roads where capacity of the roads are significantly lower, as well as windy and narrow roads where lower speed limit is necessary for safety purpose. On the other hand, higher speeds were applied to wider roads with multiple lanes and higher capacity, such as the federal road where road users can travel up to 90 km/h. The maximum number of lanes in the road network is three lanes per direction. The range of maximum road capacity for each link section is from 1000 pcu/h to 2000 pcu/h. Based on a study conducted by Leong [11] to investigate the effects of BPR function on time, speed and assigned volume, the delay calculated based on BPR function with $\alpha = 0.15$ and $\beta = 4$ has only slight increment when volume is less than 3000 pcu/h for all road categories but when the revised BPR function with α and β values of 0.8298 and 3.361 were used, the calculated delay increase significantly when volume exceeds 600 pcu/h, especially for lower hierarchy roads. In addition, the effects of BPR function on time, speed and assigned volume were also found to be less significant as compared to that of the revised BPR function. Therefore, the same volume-delay function was used in this study and is as shown in Eq. (2).

$$T = \frac{L \times 60}{v_s} \times \left(1.0 + \left(\alpha\left(\frac{volau}{lanes \times c}\right)^{\beta}\right)\right) \tag{2}$$

where L is the length of the link in km, v_s is the speed limit in km/h, $volau$ is the assigned volume at the link in pcu/h, lanes is the number of lanes at the link, c is the lane capacity in pcu/h/ln and $\alpha = 0.8298$ and $\beta = 3.361$.

Turn-penalty Function

In this study, the turn-penalty functions were developed based on the three types of fundamental delays, namely the uniform delay, random delay and overflow delay and they are then applied onto the road network model based on the road conditions. Three general turn-penalty functions were developed for the road network in the software and they are as shown in Eqs. (3) to (5). These equations are modified based on the theoretical delay equations of uniform delay, random delay and overflow delay.

$$D_U = \frac{ep1\left(1 - \frac{ep2}{ep1}\right)^2}{2\left(1 - \frac{pvolau}{S}\right)} \tag{3}$$

$$D_R = 0.9\left(\frac{ep1\left(1 - \frac{ep2}{ep1}\right)^2}{2\left(1 - \frac{pvolau}{S}\right)} + \frac{\frac{pvolau \times ep1}{(S \times ep2)^2}}{\frac{2 \times pvolau(1 - pvolau \times ep1)}{S \times ep2}}\right) \tag{4}$$

$$D_O = 1800\left(\left(\frac{pvolau \times ep1}{S \times ep2}\right) - 1\right) + \frac{0.5 \times ep1 \times (1 - ep2)}{ep1} \tag{5}$$

where *ep1* is the cycle time in minutes, *ep2* is the green time in minutes, *pvolau* is the assigned turning volume in pcu/h and S is the saturation flow in pcu/h.

DATA COLLECTION

Traffic volume, signal phasing, signal timing and junction configuration were collected and recorded at fourteen signalized intersections. Based on the traffic volume data collected, the morning peak hour is from 0700 to 0800 while the evening peak hour is from 1730 to 1830. The surveyed traffic volume were converted to passenger car equivalent (pcu) to provide consistency for analysis using the factors adopted from Arahan Teknik (Jalan) 8/86 [12]. Out of the fourteen junctions, six were three-legged junctions and the other eight were four-legged junctions. Majority of the major junctions were four-legged, with five major four-legged junctions and two major three-legged junctions. As for the minor junctions, four of them were three-legged while the other three were four-legged. Subsequently, the directional mid-block volume or link volume was then calculated for each approach based on the average of total exit volume of upstream junction with total approach volume of downstream junction of a particular road. These values were then used for model calibration process.

RESULTS DAN DISCUSSION

Traffic Volume

Out of the fourteen junctions, six were three-legged junctions and the other eight were four-legged junctions. Majority of the major junctions were four-legged, with five major four-legged junctions and two major three-legged junctions. As for the minor junctions, four of them were three-legged while the other three were four-legged. Table 1 shows the descriptions of all the junctions including the cycle time and total volume recorded for both morning and evening peak hours while Figure 1 shows the graphical presentation of total volume recorded at each junction for morning and evening peak hours. Based on the volume shown in Table 1, Junctions A and K were the two junctions with the highest total volume recorded but on the average, Junction K recorded the highest volume during both peak hours. As for the lowest total volume, Junction B recorded the lowers total volume during morning peak hour while Junction C recorded the lowest total volume during evening peak hour.

TABLE 1. Description of junctions

Junction	Descriptions	No. of phases	Cycle time (min) AM/PM	Total volume (pcu/h) AM/PM
A	Major four-legged junction	4	3.37/3.48	2690/3319
B	Minor three-legged junction	3	2.42/2.47	1204/1038
C	Minor four-legged junction	4	3.17/3.43	1461/933
D	Minor three-legged junction	3	2.67/2.67	1548/1616
E	Minor three-legged junction	3	2.50/2.50	1506/1347
F	Major four-legged junction	4	3.58/3.38	2001/1597
G	Minor four-legged junction	4	3.17/3.22	1595/1377
H	Major four-legged junction	4	2.52/2.63	2746/2719
I	Minor three-legged junction	3	1.02/1.05	1449/1715
J	Major three-legged junction	3	2.08/2.40	1851/2963
K	Major four-legged junction	4	3.37/3.40	3175/3152
L	Major four-legged junction	4	3.17/3.17	1738/1835
M	Minor four-legged junction	4	2.50/2.33	1655/1964
N	Major three-legged junction	3	2.62/2.52	2381/2716

Subsequently, the directional mid-block volume or link volume was then calculated for each approach based on the average of total exit volume of upstream junction with total approach volume of downstream junction of a particular road. These values were then used for model calibration process.

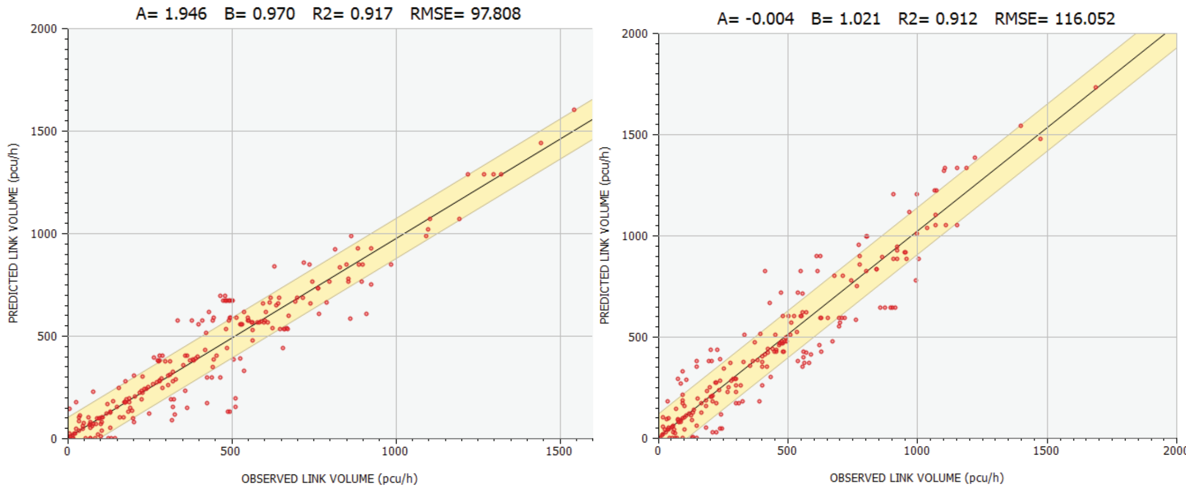
Calibration of the Road Network Model

Initially, prior to the inclusion of turn-penalty functions in the model, the road network is calibrated based on volume-delay functions. This is to ensure that the correct level of volume-delay function is applied to the link based on the corresponding road conditions. There are ten levels of volume-delay functions applied on the links in the model and they are a shown in Table 2. The volume-delay function, fd99 is applied to centroid connector that is to connect a centroid to a node.

TABLE 2. Volume-delay functions

ID	Functions
fd2	(length * 60 / 90) * (1 + 0.8298 * (volau / (lanes * 1800)) ^ 3.361)
fd3	(length * 60 / 80) * (1 + 0.8298 * (volau / (lanes * 1600)) ^ 3.361)
fd4	(length * 60 / 70) * (1 + 0.8298 * (volau / (lanes * 1600)) ^ 3.361)
fd5	(length * 60 / 60) * (1 + 0.8298 * (volau / (lanes * 1600)) ^ 3.361)
fd6	(length * 60 / 60) * (1 + 0.8298 * (volau / (lanes * 1400)) ^ 3.361)
fd7	(length * 60 / 60) * (1 + 0.8298 * (volau / (lanes * 1200)) ^ 3.361)
fd8	(length * 60 / 60) * (1 + 0.8298 * (volau / (lanes * 1000)) ^ 3.361)
fd9	(length * 60 / 50) * (1 + 0.8298 * (volau / (lanes * 1000) ^ 3.361)
fd10	(length * 60 / 40) * (1 + 0.8298 *(volau / (lanes * 1000)) ^ 3.361)
fd99	(length * 60 / 60)

Upon performing the trip assignment process using the volume-delay functions in Table 2, the predicted link volume is plotted against the observed link volume to determine the accuracy of predicted link volume based on the assigned volume-delay functions. The results obtained are shown in Fig. 1(a) for morning peak and Fig. 1(b) for evening peak.



(a) (b)

FIGURE 1. Link scatterplot of predicted versus observed link volume (a) morning peak hour (b) evening peak hour

Development and Application of Turn-penalty Functions

In order to determine the levels for turn-penalty functions, the ranges of saturation flows need to be determined first. In this study, the basic saturation flow values and the adjustment factors to take into consideration the effects of gradient, turning radius and proportion of turning traffic were adopted based on the values recommended in Arahan Teknik (Jalan) 13/87 [13]. Saturation flow values were calculated for each lane and subsequently divided into groups based on lane type which were the exclusive through lane, the shared lane of left-turn and through as well as the through and right-turn lane, the shared left-turn, through and right-turn lane and lastly, the exclusive right turn lane. The average value for each group was then calculated as approximation. Therefore, based on the pre-defined groups, four levels for each type of turn-penalty delays from Eqs. (3), (4) and (5) were developed. Table 3 shows the turn-penalty functions developed in this study. Saturation flow values were not calculated for yield left-turn lanes as they were not affected by signal timing. However, the turn-penalty function for this type of lane was based on the reduction of speed due to opposing traffic and turning radius. Upon many cycles of calibration, the turn-penalty functions developed for yield left-turn lanes are as shown in Table 4. For continuous lane, where no delay should occurred, the turn-penalty value of -1 was applied.

TABLE 3. Turn-penalty functions

ID	Functions
fp1	(ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1885))
fp2	(ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1737))
fp3	(ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1628))
fp4	(ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1538))
fp5	0.9*((ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1885))+(((pvolau*ep1)/(1885*ep2))^2)/(2*pvolau*(1-(pvolau*ep1)/(1885*ep2))))
fp6	0.9*((ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1737))+(((pvolau*ep1)/(1737*ep2))^2)/(2*pvolau*(1-(pvolau*ep1)/(1737*ep2))))
fp7	0.9*((ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1628))+(((pvolau*ep1)/(1628*ep2))^2)/(2*pvolau*(1-(pvolau*ep1)/(1628*ep2))))
fp8	0.9*((ep1*(1-ep2/ep1)^2)/(2*(1-pvolau/1538))+(((pvolau*ep1)/(1538*ep2))^2)/(2*pvolau*(1-(pvolau*ep1)/(1538*ep2))))
fp9	(1800*(((pvolau*ep1)/(1885*ep2))-1))+(0.5*ep1*(1-ep2/ep1))
fp10	(1800*(((pvolau*ep1)/(1737*ep2))-1))+(0.5*ep1*(1-ep2/ep1))
fp11	(1800*(((pvolau*ep1)/(1628*ep2))-1))+(0.5*ep1*(1-ep2/ep1))
fp12	(1800*(((pvolau*ep1)/(1538*ep2))-1))+(0.5*ep1*(1-ep2/ep1))

TABLE 4. Turn-penalty functions for yield left-turn lanes

ID	Functions
fp13	(0.00125*pvolau)/50
fp14	(0.00125*pvolau)/40
fp15	(0.00125*pvolau)/25

Upon performing the trip assignment process using the both the volume-delay functions and turn-penalty functions, the predicted turn volume is then plotted against the observed turn volume to determine the accuracy of predicted turn volume based on the assigned volume-delay functions and turn-penalty functions. The R-squared values of more than 0.90 obtained for both morning and evening peak hour models showed that both models with the assigned volume-delay functions and turn-penalty functions fit well with the observed turn volume. Further analyses were conducted to check on the accuracy of the predicted turn volume for all fourteen junctions. Based on the results obtained, the prediction of assigned volumes show close agreement to actual recorded traffic volume with 80.08% lowest percentage of accuracy and 93.04% highest percentage of accuracy for the morning peak model. As for the evening peak model, they were 75.59% and 95.33% respectively for lowest and highest percentage of accuracy. As for the yield left-turn lanes, the lowest percentage of accuracy obtained for the morning and evening peak models were 60.94% and 69.74% respectively while the highest percentage of accuracy obtained for both models were 100%. The results also indicated that the prediction accuracy is more than 60% for all turn movements except for one yield left-turn lane which only achieved 56% accuracy for morning peak hour. Out of the 118 turn movements analyzed at the fourteen signalized intersections, 41 of the turn movements achieved 100% accuracy in the prediction of turn volume. The average percentage of accuracy which is 85% for both the morning and evening peak hour models indicated that the developed and assigned turn-penalty functions were able to predict the turn volume well. Table 5 shows the average percentage of accuracy obtained for all fourteen junctions including the yield left-turn lanes.

TABLE 5. Average observed and assigned turn volume and average prediction accuracy

Junction	Description	AM Peak			PM Peak		
		Observed	Assigned	Accuracy	Observed	Assigned	Accuracy
A	Major four-legged junction	334	346	93.04%	386	412	89.04%
B	Minor three-legged junction	233	202	85.71%	123	95	77.48%
C	Minor four-legged junction	140	125	89.38%	77	78	75.59%
D	Minor three-legged junction	293	266	83.19%	262	220	76.67%
E	Minor three-legged junction	207	175	80.68%	253	196	79.68%
F	Major four-legged junction	100	85	84.93%	149	127	75.92%
G	Minor four-legged junction	156	178	80.08%	140	154	76.28%
H	Major four-legged junction	176	164	86.12%	199	182	90.09%
I	Minor three-legged junction	191	200	81.26%	261	241	89.94%
J	Major three-legged junction	318	336	90.19%	488	480	89.01%
K	Major four-legged junction	309	264	87.31%	302	304	95.33%
L	Major four-legged junction	227	219	83.16%	169	193	87.72%
M	Minor four-legged junction	142	165	92.10%	172	199	83.86%
N	Major three-legged junction	528	521	92.41%	547	632	82.70%
-	Yield left-turn lanes	147	129	78.47%	213	201	83.74%

As a rule of thumb, the turn-penalty functions assigned are based on the type of junctions. For minor signalized junctions, normally, the turn-penalty functions assigned are the uniform delay which are the functions, fp1 to fp4. For major junctions with moderate to heavy traffic flow, turn-penalty functions of fp5 to fp12 will be more suitable. Nevertheless, as this road network is comparatively a small network, further investigation should be conducted for larger and more congested network to verify the suitability of the developed turn-penalty functions.

CONCLUSIONS

In this study, two types of delay functions, namely the volume-delay functions and turn-penalty functions were investigated. The volume-delay functions used for model calibration is the revised Bureau of Public Roads (BPR) function with α and β values of 0.8298 and 3.361. The R-squared values computed based on the scatterplots of predicted versus observed link volumes which were more than 0.9 for both morning and evening peak hour models indicated that the models were well calibrated. Subsequently, turn-penalty functions for signalized intersection were developed and assigned onto the road network model. A total of twelve turn-penalty functions were developed based on uniform, random and overflow delay models and three functions were developed for yield left-turn lanes. The results indicated that the assigned turn-penalty functions fit well with the model as in overall, the average accuracies of the predicted turn volumes were 85% for both morning and evening peak hour models. However, they should be further explored and investigated for larger and more congested road network.

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