MODELLING OF TRAFFIC DELAYS AT ROUNDABOUT USING VISSIM MICROSIMULATION MODEL

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ABSTRACT

Delay is one of the significant parameters used for the operational performance evaluation of roundabouts. Even though there are various methods for estimating delays at the roundabout, the results can differ from actual delays on the field for Malaysian traffic conditions. Most of the existing models, such as HCM 2010, do not consider the impact of the geometric parameters on delays, besides the driver behaviour is different. Therefore, this study used the VISSIM microsimulation model to assess the impacts of traffic and geometric characteristics on delays at roundabouts. Video recording technique was used to collect data at Senai roundabout such as the entry flow rate, circulating flow rate, critical gap, follow-up headway, vehicle desired speed, and delay. The data collected were used to develop the base model scenario in VISSIM. The calibration and validation of the base model were then conducted using entry traffic flow, circulating traffic flow, and delays measured in the field. In VISSIM, three basic scenarios are defined, namely, the central island diameter (D_i= 60m, 70m, and 80 m), entry width (W_e= 5m, 9m, and 12 m), and the circulating roadway width (W_c= 6 m, 9m, and 12m). For each scenario case, additional scenarios were created utilizing different traffic flow rates (350-2000 veh/hr), representing low, medium, and high traffic flow rates; as a result, 351 scenarios are developed in all. Based on the outcomes of the 351 scenarios, an exponential mathematical model is developed for estimating roundabout delay using the regression analysis technique. The entry flow rate and the circulating flow rate are found to have a strong positive correlation with delay. This implies that an increase in the entry flow rate or the circulating flow rate increases the delay. In terms of geometric parameters influence on the delay, the entry width and circulating roadway width exhibit a strong negative correlation with delay (p-value < 0.05). In other words, increasing the width of the entry or circulating roadway leads to delay reduction. In contrast, the central island diameter has no significant impact on the delay (p-value > 0.05); thus, this parameter is omitted from the final model. With an R^2 of 0.79, the derived model is statistically significant at a 95% confidence level, which implies that traffic flow and the geometric parameters account for an approximate of 79% variation in the delay. Moreover, the value of the coefficient of multiple correlations ($R = 0.89$) affirmed that the relationship between delay and the combined influence of the independent variables is significantly strong. Therefore, this study would serve as a more accurate guide for determining the acceptable degree of service for Malaysian roundabouts to justify related expenditures. It is advised that the proposed model be considered into Malaysia's guidance for performance analysis on at-grade junctions, particularly roundabouts.

ABSTRAK

Kelengahan adalah salah satu parameter penting yang digunakan untuk penilaian prestasi operasi bulatan. Walaupun terdapat pelbagai kaedah untuk menilai kelengahan di bulatan, keputusannnya boleh berbeza daripada kelengahan sebenar di tapak untuk keadaan lalulintas Malaysia. Kebanyakan model semasa, seperti HCM2010, tidak mengambilkira kesan parameter geometri terhadap kelengahan, selain itu kelakuan pemandu juga berbeza. Oleh itu, kajian ini menggunakan model mikrosimulasi VISSIM untuk menilai kesan lalulintas dan ciri-ciri geometri terhadap kelengahan di bulatan. Teknik rakaman video telah digunakan untuk mengumpulkan data di bulatan Senai antaranya kadar aliran masuk, kadar aliran berpusing, sela kritikal, jarak kepala susulan, kelajuan dikehendaki kenderaan, dan kelengahan. Data yang dikumpulkan digunakan untuk membangunkan scenario model asas di VISSIM. Proses penentukuran dan pengesahan model asas telah dilakukan menggunakan aliran lalulintas masuk, aliran lalulintas berpusing dan kelengahan yang telah diukur di tapak. Di dalam VISSIM, tiga senario asas telah ditakrifkan, iaitu, diameter pulau tengah (D_i= 60m, 70m, and 80 m), lebar masuk (W_e= 5m, 9m, and 12 m), dan lebar jalan pusing (W_c= 6 m, 9m, and 12m). Bagi setiap kes senario, senario tambahan direka menggunakan kadar aliran lalulintas berbeza (350-2000 veh/hr), mewakili kadar aliran lalulintas rendah, sederhana dan tinggi; hasilnya. sebanyak 351 senario telah dibangunkan secara keseluruhan. Berdasarkan dapatan 351 senario, sebuah model matematik eksponen telah dibangunkan untuk menganggar kelengahan bulatan menggunakan teknik analisa regresi. Kadar aliran masuk dan kadar aliran berpusing telah didapati mempunyai korelasi positif yang kuat dengan kelengahan. Ini menunjukkan bahawa peningkatan kadar aliran masuk atau aliran berpusing meningkatkan kelengahan. Dari segi kesan parameter geometri kepada kelengahan, lebar masuk dan lebar jalan berpusing menunjukkan korelasi negatif yang kuat dengan kelengahan (nilai $p < 0.05$). Dalam kata lain, peningkatan lebar masuk dan jalan berpusing membawa kepada pengurangan kelengahan. Sebaliknya, diameter pulau tengah tidak mempunyai kesan signifikan terhadap kelengahan (nilai $p > 0.05$); dengan demikian, parameter ini telah dibuang daripada model akhir. Dengan R^2 0.79, model yang diterbitkan adalah signifikan secara statistik pada 95% aras keyakinan, yang membawa maksud bahawa aliran lalulintas dan parameter geometri membawa kepada anggaran 79% perubahan di dalam kelengahan. Lebih lagi, nilai pekali korelasi berganda ($R = 0.89$) memperakui bahawa hubungan antara kelengahan dan kesan gabungan dari pembolehubah tak bersandar adalah kuat secara signifikan. Oleh itu, kajian ini akan memberi panduan lebih tepat untuk menentukan tahap perkhidmatan yang boleh diterima bagi bulatan Malaysia untuk mewajarkan perbelanjaan yang berkaitan. Adalah disarankan agar model yang dicadangkan dipertimbangkan di dalam garispanduan Malaysia untuk analisa prestasi persimpangan sama aras, khususnya bulatan.

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LIST OF ABBREVIATIONS

HCM	-	Highway Capacity Manual
MHCM	-	Malaysian Highway Capacity Manual
MOE	-	Measure of Effectiveness
PDF	-	Probability Distribution Function
US	-	United States
UK	-	United Kingdom
GEH	-	Geoffery E.Havers
AD	-	Advantages
LIM	-	Limitations
M/G/1	-	Markovian (random) arrivals/generally distributed service times/one
m	-	Meter
sec	-	Second
min	-	minute
hr	-	Hour
veh/hr	-	Vehicles per hour
sec/veh	-	Seconds per vehicles
pcu/hr	-	Passenger car unit per hour
sec/pcu	-	Seconds per passenger car unit
m/sec	-	Meter per second

LIST OF SYMBOLS

Fr(t)	-	Probability function of rejected gap
Fa(t)	-	Probability function of accepted gap
Fc(t)	-	Probability function of critical gap
t_f	-	Follow-up headway
t_c	-	Critical gap
Q_e	-	Entry traffic flow
Q_c	-	Circulating traffic flow
d	-	delay
$Cl_{1-\alpha\%}$	-	Confidence interval for the true mean
S	-	Standard deviation
M	-	Model hourly traffic flow
O	-	Observed hourly traffic flow
ax	-	Desired distance between two consecutive vehicles in queue
b_{xAdd}	-	A parameter used to determine the desired safety
b_{xmult}	-	A parameter used to determine the desired safety
D_i	-	Roundabout central diameter
D_s	-	Roundabout inscribed diameter
W_e	-	Entry width
W_c	-	Circulating roadway width
N	-	Number of repetitions
v	-	Approach width
l	-	Effective flare length
s	-	Sharpness width
$F(a_i)$	-	Cumulative distribution function for normal distribution for accepted gap
$F(r_i)$	-	Cumulative distribution function for normal distribution for rejected gap
$P_{tc}(t_j)$	-	Frequencies of estimated critical gaps
t_{dj}	-	Class mean of two consecutive time gaps

Q	-	Roundabout capacity
e	-	Average width of the approach
W	-	Width of weaving section
p	-	Proportion of weaving traffic
C	-	Entry capacity
Q_{exit}	-	Exiting traffic volume
x	-	Degree of saturation
d_m	-	Minimum delay
D_s	-	Stopped delay
V_s	-	Subject approach volume
V_c	-	Circulating volume
Tt	-	Travel time
d_{st}	-	Stopped line delay
s_p	-	Speed
V_e	-	Entry volume
Q_l	-	Queue length
HV	-	Heavy vehicle

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CHAPTER 1

INTRODUCTION

1.1 Background of the study

In recent years, roundabouts are becoming very attractive to be used as an un-signalized intersection type (Oketch *et al.*, 2004; Al-madani, 2016; Hossain and Hossain, 2016; Patel and Khode, 2016; Anagnostopoulos and Kehagia, 2019). A roundabout is defined as the type of un-signalized intersection with a circular shape, characterized by the yield on entry and circulation around a central island (TRB, 2010). One of the most significant advantages of the roundabout is reducing the conflict points at an intersection; which leads to a capacity improvement as well as intersection safety (Agyeman *et al.*, 2015; Zubaidi *et al.*, 2020; Mądziel *et al.*, 2021). In addition, the total delay is also reduced (Oketch *et al.*, 2004; Sofia *et al.*, 2012; Almukdad *et al.*, 2021; Osei *et al.*, 2021).

Drivers at roundabouts entry are only required to yield for circulating vehicles in the circulating roadway. Consequently, drivers experience less delay at roundabout compared to other types of at-grade intersections; as a result of this, the fuel consumption is reduced, which in turn leads to fewer emissions at the roundabout (Lakouari *et al.*, 2020*)*. A substantial number of studies emphasize that fewer emissions are produced at roundabouts than other types of intersections (Gastaldi *et al.*, 2014; Puan *et al.*, 2014; Chen and Lee, 2016; Lakouari *et al.*, 2020; Ahmed and Easa, 2021; Mądziel *et al.*, 2021); thus, a roundabout is considered as an environmentally friendly facility.

For the purpose of designing a new intersection or improvement of an existing one, the operational performance with respect to traffic is a critical element. Capacity and delay are the most important performance measures for intersections. Delay is commonly known as the excess time spent on a transportation facility compared to that of a reference value. In other words, is the difference between actual travel time experienced by the driver and the ideal travel time at the free-flow condition. From the road users' point of view, one of the essential evaluations of the performance of an intersection is the delay; consequently, it should be precisely taken into consideration to assess an intersection's operational performance.

Several methods for estimating delays at uncontrolled intersections are well documented in the literature (Tanner, 1962; Akcelik and Troutbeck, 1991; Flannery *et al.*, 2000; TRB, 2010; Tanyel *et al.*, 2013; Ali Sahraei *et al.*, 2018; Sahraei and Akbari, 2020b; Ma *et al.*, 2021; Sahraei *et al.*, 2021). These estimation methods are either based on the empirical or analytical approach. The empirical method depends on field observation at varying sites, in which generated data are processed using regression analysis to develop an empirical model to estimating delay. On the other hand, the analytical theory is based on either queuing theory or gap acceptance theory; which considerably depends on the drivers' behaviour. These two (2) approaches were used to develop a delay equation in most countries, depending on the local conditions.

Microsimulation models have been widely used in transportation planning, design, and analysis. There are significant benefits gained from the application of the microsimulation models; such as cost-effectiveness, safety, and fast production of the results (Ciuffo *et al.*, 2008; Yu and Fan, 2017). Microsimulation models such as VISSIM can be used to model roundabout performance precisely. Roundabout simulation differs from other types of intersections, since at the roundabout entry leg, vehicle has to yield and check if there are vehicles at the circulating roadway. In the absence of vehicles, the driver can proceed to enter the circulating roadway without the need for a complete stop. In VISSIM, this process in is controlled by parameters of gaps and headways on a link by link basis (Trueblood and Dale, 2003). Many researchers employed VISSIM to model roundabout performance due to its magnificent capability to express the actual traffic conditions, especially at roundabouts (Gallelli and Vaiana, 2008; Vaiana *et al.*, 2012; Wei *et al.*, 2012; Otković, *et al.*, 2013; Mitrovic *et al.*, 2018).

As stated earlier, one of the significant advantages of the roundabout is reducing delay; nevertheless, due to high traffic volume during the rush hours, delays still occur. The roundabout delay is a critical performance measure for evaluating traffic conditions at a roundabout. This study focuses on delay at the entry leg of a roundabout. To present, limited work has been done on the topic, leading to an inaccurate assessment of the impact of the geometric and traffic parameters of roundabouts. Therefore, more studies are needed to examine the effects of geometry and traffic parameters on roundabout delays under the influence of driver behaviour in the field.

Collecting data from roundabouts with various geometric characteristics under different traffic flow conditions is a challenging process. It is required a lot of resources in terms of time and money, besides finding roundabouts under saturation conditions is challenging to find. Thus, the current study attempts to develop a base simulation model in VISSIM. Thereafter, the developed base model was calibrated and validated using field data from a representative roundabout to account for Malaysia's typical drivers' behaviour. Subsequently, different scenarios were generated in VISSIM based on varying ranges of geometric parameters and traffic flow conditions. Finally, the outputs from the VISSIM were used to formulate a relationship among roundabout delay, traffic flow, and roundabout geometric parameters.

1.2 Problem statement

Many researches have been carried out with regard to roundabout capacity (Benhadou, 2020; Almukdad *et al.*, 2021; Hamim *et al.*, 2021); whilst, studies to roundabout delay is yet to receive the most desired attention (Al-Omari *et al.*, 2004; Hossain and Hossain, 2016). Most of the studies carried out on delay estimation at roundabout were based on gap acceptance concept, from which delay prediction models are derived. This technique is theoretically grounded on knowledge of driver and vehicle behaviour. Although this method may extrapolate results to a broad range of cases, its theoretical assumptions (the gap is considered as headway, vehicles arrive stochastically, drivers on the circulating lane have homogeneous behaviour, and drivers on the entry lane recognize the vehicles going to leave the roundabout) limited its validity to express real-field conditions. Besides driver and vehicle behaviour, geometric features could impact the roundabout delay. However, the gap acceptance-based approach does not consider the impact of the roundabout geometric features in the delay estimation process. Specifically, the geometric parameters are missing from the delay models based on the approach. The use of an empirical approach allows for more insights into driver-traffic behavior in the field as it comprises of driver behaviour influencing factors, which may not be expressed in the theoretical model. Yet, this approach heavily depends on the data used in formulating the model. Therefore, the applications of the derived model could be restricted to the data ranges used in developing the model. Besides, collecting data from different roundabouts with varying geometric features consumes time and financial resources. On the other hand, microsimulation models are similar to theoretical models in terms of assumptions about driver behaviour. However, this method provides more flexibility to account for particular driver behaviour and presents more pragmatic models. However, the microsimulation models such as VISSIM demands sophisticated user knowledge and expertise, which not all engineers possess. Additionally, most research conducted to construct roundabout delay models did not consider the effect of a sufficiently wide range of geometric and traffic features in these models. Furthermore, most of these studies have been accomplished in nations where the driver behaviour, geometry, and traffic characteristics of roundabouts differ from those in Malaysia.

In Malaysia, although in the Arahan Teknik (Jalan) 11/87, a capacity model for roundabout was developed. This model was developed based on weaving theory; which is mainly based on weaving section geometric parameters without considering the impact of the traffic flow parameters (Ministry of Works Malaysia, 1987; Aziz *et al.*, 2004). On the other hand, the procedure followed to estimate roundabout delay is based on the delay model for un-signalized intersections or other roundabout delay models developed in other countries (Puan *et al.*, 2015; Ghani *et al.*, 2019). The delay model used for un-signalized intersection did not consider the influence of the geometric parameters in the estimation process. Simultaneously, using roundabout delay models developed in other countries where intersection geometric features, traffic conditions, rules, and driver behaviour differ significantly from Malaysia would result in inaccurate assessment for design, analysis, and planning roundabouts.

Accordingly, further investigation is required to evaluate the impact of various ranges of geometric and traffic parameters on delays. Using the VISSIM microsimulation model based on actual driver behaviour appears a promising solution to assess the influence of wide ranges of different roundabout's geometric features on delays instead of collecting the data from the field. Finding roundabouts with diverse geometric characteristics with varying traffic flow conditions is challenging and consume time and money. Consequently, the current study attempts to develop a user-friendly and straightforward model for roundabout's delay based on the outputs obtained from VISSIM for different scenarios cases based on Malaysian roadway and traffic conditions and motorists' behaviour. Moreover, simple application graphs could be created based on the mathematical model to estimate delay for roundabouts under different geometric and traffic flow parameters.

1.3 Aim and objectives

This research aims to evaluate the impact of traffic flow and roundabout's geometric features on delays at the subject facility using a VISSIM microsimulation model software. To accomplish this, the following specific objectives are set.

i. To develop a base model of traffic operations at roundabout using VISSIM microsimulation model;

ii. To evaluate the impact of roundabout's geometric features (i.e. central island diameter, entry width, and circulating roadway width) on delays at a roundabout;

iii. To develop a mathematical model for prediction of delay at roundabout as influenced by traffic flow and roundabout's geometric features; and

iv. To develop application charts for computing delay at roundabouts with varying ranges of traffic flow and geometric parameters.

1.4 Scope and limitation of the study

Essentially, this study's scope consists of field data collection and evaluation and roundabout simulation model development in VISSIM. In terms of data collection and evaluation, the selected site in this study is a two-lane roundabout with a central island diameter of 67 m located in Johor Bahru States, Malaysia. Modelling driver behaviour at a roundabout is a complex process. Because the possibility of vehicular conflicts circulating traffic at the roundabout is high; however, this is also the case in real-life, not only for the simulation model (Trueblood and Dale, 2003). Therefore, modelling this type of behaviour can easily be accommodated in VISSIM microsimulation model with incorporation of further scenarios in the model. The study site was selected such that it is characterized by various traffic flow conditions such that vehicular queues are at times developed at least one or two entry leg(s) of the roundabout. The data was collected during morning peak hours on working weekdays because the traffic volumes at the weekends are low; therefore, finding delayed vehicles is more diminutive. On the other hand, collecting data in the evening peak is complex because the traffic flow stream's visibility is challenging to estimate. Data evaluation involved analyzing all data related to this study, such as estimating the critical gap, follow-up headway, traffic flow parameters, traffic composition, vehicle desired speed, and delays. The evaluated delay in this study is the total delay experienced by drivers at roundabout's entry, it is composed of queuing and service time delays. Moreover, pedestrians and cyclists are not examined in this research due to the scope of the study since their presence was infrequent within the study site proximity. Furthermore, the effects of the upstream signal and the slope on roundabout delays are not considered.

In terms of roundabout simulation model development in VISSIM, data evaluated earlier were used as input parameters in VISSIM. Traffic flow parameters and delays were selected as measures of effectiveness to calibrate and validate the simulation model by comparing the simulation model outputs with those from the actual field. Several scenarios were then created in VISSIM based on varying geometric parameters (i.e. central island diameter, entry width, and circulating width) and traffic flow conditions. The outputs from VISSIM were used to develop a mathematical model describing the relationship between delays at roundabout, and entry flow rate, circulating flow rate, entry width and circulating roadway width. The mathematical model was then validated using the field's observed data from a different site. Different application graphs were generated based on varying ranges of geometric and traffic flow parameters. This research has some limitations because it is based on the evaluation of VISSIM microsimulation modelling. Moreover, the applicability of the developed model is restricted to delay estimation at urban roundabouts with a low proportion of heavy vehicles.

1.5 Significance of the study

This study investigates and developed a model for estimating delay at an urban roundabout. Since the models developed are based on data collected with varying ranges of traffic flow conditions, geometric parameters as well as under local driver behaviour in Malaysia, it is anticipated that the new method would be valuable in contributing to the Malaysian practice relating to the roundabout operational performance assessment. Because, the newly proposed model in this study is first of its kind meant for delay estimation at urban roundabout, which was developed on Malaysian local condition.

This study's outcomes would serve as a basis to prove the effectiveness of the method's suitability in terms of applicability for estimating delay. Moreover, the developed model would serve as a guide to decision makers regarding urban roundabout’s operational performance assessment, particularly to justify expenses relating to the improvement of the subject facility.

1.6 Thesis structure

This thesis is structured into seven (7) chapters, with one of them discussing a particular aspect of the entire research. Chapter one describes the study’s background, problem statement, aim and research objectives, scope of the study, and the significance of the research.

Chapter two contains a comprehensive review and discussions of the existing researches in the literature relating to the roundabout operational performance, estimation of the critical gap, follow-up headway, and estimation methods of roundabout capacity and delays. Besides this, the chapter introduces the current issue regarding the methods applied in estimating the roundabout delay, highlighting both their strengths and weaknesses.

Chapter three describes the research methodology employed in conducting the study, which includes the detailed descriptions of procedures adopted for the various components of the work. This chapter covers two (2) main sections, data collection and data analysis. For the data collection, all data required for this research were described and generated using standard techniques. Likewise, the procedures followed for measuring the relevant input parameters were also described in this chapter. These include estimations of critical gap, follow-up headway, vehicle desired speed, delay, and development of a roundabout model in VISSIM.

Chapter four describes the approach used in analysing the data collected at a two-lane roundabout. Data analysis carried out includes traffic composition at the roundabout, estimation of the critical gap, follow-up headway, vehicle-desired speed, and delay evaluation. The data analyzed in this section are used to build the simulation model in the VISSIM software.

Chapter five presents the detailed description of the procedures followed to build the simulation model in the VISSIM software. It also describes the steps are followed to verify, calibrate, and validate the simulation model.

Chapter six present and discusses all the steps followed to create different scenarios in VISSIM. It also exhibits the influence of roundabout geometric features on delays at the facility. Furthermore, it presents the mathematical model's development process used for the estimation of delay based on roundabout geometric features and traffic flow parameters. The model was derived from the outputs of the analysis performed in the VISSIM. Moreover, the chapter presents the validation of the developed model using data obtained from a different roundabout site. Subsequently, application graphs were generated to estimate roundabout delays based on varying ranges of geometric features and traffic flow conditions.

Chapter seven presents the summary of the conclusions drawn from the current research and suggestions made for further works in the future.

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