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Optimising Layout of a Left-Turn Bypass Intersection under Mixed Traffic Flow using Simulation: A Case Study in Pulau Pinang, Malaysia

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ABSTRACT

Various unconventional arterial intersection designs (UAIDs) have been proposed as novel approaches to alleviate congestion at signalised intersections. However, little research has focused on the UAIDs under mixed traffic flow. In Malaysia, a type of unconventional arterial intersection, i.e., the left-turn bypass intersection, is very common. Hence, an alternative two-lane left-turn bypass intersection layout is proposed and compared with two other layouts under mixed traffic flow. An existing intersection in Pulau Pinang, Malaysia is selected as the location of our case study. To compare the three layouts, the state-of-the-art traffic micro-simulation software SUMO is used to model, analyse and estimate operational performances of the studied intersection layouts. To make simulation results more reliable, the simulation model is validated using the GEH empirical test. The performance indicators delay, travel time, speed, and number of stops are used to evaluate the three layouts for low, medium and high traffic volumes. The simulation results show that the left-turn bypass intersection outperforms the intersection without any bypasses, and the proposed intersection performance is better than the two other considered intersections. More specifically, the average delay of the proposed intersection is lower by 2.54s and 4.4s compared to the two other considered intersections in high traffic volume, respectively. Thus, this proposed intersection could be used in urban cities with traffic demand and congestion issues similar to those in this study.

1. Introduction

Due to the rapid development of society, urban populations and urban areas are continually growing. The population living in urban areas is expected to increase to 68% of the world population by 2050 [1]. This has a serious impact on the economy, transportation, environment as well as daily life [2]. With rapid urbanisation, the vehicle population of the world has expanded dramatically during the previous decade. This large number of vehicles has caused severe vehicular traffic congestion [3], which resulted in numerous issues such as time waste and environmental pollution [4,5]. Transportation consumes the most energy in the world, making up 29% of global energy

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consumption and 24% of global CO_2 emissions [6]. According to the World Bank, 24.7 billion MYR of Malaysia has been cost for traffic congestion in 2014 [7]. Nearly 66% of air pollution in Malaysia is caused by ground-based transportation, which mostly comprises of hazardous emissions from cars, heavy duty vehicles, and motorbikes [8]. Therefore, it is important to study transportation optimisation with the aim of making traffic infrastructure in Malaysia more efficient for users, and environmentally sustainable.

Intersections play a crucial role in ensuring smooth flow and conveying turns in the whole road network [9]. Many studies have concentrated on alleviating traffic congestion at heavily congested signalised intersections. The main perspectives of these studies can be classified into two aspects: traffic signal control optimisation, and arterial intersection layout optimisation. Our focus is on arterial intersection layout optimisation. An appropriate intersection layout is important in ensuring smooth traffic flow. Unconventional arterial intersection designs (UAIDs) have been developed as an innovative approach to help alleviate traffic congestion at signalised intersections. UAIDs includes many intersection types, like the left-turn bypass intersection, and the displaced left-turn (DLT) intersection. Shokry *et al*., [10] compared the proposed DLT intersection and superstreet median intersection with existing conventional signalised intersections. The simulation results showed that the performances of the proposed DLT intersection and SSM intersection were better than their conventional counterparts. Ahmed *et al*., [11] assessed the safety performance of DLTs using two common methods. Similarly, other researchers have also studied DLT intersection [12-15], and the results show the DLT intersection had better performance for traffic operation. However, little research has considered left-turn bypass intersection, except Olarte *et al*., [16]. A typical characteristic of traffic in many South-East Asian countries, including Malaysia, is mixed traffic flow. Mixed traffic flow is comprised of not just four-wheeled vehicles, but also a significant number of two-wheeled vehicles (motorcycles). Hence, mixed traffic flow does not move in a single file, and there are substantial lateral movements, mainly among smaller vehicles (motorcycles) [17].

Specifically at intersections, smaller vehicles utilise the lateral gaps between bigger vehicles in order to advance to the front of the line. Not many studies have taken mixed traffic flow into account. As a note, Yu *et al*., [18] and Qi *et al*., [19] defined mixed traffic flow as traffic that is a mix of human-driven and autonomous vehicles. In this study, mixed traffic flow is defined as human-driven traffic comprising motorcycles, cars, buses, and lorries.

Although many studies have focused on optimising the DLT intersection of UAIDs, the left-turn bypass intersection under mixed traffic flow has not been considered. However, the left-turn bypass intersections are very common in Malaysia. Therefore, the three layouts of a left-turn bypass intersection under mixed traffic flow at a specific location in Malaysia are evaluated, which are the existing one-lane left-turn bypass intersection, the proposed two-lane left-turn bypass intersection, and an intersection without any bypasses. The objective is to determine which layout best alleviates traffic congestion at the intersection.

2. Methodology
2.1 Intersection Description

Pulau Pinang, one of the states in Malaysia, is a famous natural and cultural tourist destination. It is culturally diverse and has a beautiful environment for human habitation. However, as of 2019, the population density of Pulau Pinang was as high as 1,684/km^2, according to Department of Statistics Malaysia [20]. Pulau Pinang is one of the highest population states in Malaysia [21]. Therefore, traffic in Pulau Pinang is very congested, especially during rush hour. In order to alleviate traffic congestion, this study analyses different layouts of a left-turn bypass intersection at a specific location (the Lebuhraya Thean Teik-Jalan Thean Teik intersection in Pulau Pinang Malaysia, as shown in Figure 1).

(a) Source: real world picture (b) Source: OpenStreetMap Web Wizard

Fig. 1. The Lebuhraya Thean Teik-Jalan Thean Teik intersection

The geometric layout of this specific left-turn bypass intersection is given in Figure 2. In each direction of this left-turn bypass intersection, there are three lanes for vehicles to enter the intersection, two lanes for vehicles to exit the intersection, and one lane for protecting right-turn vehicles. There are also four left-turn bypasses for vehicles to turn left for every direction, where left-turn vehicles are not controlled by traffic signal.

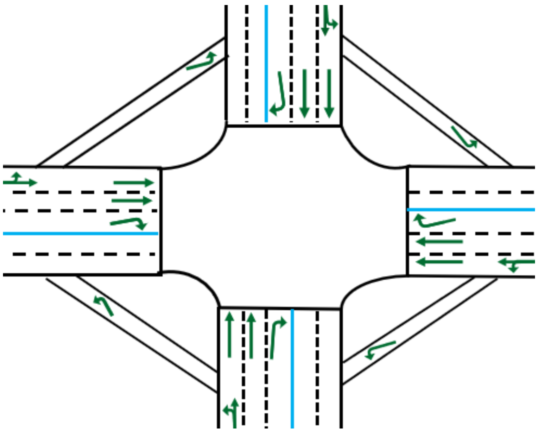
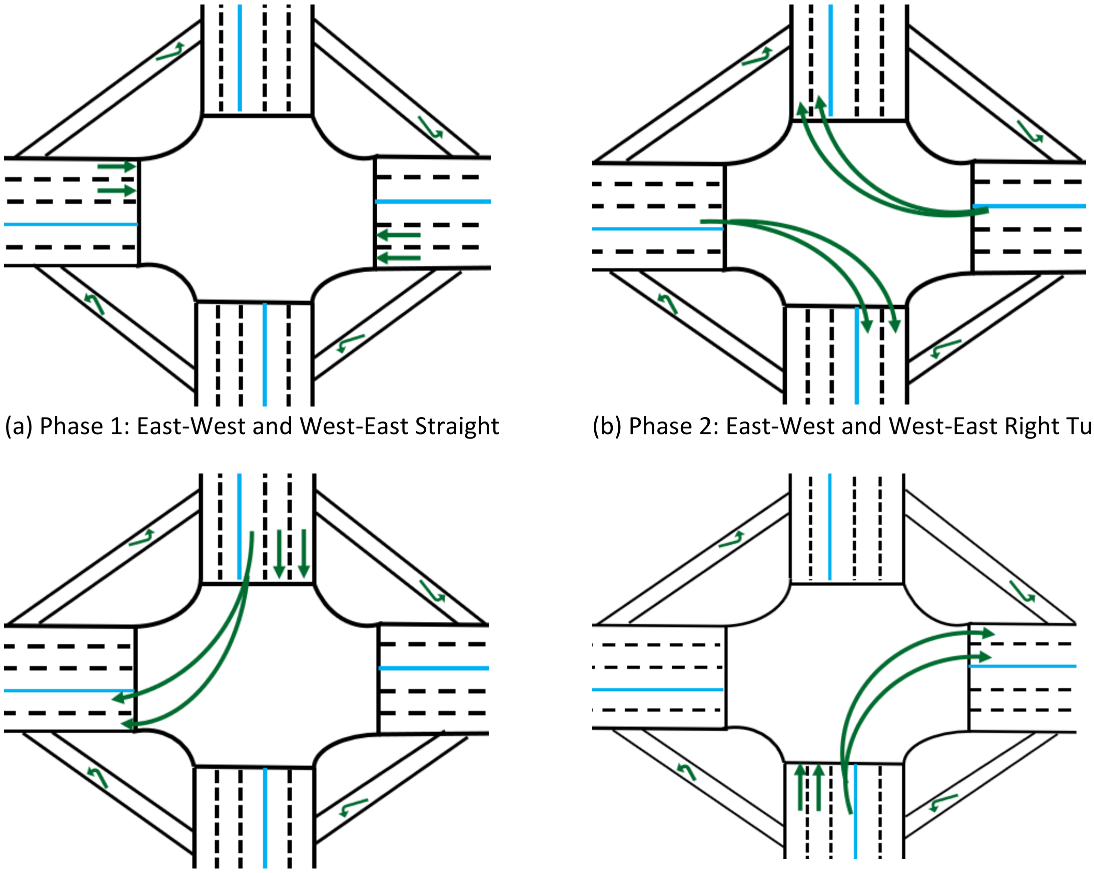


Fig. 2. One-lane left-turn bypass intersection

A bypass is a traffic road built at an intersection to allow vehicles to turn left without entering the intersection and interrupting through traffic. When vehicles exit the bypass and enter the main road, they must give way to vehicles on the main road. This intersection is located in an urban region, and thus the speed limit of the roads is 60 km/h except for the four left-turn bypasses where the speed limit is 40 km/h. The traffic signal timing plan of this left-turn bypass intersection consists of four phases, namely East-West and West-East Straight, East-West and West-East Right Turn, North-South Straight with Right Turn, and South-North Straight with Right Turn as shown in Figure 3.



(a) Phase 1: East-West and West-East Straight

(b) Phase 2: East-West and West-East Right Turn

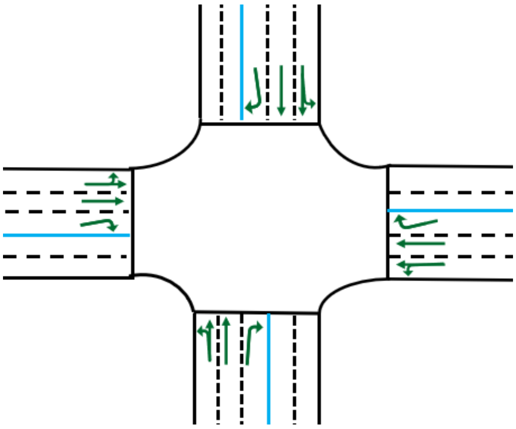
(c) Phase 3: North-South Straight with Right Turn

(d) Phase 4: South-North Straight with Right Turn

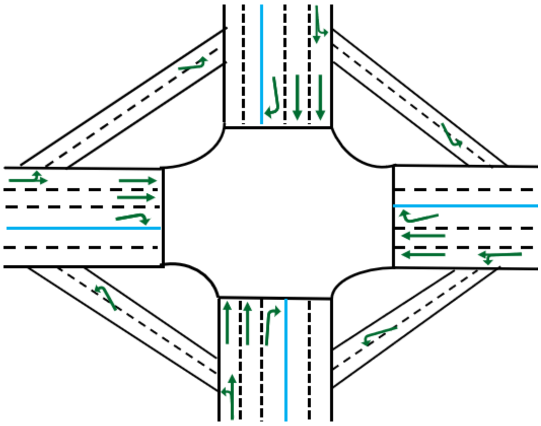
Fig. 3. Traffic signal phases

This study analyses three different layouts of a signalised cross intersection under mixed traffic flow for different traffic volumes at a specific location (the Lebuhraya Thean Teik-Jalan Thean Teik intersection, as shown in Figure 1). The objective is to determine the optimal layout for the intersection to alleviate traffic congestion at this intersection. Three scenarios for the signalised cross intersection are considered, namely:

i. Scenario 0: An intersection without any bypasses as shown in Figure 4a (referred to as LTB-0).
ii. Scenario 1 (Existing intersection): A one-lane left-turn bypass intersection, where each bypass consists of one lane as shown in Figure 2 (referred to as LTB-1).
iii. Scenario 2 (Proposed intersection): A two-lane left-turn bypass intersection, where each bypass consists of two lanes as shown in Figure 4b (referred to as LTB-2).



(a) Scenario 0: Intersection without any bypasses



(b) Scenario 2: Two-lane left-turn bypass intersection

Fig. 4. Intersection layouts for Scenario 0 and Scenario 2

Performance indicators for an intersection are also called measure of effectiveness (MOE) [22]. In this study, the average delay, average travel time, average speed, and average number of stops are considered to evaluate the performances of the intersection layouts under mixed traffic flow. Average travel time is the average time for all vehicles to pass through an intersection, average speed is the average speed for all vehicles to pass through an intersection, and average number of stops refers to the average number of stops for all vehicles to pass through an intersection. Delay of a vehicle refers to the difference between the time it takes for a vehicle to pass an intersection under obstructed conditions, and the time it takes for a vehicle to pass the same distance at maximum speed. If an intersection contains m traffic signal phases, the average delay $\overline{D}$ of an intersection can be expressed as follows:

$$\overline{D} = \frac{\sum_{i=1}^{m} D_i}{\sum_{i=1}^{m} q_i} , \quad (1)$$

where q_i denotes traffic volume of the i th phase, and D_i denotes total delay of the i th phase.

2.2 Data Collection

To improve the validity of this study, actual traffic composition data made available by the Ministry of Transport Malaysia [23] is used. The Ministry of Transport Malaysia selected 14 stations throughout the country and recorded the vehicle composition at each station for 16 hours as shown in Table 1. The average value of each vehicle type for all stations is calculated as the vehicle composition (in %) for this study. The mixed traffic flow in this study includes motorcycles (14%), buses (1%), cars (60%), and lorries (25%), where lorries include light lorries, medium lorries, and heavy lorries. Traffic volume data was also collected through video recordings at the intersection at different periods of the day on September 13th, 2022, which was a sunny day.

Table 1
16 hours traffic and traffic composition (%) by type of vehicle at 14 selected stations, Malaysia, 2021

Station	Total number of vehicles	Traffic Composition (%) by type of vehicle					
		Car/Taxi	Light lorry	Medium lorry	Heavy lorry	Bus	Motorcycle
			Peninsular Malaysia				
JR 204	42,046	73.0	3.5	6.8	0.9	4.9	10.9
JR 501	8,800	57.2	8.2	5.5	3.4	0.0	25.7
NR 501	3,346	72.4	5.1	5.5	3.8	1.0	12.3
PR 115	22,760	60.4	8.9	8.2	1.7	0.6	20.4
AR 301	12,642	75.1	5.0	6.3	1.7	1.8	10.1
KR 501	7,794	67.9	4.6	7.6	3.2	1.1	15.6
CR 805	5,006	57.5	13.5	8.6	6.7	0.7	13.0
CR 902	12,455	62.2	14.2	5.4	8.8	0.2	9.2
TR 402	25,665	61.1	12.9	2.9	0.6	0.4	22.2
DR 802	16,159	61.4	13.5	5.6	3.1	0.6	15.8
			Sabah				
HR 201	12,212	61.7	23.6	5.8	2.6	0.9	5.4
HR 501	9,842	37.7	35.3	9.8	6.6	0.4	10.2
			Sarawak				
SR 103	31,432	55.7	16.2	7.3	5.7	0.7	14.3
SR 402	5,388	36.0	37.9	7.6	11.6	0.8	6.1
Average	12,766	60.0	14.0	7.0	4.0	1.0	14.0

*The first column represents 14 selected locations.
*The second column represents the total number of vehicles at locations.

The genetic algorithm combined with the simulation method [24] is utilised to optimise traffic signal timing plans for this left-turn bypass intersection under mixed traffic flow (the Lebuhraya Thean Teik-Jalan Thean Teik intersection) and this study obtain traffic signal plans for low (1465 veh./h), medium (3022 veh./h), and high (4813 veh./h) traffic volumes as shown in Table 2. These signal plans for corresponding traffic volumes are used as inputs in this study.

Table 2
Traffic signal timing plans for corresponding traffic volumes at the intersection under mixed traffic flow

Traffic signal timing plans	Traffic volumes (vehicles/h)	Phase sequence	Offset (s)	Green duration (s)	Cycle length (s)
Plan1	Low (1465/h)	1243	1	G_1=16, G_2=8, G_3=16, G_4=16	62
Plan2	Medium (3022/h)	1243	2	G_1=24, G_2=16, G_3=16, G_4=16	80
Plan3	High (4813/h)	2143	2	G_1=24, G_2=16, G_3=24, G_4=24	96

*High traffic volumes refer to rush hour traffic.
*G_j represents the green duration of corresponding phase in each traffic signalised timing plan.

Based on observation, it can be seen how mixed traffic flow affects traffic operational performance. The aggressiveness of drivers is observed by lane changing behaviour and the manoeuvrability of small vehicles. Some drivers try to laterally encroach on other drivers' lanes. Also, two-wheeled vehicles (motorcycles) are very special due to their size and mobility. Sometimes they do not follow the same physical traffic rules as other large vehicles. They can accelerate and decelerate faster, manoeuvre between lanes or in a shared lane, move to adjacent lanes, or even form dense traffic when stopped at a red light.

2.3 Traffic Micro-Simulation

As a state-of-the-art micro-simulation software, SUMO has been broadly used by many practitioners and researchers to simulate and evaluate different traffic scenarios. Traffic simulation is one of the most useful and cost-effective tools for analysing and researching traffic systems [25]. For this study, microscopic models for the proposed LTB-2, the existing LTB-1, and LTB-0, are tested using SUMO. The primary objective of utilising SUMO is to study whether the proposed intersection layout could provide some benefits and how significant these benefits might be. The simulated models are built based on the Krauss model as a psychophysical car-following model, which can represent the driving behaviour under mixed traffic flow. Similarly, in order to model the field conditions of under mixed traffic flow as close as possible to the real world, the sub lane model [25] which allows motorcycles to share the lane is introduced. Vehicle overtaking is also allowed on both sides (left and right).

2.4 Model Calibration

Although SUMO is currently one of the best-suited tools for modelling, analysing, and evaluating various intersection layouts, the default set may not produce results that are credible and close to reality. As a result, inaccurate, unrealistic, and unreliable models may be given [26], particularly, when the mixed traffic flow is considered. It is necessary to calibrate the microscopic model to avoid such inaccurate results and discrepancies. Model calibration is the process of adjusting the simulation model's default parameters until the model accurately mimics the traffic flow in the real world. In other words, it is essential to ensure that the probability (*P*) (as shown in Inequality Eq. (2)) of a deviation between the output of the real system and the output of the simulated system is less than a predetermined acceptable deviation [27,28].

$$P\left(\,|\,real\ system - simulated\ system\,| \leq \varepsilon\right) > \alpha, \tag{2}$$

where ε is the tolerable deviation threshold that indicates how close the simulated system is to the real system, and α is the significance level which notifies the analyst how certain the obtained result is. Hence, in SUMO, the geometric configuration, the driving behaviour parameters (such as driver imperfection (sigma) and driver reaction time (tau)), and vehicle dynamic & static characteristics (such as length, acceleration, deceleration, and mingap) are adjusted to make the model as close as possible to reality. These values are calibrated based on previous studies and guides [26,29].

During calibration, only some parameters may have a substantial effect on the models even though SUMO has many simulation parameters that can be adjusted and improved. Based results from studies [30,31], driving behaviour factors, and vehicle dynamic & static characteristics are taken into account in this study to complete the calibration process. In addition, One-Way Analysis of Variance (ANOVA) test is used to conduct a sensitivity study and determine the most significant parameters that affect model accuracy. ANOVA is utilised to determine whether the factors under investigation have an effect on the response variable.

The ANOVA results are shown in Table 3, where P-value is the significance value, and the interpretation of other parameters can be found in [10]. As the P-value (0.00001) is less than 0.05, the null hypothesis is rejected, which means the variances of the simulation results obtained for different simulation parameters are significantly different at the 0.05 level of significance. In other words, these simulation parameters have a big effect on how accurate the models are. The calibration results indicate that the driving behaviour parameters, and vehicle dynamic & static characteristics have a substantial effect on model accuracy.

Table 3
One-Way Analysis of Variance test results of average delay by different simulation trials

Source of variation	SS	df	MS	F	P-value	F crit
Between groups	20.5371	5	4.10742	9.89243	0.00001	2.53355
Within groups	12.4562	30	0.41520			
Total	32.9933	35				

2.5 Model Validation

Model validation is usually carried out during the simulation model building process to check to what extent the model represents reality. In order to validate the model, statistical validation is used to test the goodness of fit and the confidence intervals to quantify the similarity between observed and simulated values [32,33]. For this purpose, traffic volumes generated by SUMO are compared with the corresponding observed volumes. The most used goodness of fit measures GEH empirical test is used in this study. The GEH index, designed as a modified Chi-square static test, can be calculated based on Eq. (3), where S_{sim} is the simulated traffic volume, and $O_{observed}$ is the real traffic volume.

$$GEH = \sqrt{\frac{2(S_{sim} - O_{observed})^2}{S_{sim} + O_{observed}}} \quad (3)$$

Regarding the GEH test, the model can be accepted when the variance (the difference between the observed and simulated traffic volumes) of 85% of the total population is less than 5 [34]. A comparison between the average observed and average simulated traffic volume is utilised for the model validation. The comparison results are as shown in Table 4. As all GEH values are less than 5, these results indicate that the models are accurate.

Table 4
Model validation by GEH values

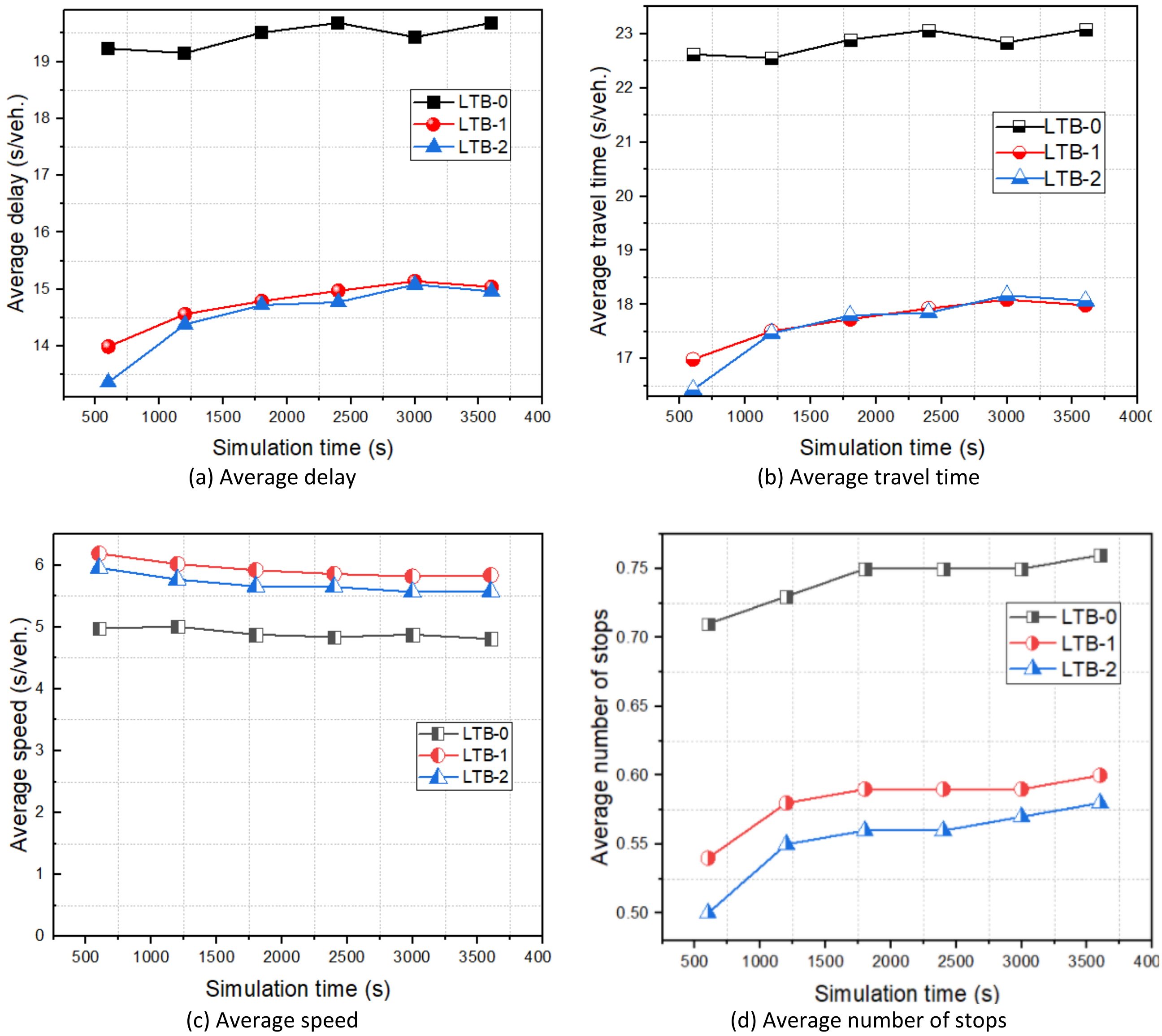
Traffic volume	Average observed volume (veh/h)	Average simulated volume (veh/h)	GEH variance values
Low	366	364	0.105
Medium	756	685	2.65
High	1203	1051	4.53

*Average observed (resp. simulated) volume represents the average of observed (resp. simulated) traffic volume in four directions (east, west, south, and north) of an intersection.

3. Results and Discussion

The performance evaluation indicators average delay, average travel time, average speed, and average number of stops for all vehicles are estimated for the three different layouts of the left-turn bypass intersection under mixed traffic flow in different traffic volumes (i.e., low, medium, and high traffic volumes). The simulation time in this study is 3600s. The results are presented in Figures 5 to 7.

For low traffic volume, all three intersection layouts (i.e., LTB-0, LTB-1, and LTB-2) are operating at 62s cycle length (corresponding to traffic signal timing plan 1, as shown in Table 2). The performance indicators considered for comparison are average delay, average travel time, average speed, and average number of stops for all vehicles. Specifically, the average number of stops of LTB-2 is lower by almost 0.02 and 0.18 compared to LTB-1 and LTB-0 respectively. In terms of the other three performance indicators, LTB-2 and LTB-1 perform almost the same as one another and better than LTB-0, as shown in Figure 5.

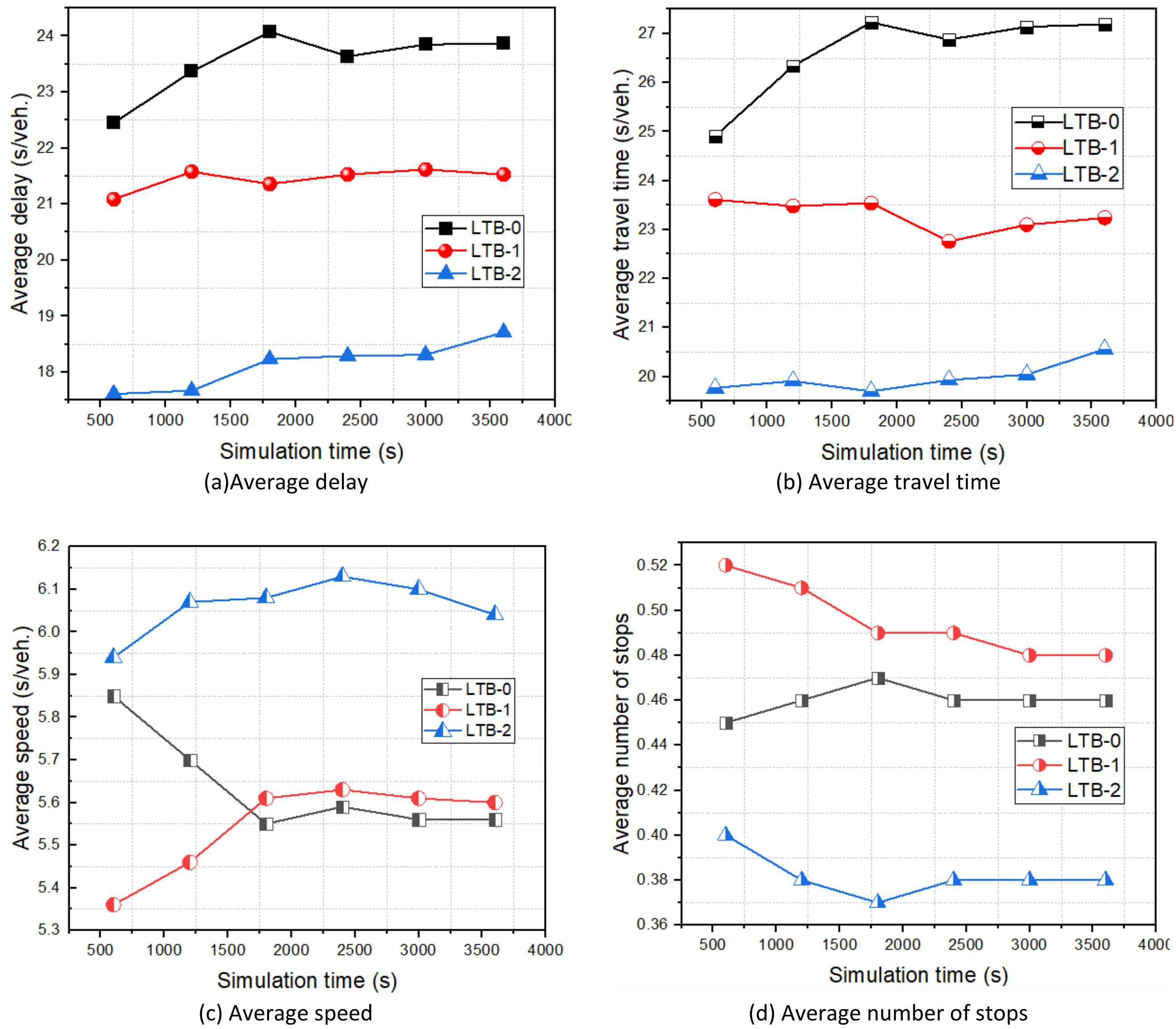


(a) Average delay (b) Average travel time

(c) Average speed (d) Average number of stops

Fig. 5. Performance indicators for LTB-0, LTB-1, and LTB-2 in low traffic volume

For medium traffic volume, the cycle length is 80s (corresponding to traffic signal timing plan 2, as shown in Table2). The four performance indicators show that LTB-2 performs the best, followed by LTB-1, while LTB-0 performs the worst (as shown in Figure 6). Specifically, the average delay of LTB-2 is lower by 2.82s and 5.16s compared to LTB-1 and LTB-0 respectively. Likewise, this trend is also evident in the other three performance indicators.

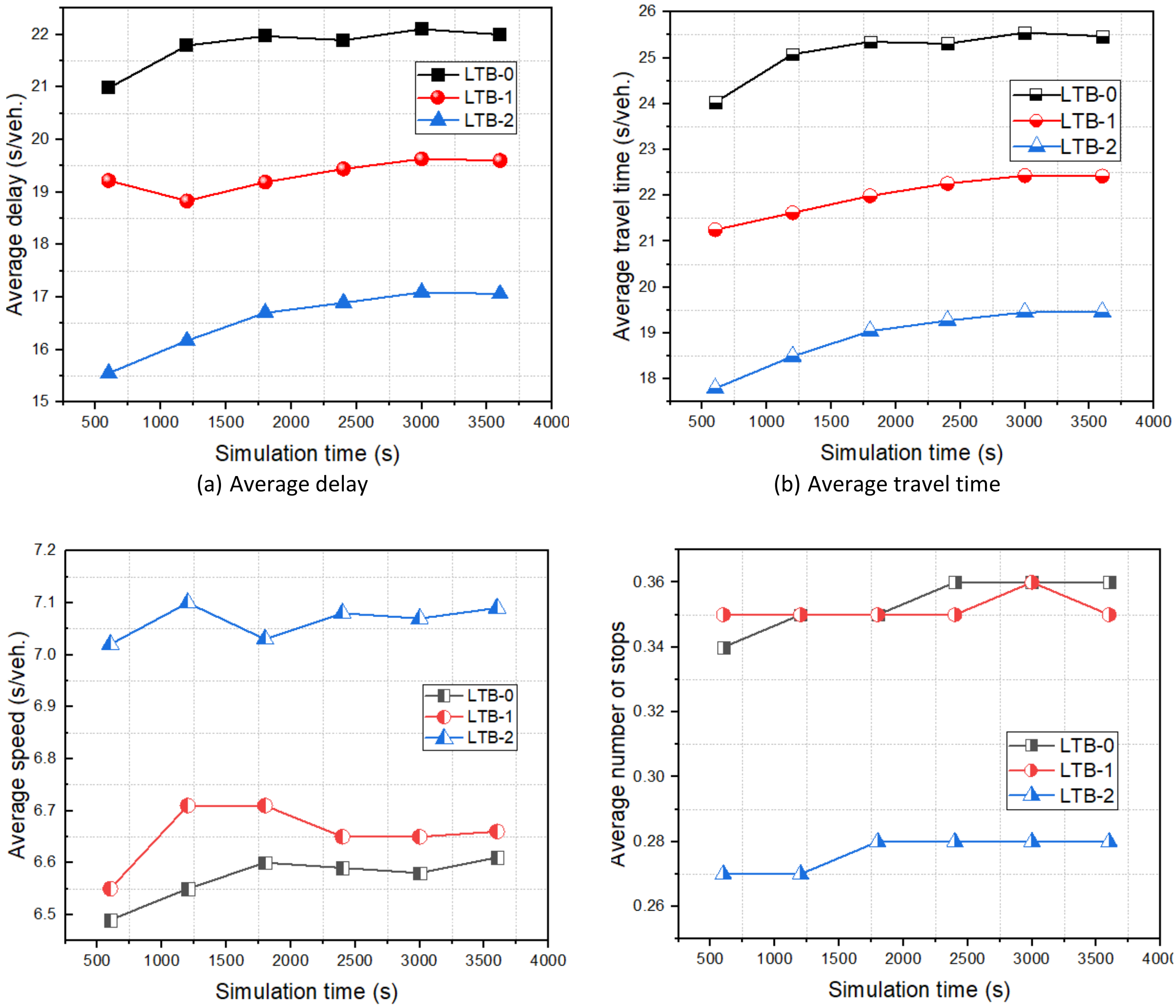


(a)Average delay (b) Average travel time

(c) Average speed (d) Average number of stops

Fig. 6. Performance indicators for LTB-0, LTB-1, and LTB-2 in medium traffic volume

For high traffic volume, all three intersection layouts (i.e., LTB-1, LTB-2, and LTB-0) are operating at 96s cycle length (corresponding to traffic signal timing plan 3, as shown in Table 2). The four performance indicators show that the proposed LTB-2 again performs the best (as shown in Figure 7). Specifically, the average delay of LTB-2 is lower by 2.54s and 4.4s compared to LTB-1 and LTB-0, respectively. The other three performance indicators again show same trend that LTB-2 performs the best, followed by LTB-1, while LTB-0 performs the worst. These results demonstrate efficiency of the proposed layout at the case study location.



(a) Average delay (b) Average travel time
(c) Average speed (d) Average number of stops

Fig. 7. Performance indicators for LTB-0, LTB-1, and LTB-2 in high traffic volume

Based on the above analyses, it is to be noted that in different traffic volumes (i.e., low, medium, and high traffic volumes), the proposed LTB-2 layout is more effective in relieving traffic congestion, followed by LTB-1, whereas LTB-0 performs the worst. Hence, the proposed LTB-2 layout could operate better than the other intersection layouts at the case study location.

4. Conclusions

This study proposes an innovative intersection layout (LTB-2), which is applicable at intersections under mixed traffic flow for Malaysian traffic conditions. Mixed traffic flow, which consists of four-wheeled and two-wheeled vehicles, is very different from homogeneous traffic flow as there are differences in the operation and performance characteristics of different vehicles. The performance of the proposed intersection layout (LTB-2) is evaluated against two other intersection layouts (including the existing layout) for a case study location in Pulau Pinang, Malaysia. All considered intersection layouts are modelled and simulated using the micro-simulation software, SUMO. The models are finely calibrated and validated to make the results from them more accurate and reliable. ANOVA test is used to determine which specific simulation parameters have a significant impact on the simulation results, and the goodness of fit measures GEH empirical test is used to test model accuracy.

The performance indicators average delay, average speed, average travel time, and average number of stops per vehicle are used in the evaluation process. The results show that LTB-2 is promising and operates efficiently compared to LTB-1 and LTB-0 in the four performance indicators for different traffic volumes (i.e., low, medium, and high traffic volumes). Generally, the intersection congestion at this location would be greatly alleviated, and the intersection could efficiently manage mixed traffic flow if this proposed LTB-2 layout was applied.

This study is one of the first scientific studies on this topic and adds value to the scientific community on a local context. The findings of this study could serve as an important reference for intersection layout selection to alleviate traffic congestion. A possible future extension of this work is investigating operational performances of different unconventional arterial intersection designs under mixed traffic flow. It is also recommended to consider designing a better intersection layout to optimise the movement of mixed traffic flow.

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