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BORANG FRGS – P3(R)

KEMENTERIAN PENDIDIKAN MALAYSIA

FINAL REPORT
FUNDAMENTAL RESEARCH GRANT SCHEME (FRGS)

Laporan Akhir Skim Geran Penyelidikan Fundamental (FRGS)
Pindaan 1/2015

A

RESEARCH TITLE: INVESTIGATION ON VOLUME-DELAY FUNCTIONS FOR ARTERIAL ROADS

PHASE & YEAR: 1 & 2013

START DATE: 1 MAY 2013
END DATE: 30 APRIL 2016
EXTENSION PERIOD (DATE): RMC LEVEL: 31 OCTOBER 2016
KPM LEVEL: 30 APRIL 2016

PROJECT LEADER: ASSOCIATE PROFESSOR IR. DR. LEONG LEE VIEN
I/C / PASSPORT NUMBER: 760522-07-5088

PROJECT MEMBERS: (including GRA)
1. **PROFESSOR AHMAD FARHAN MOHD. SADULLAH**
2. **PUAN SHAFIDA AZWINA MOHD. SHAFIE**

PROJECT ACHIEVEMENT *(Prestasi Projek)*

B

ACHIEVEMENT PERCENTAGE			
Project progress according to milestones achieved up to this period	**0 - 50%**	**51 - 75%**	**76 - 100%**
Percentage (please state #%)			**100%**

RESEARCH OUTPUT		
Number of articles/ manuscripts/ books *(Please attach the First Page of Publication)*	**Indexed Journal**	***Non-Indexed Journal***
	2 (published) + 1 (under review)	
Conference Proceeding *(Please attach the First Page of Publication)*	**International**	***National***
	1	
Intellectual Property *(Please specify)*		

HUMAN CAPITAL DEVELOPMENT					
Human Capital	**Number**				**Others** (please specify)
	On-going		**Graduated**		
Citizen	Malaysian	Non Malaysian	Malaysian	Non Malaysian	
No. PHD STUDENT	-	-	-	-	
Student Fullname: IC / Passport No: Student ID:					
No. MASTER STUDENT	-	-	-	-	
Student Fullname: IC / Passport No: Student ID:					
No. UNDERGRADUATE STUDENT	-	-	3	-	
Student Fullname: IC / Passport No: Student ID:			Tan Kwang Yew 901224-14-5291 108117 Chew J-Wei 920223-07-5029 113587 Lim Jin Keong 920713-05-5063 115668		
Total	-	-	3	-	

EXPENDITURE *(Perbelanjaan) as Borang K1(RMC)*

C

Budget Approved *(Peruntukan diluluskan)* : **RM 72,000.00**
Amount Spent *(Jumlah Perbelanjaan)* : **RM 59,753.09**

Balance *(Baki)* : **RM 12,246.91**
Percentage of Amount Spent *(Peratusan Belanja)* : 83%

ADDITIONAL RESEARCH ACTIVITIES THAT CONTRIBUTE TOWARDS DEVELOPING SOFT AND HARD SKILLS
(Aktiviti Penyelidikan Sampingan yang menyumbang kepada pembangunan kemahiran insaniah)

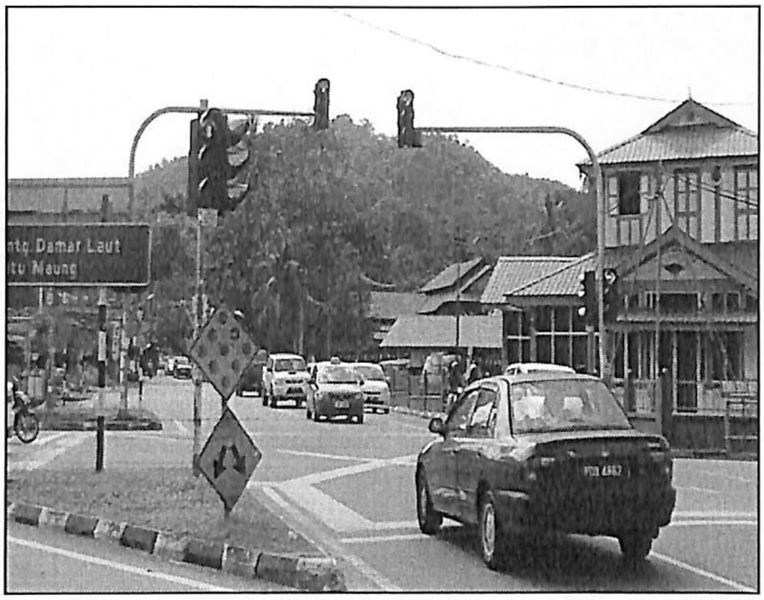
D

International		
Activity	Date (Month, Year)	Organizer
(e.g : Course/ Seminar/ Symposium/ Conference/ Workshop/ Site Visit)		
National		
Activity	Date (Month, Year)	Organizer
(e.g : Course/ Seminar/ Symposium/ Conference/ Workshop/ Site Visit)		

E	**PROBLEMS / CONSTRAINTS IF ANY** *(Masalah/ Kekangan sekiranya ada)*
	We were unable to recruite any post-graduate student under this grant but we manage to complete this research through the good works of three undergraduate students. We have presented our findings in an international conference, published two papers in indexed journals and currently, one paper about the overall findings from this research is under review by another indexed journal. Nevertheless, initially, we encountered problems in getting good and useful results but after refining our approach to include the turn-penalty functions in the model, we manage to get good and accurate results. As such, we need to collect more data to develop another road network to validate the findings and due to this reason, we need to use the allocation from other Vot to cover the expenses for data collection. However, as normally there is a long delay for *Bendahari* to update the allocation upon approval of virement, that is until being asked personally to do so, we were unable to keep track of the budget efficiently. Aslo, due to the reason of not being able to recruit any post-graduate student, and hence no GRA, the budget allocated for Vot 11000 couldn't be used.
F	**RECOMMENDATION** (*Cadangan Penambahbaikan*)
	Bendahari to update grant allocation in the system as soon as approval of virement is obtained.
G	**RESEARCH ABSTRACT – Not More Than 200 Words** (*Abstrak Penyelidikan – Tidak Melebihi 200 patah perkataan*)
	Volume-delay functions and turn-penalty functions are needed in traffic assignment to determine travel time on road network links. Volume-delay function is the function describing speed-flow relationship while turn-penalty function is the 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 α and β values of 0.8298 and 3.361 while the turn-penalty functions for signalized intersection were developed based on delay models. Parameters such as green time, cycle time and saturation flow were used in the development of turn-penalty functions. Two road networks, one in Balik Pulau, Penang and the other in areas of Nibong Tebal, Penang and Parit Buntar, Perak were modelled using a transportation demand forecasting software. Traffic volumes at twenty-two and fourteen junctions within both study areas were collected during morning and evening peak hours and used in model calibration. The prediction of assigned volumes obtained using the revised BPR function and the developed turn-penalty functions show close agreement to actual traffic volume recorded at sites. Output from this research is important as better understanding of delay functions can produce accurate estimate of link travel times and better planning for future scenarios.
	Date : 20th July, 2016 *Tarikh* **Project Leader's Signature:** *Tandatangan Ketua Projek* PROF. MADYA IR. DR. LEONG LEE VIEN PUSAT PENGAJIAN KEJURUTERAAN AWAM KAMPUS KEJURUTERAAN UNIVERSITI SAINS MALAYSIA
H	**COMMENTS, IF ANY/ ENDORSEMENT BY RESEARCH MANAGEMENT CENTER (RMC)** *(Komen, sekiranya ada/ Pengesahan oleh Pusat Pengurusan Penyelidikan)*
	.... **Name:** *Nama:* PROF. DR LEE KEAT TEONG Pengarah Pejabat Pengurusan & Kreativiti Penyelidikan Universiti Sains Malaysia **Signature:** *Tandatangan:* **Date:** *Tarikh:* 7/10/16

LAMPIRAN B

TEMPLATE
PROFIL PENYELIDIKAN



INVESTIGATION ON VOLUME-DELAY FUNCTIONS FOR ARTERIAL ROADS

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ABSTRACT (120 words)

Delay functions are the fundamental component in an equilibrium trip assignment model. 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 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. Two road networks, one in Penang and the other in Perak were modelled. The output from this research is very important as better understanding of volume delay function can produce better estimate of link travel times and hence better planning for future scenarios.

1. INTRODUCTION

Transportation planning utilizes travel forecasting models to predict changes in travel patterns and for potential improvements in response to changes in regional development, demographics, and transportation supply. The four stage demand model which comprises of trip generation, trip distribution, modal split, and traffic assignment is the primary tool for forecasting travel demand. Trip assignment is the last step in the four-stage demand modelling in which an equilibration of demand and performance is produced. In trip assignment, forecasted and generated peak hour trips are assigned on the accessible junctions surrounding the development area in which modal OD trip matrices are loaded on the modal networks usually under the assumption of user equilibrium where all paths utilized for a given OD pair have equal impedances. The assigned trips in trip assignment is usually computed based on the estimates of link travel times which includes the turn delay and in order to calculate travel time between origin and destination, delay functions, namely the volume-delay function and turn-penalty functions were used. 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. In Malaysia, traffic consultants and transport modellers often adopt delay functions developed from other countries but calibrated them manually based on much localised traffic conditions. Different traffic consultants in Malaysia adopt different functions. This study aims to investigate and improve delay functions for different type of arterial roads. Primary data such as traffic volume and speed were collected at three types of arterial roads, which are the principal arterial, minor arterial and collectors to derive the parameters required in the function. The improved functions are then validated with field data using the transportation planning software.

2. RESEARCH METHODOLOGY

Site survey was conducted in Penang and Perak to find and select suitable sites for data collection at different types of arterial roads namely; principal arterial, minor arterial and collectors. Urban arterial and collector streets are designed to accommodate longer trips than local streets. They also have a significant mobility function and support the hierarchy of movement by connecting to streets of higher and lower functionality class. An urban street facility with these attributes typically has a length of 1.6 km or more in CBD areas and 3.2 km or more in other areas. At least one intersection along the facility must have a type of control that imposes a legal requirement on through movement to stop or yield. A significant change in one or more facility characteristics may indicate the end of one facility and the start of a second facility. These characteristics include cross section features (e.g., number of through lanes, shoulder width, curb presence), annual average daily traffic volume, roadside development density and type and vehicle speed. One or more of these characteristics will often change significantly when the street crosses an urban-to-suburban area boundary or intersects a freeway interchange. Therefore, this is a crucial step to identify suitable sites as the process of data collection in terms of the equipment used, location to set up the equipment, availability and etc. depends very much on the selected sites. Also, different sites have different characteristics and therefore, needs to be categorised according to common characteristics as mentioned earlier. Primary data to be collected are classified volume and travel time.

Calibration and validation will be conducted using a transportation planning software. Link volumes obtained from the trip assignment procedure in the software will be compared with field data. Model validation involves conducting tests which documented that the given site-specific model is capable of making sufficiently accurate predictions. This required using the calibrated delay functions, without changing the parameter values, to simulate the response for a period other than the original period. The model is said to be validated if its accuracy and predictive capability in the validation period have been proven to lie within acceptable limits or to provide acceptable errors. In other words, validation is the testing of calibrated models with respect to additional set of field data preferably under different environmental conditions to further examine the validity of the model. Validation testing is designed to confirm that, the calibrated model is applicable over the limited range of conditions defined by the calibration and validation data sets. Hence it is important that collection of calibration and validation data must cover the range of conditions over which predictions are desired. The data should be such that, the calibration parameters are fully independent of the validation data. During the validation process, evaluation of the delay function curve fits will be based on the R-squared value. Two road networks, one in Balik Pulau, Penang and the other in areas of Nibong Tebal, Penang and Parit Buntar, Perak were modelled using the transportation demand forecasting software. Traffic volumes at twenty-two and fourteen junctions within both study areas were collected during morning and evening peak hours and used in model calibration and validation.

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. For the road network developed for Balik Pulau, a total of 40 traffic analysis zones were created in which 10 of them are external zones representing various inter-urban roads leading to external regions. For base year traffic models, traffic assignment is achieved based upon the estimated peak hour demand matrices, which is based on passenger car unit. For the study area in areas of Nibong Tebal, Penang and Parit Buntar, Perak, a total of twenty-one traffic analysis zones were created in which twelve of them are external zones. 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.

For the first network model developed for Balik Pulau, the methodology adopted to evaluate the volume-delay function takes the following steps:

1. Inventory review of the existing roadway facilities and rationalization of future road network based on the local plan were conducted.
2. Traffic survey conducted at twenty-two main junctions in the study area as well as major corridor junctions surrounding the study area on typical weekday.
3. Existing traffic network model that simulates land use activity using a transportation planning software was developed based on the following steps:
   i. Peak hour origin-destination trip matrix based on passenger car unit was built.
   ii. Base model with assumed volume-delay functions was built.
   iii. Calibrations of the base year models which are the morning and evening peak hour models, by applying different conditions for the volume-delay functions were conducted.
   iv. Validations of the above-mentioned base year models based on existing peak hour traffic flow surrounding the area were conducted.

The road network is first developed 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, the common conditions shown in Table 1 which are applicable for link/roads in urban areas can be used to calibrate the volume-delay functions based on the general BPR function. In this study, each section of lane is assigned with a different level of volume-delay function based on the general Bureau of Public Roads (BPR) [1] equation shown in Eq. (1), initially with $\alpha = 0.15$ and $\beta = 4$ and subsequently changed to different values of α and β.

$$T = T_o[1 + \alpha(v/c)^{\beta}] \quad (1)$$

where

T = Travel time (minute)

T_o = Free flow travel time (minute)

v = Traffic volume (passenger car unit/hour)

c = Capacity (passenger car unit/hour)

Levels of volume-delay functions are based on the link/road conditions as presented in Table 1.

Table 1 Link/road conditions used to calibrate volume-delay function

Link / Road	Speed limit (km/hr)	Capacity, *c* (pcu/hr/ln)
Expressway	110	$2000 \le c < 2200$
Highway	90	$1900 \le c < 2000$
Primary Road	80	$1800 \le c < 1900$
Secondary Road	70	$1600 \le c < 1800$
	60	$1400 \le c < 1600$
	50	$1200 \le c < 1400$
Local Road	20, 30, 40	$1000 \le c < 1200$

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. In addition, a study conducted by Deardoff et al. [2] to estimate free-flow speed from posted speed limit signs at ten sites in South Dakota, have shown that average free-flow speeds are 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. In that regard, the determination factor of volume-delay function is affected by vehicle speed limit on the links. Higher speed limits represent shorter time taken from one place to another, hence taking shorter travel time. In view of this representation, volume-delay function acts as to help user to define the lanes on links in the modeled road network to resemble the actual road situation. This is essential as the impact on travel time on links contributes to how the trip is assigned, which is based on shortest time travel on a specific route.

The ranges of vehicle speed limit to be defined based on road network in study area are from 20 km/h to 110 km/h. Lower speed is assigned to smaller roads where capacity of the roads are significantly lower as well as windy and narrow roads where lower speed is necessary for safety purpose. On the other hand, higher speeds were applied to wide and multiple lanes with higher capacity, such as the federal highway where road users can travel up to 110 km/h. The maximum number of lanes in the road network is three lanes per direction. The range of maximum road capacity for each lane section is from 1000 pcu/h to 2200 pcu/h. The volume-delay function used in the model, which is the revised BPR function is as shown in Eq. (2).

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

where

L	= Length of link (km)
v_s	= Speed limit (km/h)
lanes	= Number of lanes at link
volau	= Estimated volume at the link (pcu/h)
α, β	= Parameters to be determined

For the second network model developed for Nibong Tebal, Penang and Parit Buntar, Perak, other than to validate the revised BPR function, the main objective was to develop the turn-penalty functions. 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.

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

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

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

where

ep1	= Cycle time (minutes)
ep2	= Green time (minutes)
pvolau	= Assigned turning volume (pcu/h)
S	= Saturation flow (pcu/h)

In this network, 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.

3. LITERATURE REVIEW

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. Origin-destination matrix represent the movement of vehicle from one zone to another zone. Trip assignment can also be used to estimate the internal zone and external zone travel pattern. 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 are being utilized by road network planners or designers in Malaysia. As such, volume-delay function is used to express travel times of a road link as a function of traffic volume. Volume delay function has characteristic that will represent a traveler's behavior which is essential to resemble the actual behavior of a road network modeled Usually these 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.

Volume-delay function contributes to delay time on a link to stimulate the properties of the lanes on the link which attributes to the driving behavior of road users. In most traffic assignment models, volume-delay function is used to express travel times of a road link as a function of traffic volume. Usually these functions are expressed as the product of the free flow time multiplied by a normalized congestion function. Some of the earlier developed volume-delay functions are by Overgaard (1967) in which he has proposed an exponential function while Mosher (1963) suggested logarithmic and hyperbolic functions [3]. According to Jastrzebski [4], any type of volume-delay function should meet two major conditions which are the mathematical and behavioural conditions. According to his research, from the mathematical point of view, the function should be continuous, strictly increasing and non-negative in order to satisfy system optimal principle. As for the behaviour conditions, commuters are familiar with traffic conditions during different time of the day on different paths, they tend to put more weight on the time spent in congestion rather than travel time and they prefer to travel at constant journey speed. Therefore, they can and will make ad-hoc decision to change path if they knew in advance of congestion or encountered with congestion. 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. According to Singh [5], the problems with the BPR function is that it overestimates speeds when $v/c > 1$ and underestimates speeds when $v/c < 1$. Spiess [6] also has discovered some inherent drawbacks in the BPR function and has developed a new class of volume-delay functions which is the conical functions. According to Spiess [6], the interpretation of the parameters used to characterize the specific congestion behaviour of a road link, i.e. capacity and steepness, is the same for both BPR and conical function, which makes the transition to conical functions particularly simple. Also, since the difference between a BPR function and a conical function with the same parameter is very small within the feasible domain, i.e. v/c < 1, the BPR parameters can be transferred directly in most cases. However, these volume-delay functions are developed mainly for homogeneous traffic. These volume-delay functions relate stream speed of single class vehicle with stream volume and do not account for speeds of various classes present in the stream. Thus, they may not be directly suitable for many applications in heterogeneous traffic as motorists do not follow a perfect lane discipline [7, 8].

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. Therefore, it is important to analyze delay at signalized intersections.

Delay at signalized intersection is also interpreted as a measure which directly relates to a driver experience contributing to travel time specifically the measure of excess time spent while traversing through the signalized intersection. 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 [9]. 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 [10]. The path of individual vehicles were tracked to collect the delay values in different movements of each intersection. Sample of cars which passes predefined points located in different entrances/exits of each intersection were recorded. Vehicle number plates recorded in different entrances/exits of each intersection are matched and the travel time of each vehicle was calculated. 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, nodes are expanded and representing each turn as a dummy link [11]. Delays at intersecting links depends on physical characteristic, control policies at intersections and also the traffic flows of other links. It is problematic to convert every turn to a link as the network size is too large or the delay function for dummy links depend on the traffic flow of other links. Hence, assumptions are made. First, nodes are not needed to be expanded. Second, delay associated with intersection depends on its own physical characteristic and control policies. The function used for calculation of time delay at signalized intersection is based on Webster's formula, while involves additional steps for calculation of red and total cycle time.

In another study conducted in Harbin, theoretical delay values were compared with actual values measured [12]. 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.

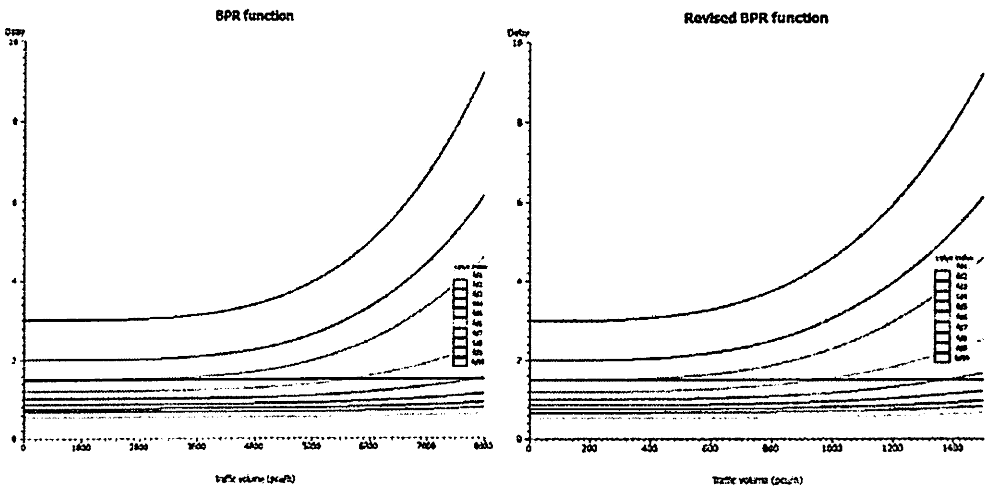
Hence, having a predictive model to estimate delay is more convenient and appropriate to investigate the effects of turn delay on travel time. Further knowledge regarding turn delay could definitely increase the preciseness of the delay calculations or functions. However, the development of signalized 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.

4. FINDINGS

In this study, two road networks were developed using a transportation planning software. One of the road network that is the road network in Balik Pulau area is developed to investigate the volume-delay functions, specifically the BPR function, while the other network that is the Nibong Tebal and Parit Buntar road network is used to validate the revised BPR function and to develop the turn-penalty functions. Initially, during the calibration process, the results obtained from trip assignment indicated that the trips assigned at intersections were different from the values obtained from field survey even though the assigned trips on the links were satisfactory. This has prompted the investigation of another type of delay function which is the turn-penalty function. Turn-penalty function can be included in the model to indicate the presence of signalized intersections and further distinguish turns at signalized intersections from the general turns. Turn-penalty function in default is on auto mode where all turns are allowed and non-penalized except U-turns, which are prohibited. Inclusion of turn penalty function in the model is important since in urban areas, signalized intersections contribute to significant delays, causing high impacts on travel time. In the development of turn penalty function, the uniform delay, random delay and overflow delay models were adopted. The turn-penalty functions were developed based on three input parameters namely; green time, cycle time and saturation flow. Turn-penalty function is included in the model to indicate the presence of signalized intersections in the road network and to reflect the actual turning traffic volume at signalized intersections.

4.1 Volume-delay Functions

Figure 1 shows the function graph plotted for (a) BPR functions and (b) the revised BPR functions. Based on the graph shown in Figure 1(a), the delay calculated based on BPR function with α = 0.15 and β = 4 has only slight increment when volume is less than 3000 pcu/h for all road categories. Subsequently, α and β values of 0.8298 and 3.361, which were used by consultants in the road network model of Kuala Lumpur were tested in this study. The function chart in Figure 1(b) indicated that the calculated delay based on the revised BPR function will increase significantly when volume has exceeds 600 pcu/h, especially for lower hierarchy roads.



(a) (b)

Figure 1: Volume-delay functions (a) BPR function (b) revised BPR function

Scatterplot of turn volume is used for calibration and validation of the assigned volume-delay functions for base year model. The R-squared values obtained from scatterplot based on the BPR functions were lower than those obtained based on the revised BPR functions for both morning and evening peak hours. Figure 2 shows the results of turn scatterplots for morning and evening peak hours based on the BPR and revised BPR functions. The R-squared values of more than 0.95 based on revised BPR functions obtained for both morning and evening peak hours showed that the based year traffic models are well calibrated.

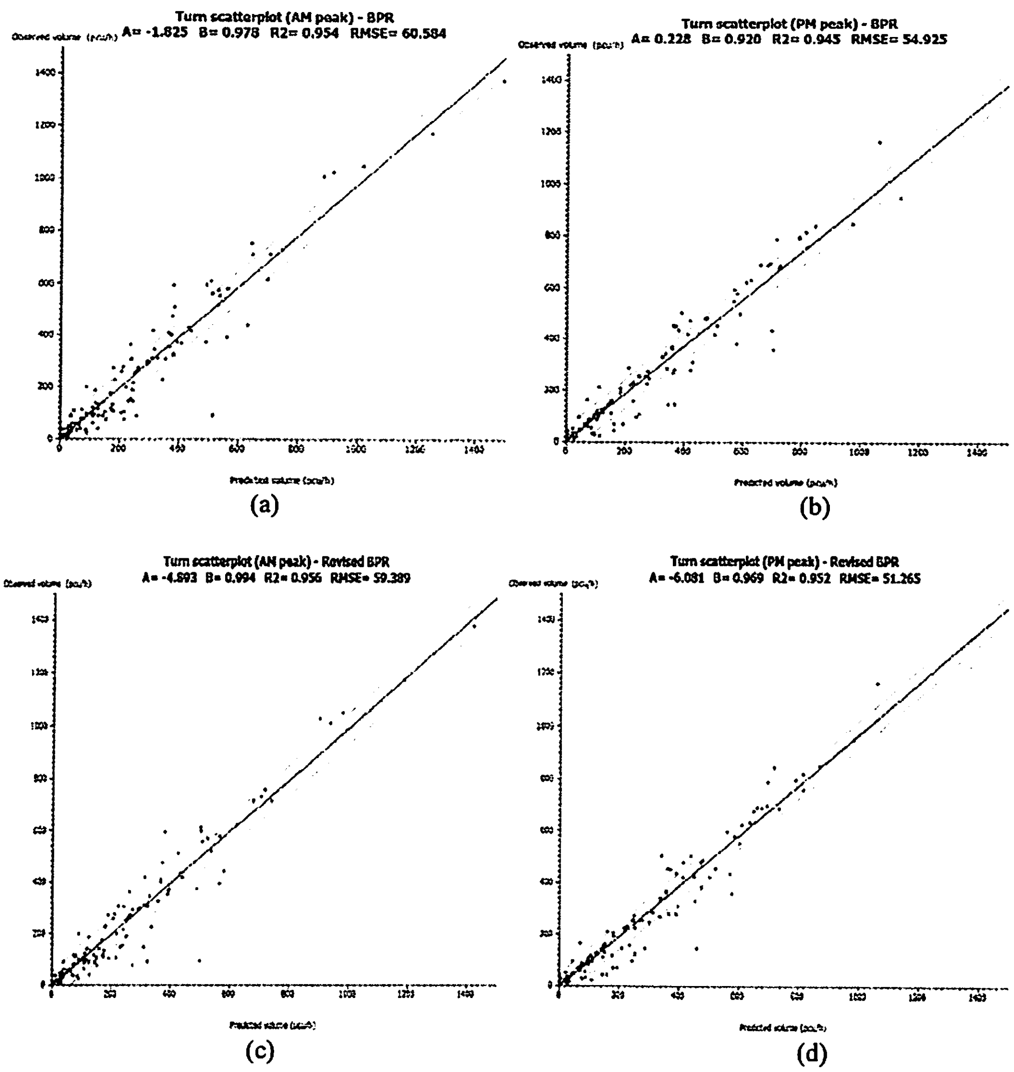


Figure 2: Turn scatterplot for base year model (a) AM peak model based on BPR function (b) PM peak model based on BPR function (c) AM peak model based on revised BPR function (d) PM peak model based on revised BPR function

The results indicated that in general the BPR function was found to have less impact on delay and hence less sensitive when volume is lower than 3000 pcu/h for all road type but the revised BPR function was found to be more sensitive when volume exceeds 600 pcu/h especially for lower hierarchy roads.

4.2 Turn-penalty Functions

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 determined from Table 1. 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 6, 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 Figure 2(a) for morning peak and Figure 2(b) for evening peak.

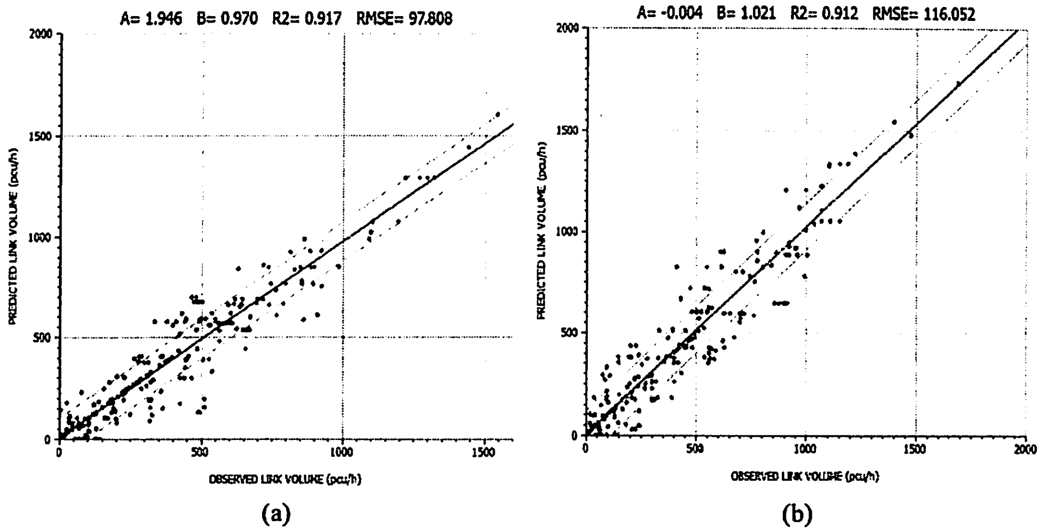


Figure 3 Link scatterplot of predicted versus observed link volume (a) morning peak hour (b) evening peak hour

The R-squared values of more than 0.90 obtained for both morning and evening peak hours showed that the road network models for morning and evening peak hours are well calibrated.

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 are 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 results obtained are shown in Figure 3(a) for morning peak and Figure 3(b) for evening peak.

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.

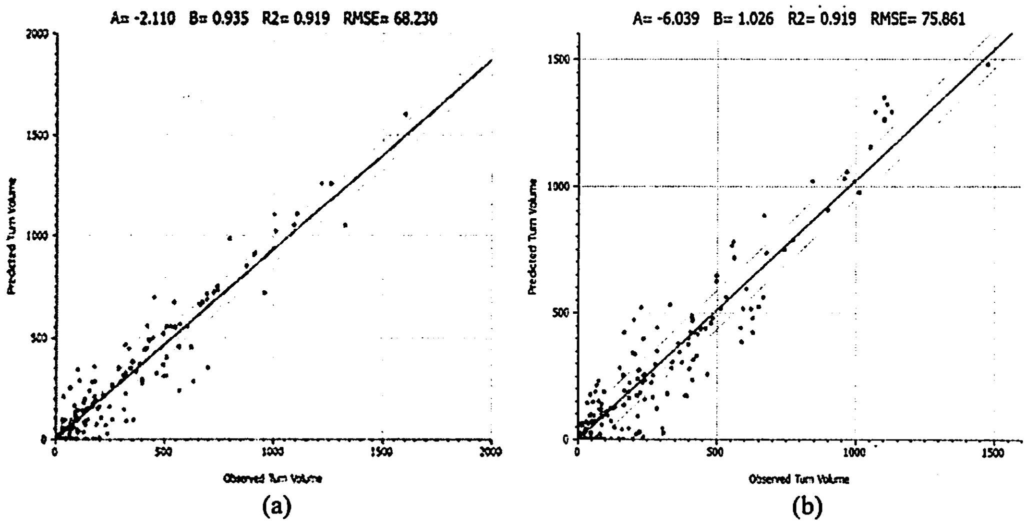


Figure 3 Turn scatterplot of predicted versus observed turn volume (a) morning peak hour (b) evening peak hour

Subsequently, further analyses were conducted to check on the accuracy of the predicted turn volume for all fourteen junctions. The results 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 are able to predict the turn volume well.

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.

5. CONCLUSION

In this study, two types of delay functions, namely the volume-delay functions and turn-penalty functions were investigated. The results indicated that in general the BPR function was found to have less impact on delay and hence less sensitive when volume is lower than 3000 pcu/h for all road type but the revised BPR function was found to be more sensitive when volume exceeds 600 pcu/h especially for lower hierarchy roads. Hence, 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 are more than 0.9 for both morning and evening peak hour models indicated that the models are 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 are 85% for both morning and evening peak hour models. However, they should be further explored and investigated for larger and more congested road network.

ACHIEVEMENT

Published papers in indexed journals:

i) Lee Vien Leong and Kwang Yew Tan (2015). Volume-Delay Function in Trip Assignment, Applied Mechanics and Materials, Vol. 802, pp 351 – 356, Trans Tech Publications, Switzerland, DOI: 10.4028/www.scientific.net/AMM.802.351

ii) Leong, L.V. (2016). Effect of Volume-delay Function of Time, Speed and Assigned Volume in Transportation Planning Process, International Journal of Applied Engineering Research, Volume 11, Number 13, pp. 8010 – 8018, ISSN: 0973-4562.

Paper under review in indexed journal:

i) Leong, L.V., Chew, J-W and Lim, J.K. (2016) Delay Functions In Trip Assignment For Transport Planning Process, Jurnal Teknologi, E-ISSN:2180-3722 (under review)

Title of paper presentations (international/ local):

i) Volume-Delay Function in Trip Assignment, AWAM International Conference on Civil Engineering 2015 (eco-AICCE'15), Putra World Trade Centre, Kuala Lumpur, Malaysia, 9th – 11th September 2015.

Human Capital Development:

Undergradute students:

i) Tan Kwang Yew
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Effects of Volume-Delay Function on Time, Speed and Assigned Volume in Transportation Planning Process

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Abstract
In transportation planning process, especially in trip assignment, volume-delay function is essential to determine travel time on the network links when traffic is assigned on a network. In this study, the road network in Balik Pulau area which is located on the southwestern part of Penang Island, Malaysia, including other areas on the southern part of Penang Island such as Gertak Sanggul, Teluk Kumbar, Bayan Lepas and Batu Maung were modelled using a transportation demand forecasting software. Traffic volumes at twenty-two junctions located within the study area were collected during the morning and evening peak hours and subsequently used in the calibration process. Two types of volume-delay functions, namely the well-known BPR function and revised BPR function were used in this study, and the effects of these volume-delay functions on time, speed and assigned volume on links for base year of morning and evening peak hour models and future year, morning and evening peak hour models were investigated. The results obtained from this study indicated that the original BPR functions with α and β values of 0.15 and 4.0 respectively were found to have less impact on delay when volume is less than 3000 pcu/h for all road categories but the calibrated BPR functions with α and β values of 0.8298 and 3.361 were found to produce higher delay when volume exceeds 600 pcu/h, especially for lower hierarchy roads. Models with revised BPR functions also show more variations in terms of time, speed and assigned volume between base year and future year models for both morning and evening peak models. The output from this research is very important as better understanding of delay functions which is the determining factor in trip assignment can produce better estimate of link travel times and hence better planning for future scenarios.

Keywords: Traffic assignment, transportation planning, volume-delay functions

INTRODUCTION

The four-stage demand models are the most popular travel demand forecasting models. The first stage which is trip generation, determines the frequency of origin or destination trips in each zone, as a function of land use intensity and its associated activities. In Malaysia, trips generated by a particular development are calculated based on Malaysian Trip Generation Manual 2010 [1] which is the fourth edition of manual. The second stage which is trip distribution is to recombine trip ends, which has two ends; an origin and a destination to generate a zone-to-zone trip matrix of origin-destination pairs. The third stage in the transportation planning process is mode choice, in which mode choice effectively factors the origin-destination trip matrix from trip distribution to produce mode-specific trip matrices. However, according to the guidelines for traffic impact assessment in Malaysia, for the purpose of traffic impact analysis, modal split between private and public transport shall not be considered and there shall be no reduction in the projected generated traffic due to the anticipated usage of public transport except for the case of a transit-oriented development [2]. Therefore, in the study, only origin-destination trip matrix for private vehicles is developed. Trip assignment is the last step in the four-stage demand modelling, in which an equilibration of demand and performance is finally produced. Trip assignment will assign forecasted and generated peak hour trips on the accessible junctions surrounding the development area and it is usually based on the estimates of link travel times. In order to calculate travel time between origin and destination, a function presenting the relationship between link delays and link flows is used. This function is known as volume-delay function and it is the fundamental component of equilibrium trip assignment models.

LITERATURE REVIEW

Volume-delay function has characteristic that will represent a traveler's behavior which is essential to resemble the actual behavior of a road network modeled. Volume-delay function contributes to delay time on a link to stimulate the properties of the lanes on the link which attributes to the driving behavior of road users. In most traffic assignment models, volume-delay function is used to express travel times of a road link as a function of traffic volume. Usually these functions are expressed as the product of the free flow time multiplied by a normalized congestion function as shown in Eq. (1).

$$T = T_o \times f\left(\frac{v}{v}\right) \tag{1}$$

where

T = Travel time (minute)
T_o = Free flow travel time (minute)
v = Traffic volume (passenger car unit/hour)
c = Capacity (passenger car unit/hour)

Some of the earlier developed volume-delay functions are by Overgaard (1967) in which he has proposed an exponential function while Mosher (1963) suggested logarithmic and

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Volume-Delay Function in Trip Assignment

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Keywords: Trip assignment, volume-delay functions, travel time, BPR function.

Abstract. Four-stage demand models are the most popular travel demand forecasting models. Trip assignment which is the last stage in the four-stage demand modelling is a key element in travel demand forecasting process. Traffic assignment model is used to assign travel demands into the road network and predict network flows that are associated with future planning scenarios based on the estimates of link travel times. In order to calculate travel time between origin and destination, a function presenting the relationship between link delays and link flows is used. This function is known as Volume-Delay Function (VDF) and it is the fundamental component of equilibrium trip assignment models. This study aims to investigate and improve VDFs for heterogeneous traffic at different type of arterial roads in Malaysia by using the road network in Balik Pulau, Penang as a case study. Primary data such as traffic volume and speed are collected at three types of arterial roads, which are the principal arterial, minor arterial and collectors to derive the parameters required in the VDFs. In this study, the most well-known and most widely-used volume-delay function which is known as the BPR function developed by the U.S. Bureau of Public Roads was investigated and calibrated using the transportation planning software, EMME 4.1.3. The calibrated functions are then validated with field data. The output from this research is very important as better understanding of VDFs can produce better estimate of link travel times and hence better planning for future scenarios.

Introduction

Trip assignment is the last major step in the four-stage demand modelling in which an equilibration of demand and performance is finally produced. Assign forecasted and generated peak hour trips on the accessible junctions surrounding the development area in which the origin-destination matrices are loaded on the modal networks is usually under the assumption of user equilibrium where all paths utilized for a given origin-destination pair have equal impedances. Generally, based on the estimates of link travel times and in order to calculate travel time between origin and destination, a function presenting the relationship between link delays and link flows is used. This function is known as "Volume-Delay Function" (VDF) and it is the fundamental component of equilibrium trip assignment models. There are many VDFs developed around the world and they may range from simple linear function to more complicated formula. In most traffic assignment models, VDF is used to express travel times of a road link as a function of traffic volume. Usually these functions are expressed as the product of the free flow time multiplied by a normalized congestion function. Some of the earlier developed VDFs are by Overgaard [1] in which he has proposed an exponential function while Mosher [2] suggested logarithmic and hyperbolic functions. According to Jastrzebski [3], any type of VDF should meet two major conditions which are the mathematical and behavioural conditions. According to his research, from the mathematical point of view, the function should be continuous, strictly increasing and non-negative in order to satisfy system optimal principle. As for the behaviour conditions, commuters are familiar with traffic conditions during different time of the day on different paths, they tend to put more weight on the time spent in congestion rather than travel time and they prefer to travel at constant journey speed. Therefore, they can and will make ad-hoc decision to change path if they

Conclusions

Generally, the results indicate variation in terms of the result obtained for certain link type. The reason for the variation and lower R-square values for certain link type due to the reason that the BPR function is developed for homogeneous traffic and the function only relates the speed of single type vehicle with volume but do not account for speed of various classes of vehicles present in the traffic stream. Thus, they may not be suitable for many applications in heterogeneous traffic like in Malaysia as drivers especially motorcyclists do not follow a perfect lane discipline and the road conditions are different than those in the developed countries. Therefore, the concept of vehicle density, lane occupancy and queuing theory based on homogeneous lane-based traffic flow might not be applicable for mixed traffic conditions in Malaysia. In addition, additional travel time delay might occurred due to the interaction and frequent lane changed by smaller size vehicles such as motorcycles and fast-moving vehicles such as cars with slow-moving vehicles such as lorries, trailers and buses. Nevertheless, traffic consultants and transport modellers in Malaysia often do adopt VDFs developed from other countries but calibrated them manually based on much localised traffic conditions. Therefore, the output from this research is important as better understanding of VDFs can produce better estimate of link travel times and hence better planning for future scenarios.

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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 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. Road network in areas of Nibong Tebal, Penang and Parit Buntar, Perak were modelled using a transportation demand forecasting software. Traffic volumes at fourteen junctions within the study area were collected during morning and evening peak hours and used in model calibration. The prediction of assigned volumes obtained using the revised BPR function and the developed turn-penalty functions show close agreement to actual traffic volume recorded at sites. Output from this research is important as better understanding of delay functions can produce accurate estimate of link travel times and better planning for future scenarios.

Keywords: Traffic assignment; transportation planning; volume-delay function; turn-penalty function

Abstrak

Dalam proses perancangan pengangkutan, fungsi kelewatan-isipadu dan fungsi penalti-pembelokan adalah fungsi yang diperlukan dalam umpukan lalu lintas untuk menentukan masa perjalanan pada pautan rangkaian jalan. Fungsi kelewatan-isipadu adalah fungsi kelewatan yang menggambarkan hubungan laju-aliran manakala fungsi fungsi penalti-pembelokan adalah fungsi kelewatan yang berkaitan dengan pembelokan di persimpangan. Fungsi kelewatan-isipadu yang digunakan dalam kajian ini adalah fungsi Bureau of Public Roads (BPR) yang disemak semula dengan nilai α dan β, 0.8298 dan 3.361 manakala fungsi penalti-pembelokan yang dibangunkan untuk persimpangan lampu isyarat adalah berdasarkan kepada model kelewatan seragam, kelewatan rawak dan kelewatan limpahan. Parameter seperti masa hijau, masa kitar dan aliran tepu telah digunakan dalam pembangunan fungsi penalti-pembelokan. Rangkaian jalan raya di kawasan Nibong Tebal, Pulau Pinang dan Parit Buntar, Perak telah dimodelkan menggunakan perisian ramalan permintaan pengangkutan. Jumlah trafik di empat belas persimpangan dalam kawasan kajian telah diambil pada waktu puncak pagi dan petang dan digunakan dalam penentukuran model. Anggaran ke atas umpukkan lalu lintas yang diperolehi dengan menggunakan fungsi BPR yang disemak semula dan fungsi penalti-pembelokan yang dibangunkan menghampiri nilai isipadu lalu lintas sebenar yang dicatatkan di tapak. Hasil kajian ini adalah sangat penting kerana pemahaman yang lebih baik ke atas fungsi kelewatan boleh menghasilkan anggaran masa perjalanan yang lebih tepat dan perancangan senario masa depan yang lebih baik.

Kata kunci: Umpukkan lalu lintas; perancangan pengangkutan; fungsi kelenghan-isipadu; fungsi penalti-pembelokan

PENYATA PERUNTUKAN DAN PERBELANJAAN SEHINGGA 16 Julai 2016

Kwg	Akaun	PTJ	Projek	Peruntukan	Bel.T'kumpul	Baki Peruntukan Tahun Lalu	Peruntukan Tahun Semasa	Jumlah Peruntukan Tahun Semasa	Tanggungan Semasa	Bayaran Tahun Semasa	Jumlah Belanja Tahun Semasa	Baki Projek
				RM	RM	RM	RM	RM	RM	RM	RM	RM
203	111	PAWAM	6071240	18,000.00	-	18,000.00	-	18,000.00	-	-	-	18,000.00
203	221	PAWAM	6071240	1,500.00	271.70	16,728.30	(15,500.00)	1,228.30	-	858.10	858.10	370.20
203	224	PAWAM	6071240	8,500.00	5,437.22	62.78	3,000.00	3,062.78	-	3,327.03	3,327.03	(264.25)
203	226	PAWAM	6071240	500.00	200.00	(200.00)	500.00	300.00	-	167.00	167.00	133.00
203	227	PAWAM	6071240	20,000.00	15,264.00	(264.00)	5,000.00	4,736.00	-	10,268.53	10,268.53	(5,532.53)
203	229	PAWAM	6071240	20,500.00	16,440.00	60.00	4,000.00	4,060.00	-	6,566.14	6,566.14	(2,506.14)
203	552	PAWAM	6071240	3,000.00	308.58	(308.58)	3,000.00	2,691.42	-	644.79	644.79	2,046.63
				72,000.00	37,921.50	34,078.50	-	34,078.50	-	21,831.59	21,831.59	12,246.91

Unit Perngurusan Perakaunan

Jabatan Bendahari,Kampus Kejuruteraan

PH2PA2P017/07/2016