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Capacity Analysis of Unsignalized Intersection Under Mixed Traffic Conditions

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Abstract

Unsignalized intersection is implemented to regulate low volume of traffic flow. The gap-acceptance method is the common approach to assess the performance of the intersection. However, among the drawbacks of the gap-acceptance method are the non-compliance to the right of way, and the heterogeneous traffic condition. Conflict method is developed to overcome these shortcomings. Surveillance equipment is used to obtain the required data, such as traffic volume and occupation time. The occupation time of vehicle is used to calculate the capacity of vehicular movements for each conflict group. The control delay and level of service of the vehicular streams are evaluated according to the procedures in HCM 2000. Result comparison is made between the conflict method and the HCM 2000. The relationship between the occupation time and critical gap is discovered. The results of the conflict method are found to be comparable with the HCM 2000 using field data.

Keywords: conflict method, additive conflict flow, discharging service time, conflict group, gap-acceptance

1. Introduction

Traffic conflicts between vehicular movements are created when two or more roads crossed each other. Such conflicts may cause delay and traffic congestion with the possibility of road accidents. Thus, each intersection requires traffic control. It is regulated with stop signs, traffic lights, and roundabout. The common type of intersection is the unsignalized intersection, which is used to regulate low volume of

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traffic flow between the major and minor streets. The two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) are among the types of operation for unsignalized intersection. Troutbeck and Brilon (1992) stated that unsignalized intersection operates without positive indication or control to the driver. It depends on the driver's decision to take the right opportunity to enter the major street. This behavior is defined as gap acceptance. In this case, the driver in the minor street will wait for an adequate gap before entering the major street. On the other hand, small gaps are typically rejected.

The gap-acceptance method assumed the drivers to comply with the priority of right-of-way of each traffic stream. However, Brilon and Wu (2002) stated that the gap-acceptance method has a few drawbacks. It does not take the driver behavior into consideration, particularly on the compliance with priority rules. Forced gap caused by aggressive driver, and polite behavior of drivers that purposely provide gap clearly are not in accordance to the rules of priority. The situation is worsened by heterogeneous traffic, a mix of motorized and non-motorized modes (Prasetijo, 2007).

Therefore, the conflict method is developed to overcome the problems in the gap-acceptance method. This method is also known as the additive conflict flow (ACF) method. Wu (2000) stated that it is easier to consider the distribution of traffic flow rates, the number of lanes and pedestrian on different approaches, and flared approaches. The conflict method simplifies the intersection capacity analysis. It improves the reliability of the techniques used to assess the condition of unsignalized intersection.

The key parameter for the conflict method is the occupation time, $t_{B,q}$. It is the time spent by a vehicle for occupying the conflict area. Brilon and Wu (2002) used the term $t_{B,q,m}$ and $t_{B,q,i}$ alternatively to describe the occupancy time of vehicles at the conflict area. Another parameter to be considered in the conflict method is the blocking time of conflict area due to approaching vehicle, $t_{B,a}$. Thus, the objectives of this study are to determine the $t_{B,q}$ of vehicle, and to evaluate the performance of the unsignalized intersection based on the occupation time values.

Here introduce the paper, and put a nomenclature if necessary, in a box with the same font size as the rest of the paper. The paragraphs continue from here and are only separated by headings, subheadings, images and formulae. The section headings are arranged by numbers, bold and 10 pt. Here follows further instructions for authors.

2. Methodology

Two T-intersections in Parit Buntar, Perak has been selected for this study. Parit Buntar Town intersection is labelled as Intersection A, while Jalan Sekolah intersection shall be Intersection B. Both intersections have atypical layout with the combination of shared lane and flared approach. Surveillance equipment is used during field observation. The video capture contains information such as the traffic volume for each stream, the time taken by vehicles to occupy the conflict area, and the approaching time of major vehicles. Traffic count is conducted beforehand to identify the peak hour for suitable observation period.

The values of approaching and occupation time are determined with VDET, a time-marking computer software. When using this software, driver behavior should be taken into consideration. For instance, some drivers did not completely stop their vehicles at the minor street, but gradually approached the intersection (Gattis and Low, 1998). To maintain consistency, the occupation time of the subject vehicle is taken from the point where it is fully stopped until its back bumper clears the conflict area. If the subject vehicle travels without being blocked, the occupation time is measured from the moment it crosses the stop line until it completely enters its destination approach.

According to Brilon and Wu (2002), a conflict group consists of several movements that cross the same area within an intersection. Generally, the capacity of a minor stream is expressed by Eq. (1). On the other hand, the proportion of time spent by discharging vehicle in the conflict area is calculated using Eq. (2). The conflict area can be blocked by the approaching vehicles of higher priority. The proportion of time the approaching vehicle is blocking the conflict area is defined by Eq. (3).

$$C_m = C_{\max,m} \cdot p_0 \tag{1}$$

where,

C_m=Capacity of movement m [veh/h]

$C_{\max,m}$=Maximum possible capacity of movement m [veh/h]

$=\left(\dfrac{3600}{t_{B,q,m}}\right)$

$t_{B,q,m}$=Occupation time of movement m [s]

p_0=Pr(no blockage) [-]

$$B_{q,m} = \frac{Q_m \bullet t_{B,q,m}}{3600} \tag{2}$$

where,

Q_m=Traffic demand of movement m [veh/h]

$t_{B,q,m}$=Occupation time of movement m [s]

$B_{q,m}$=Proportion of occupancy by discharging vehicle m [-]

with the restriction of $Q_m \cdot t_{B,q,m} \leq 3600$

$$B_{a,m} = \frac{Q_m \bullet t_{B,a,m}}{3600} \tag{3}$$

where,

$t_{B,a,m}$=Approaching time of movement m [s]

$B_{a,m=}$ Proportion of period the conflict area is blocked by approaching vehicle m [-]

The probability p_0 can also be computed as the product of the probability whereby the conflict area is not occupied by standing or discharging major vehicles, and the probability that the approaching major vehicles are not occupying the conflict area. It is computed using Eq. (4). This study focuses on the T-intersection, shown in Fig. 1. The capacity of each movement is computed with Eq. (5) until Eq. (10).

$$p_0 = p_{0,q} \cdot p_{0,a} \tag{4}$$

where,

p_0=Pr (no blockage) [-]

$p_{0,q}$=Pr (no discharging of major stream vehicles [-]

$p_{0,a}$=Pr (no approaching major vehicles) [-]

and

$$C_2 = C_{\max,2} \tag{5}$$

$$C_3 = C_{\max,3} \cdot (1-B_{q,5}) \cdot (1-B_{q,4}) \cdot \exp[-(B_{a,5}+B_{a,4})] \tag{6}$$

$$C_4 = C_{\max,4} \tag{7}$$

$$C_5 = C_{\max,5} \tag{8}$$

$$C_7 = C_{\max,7} \cdot (1-B_{q,5}) \cdot \exp[-(B_{a,5})] \tag{9}$$

$$C_9 = C_{\max,9} \cdot [1-(B_{q,5}+B_{q,3})] \cdot (1-B_{q,2}) \cdot \exp[-(B_{a,5}+B_{a,3}+B_{q,2})] \tag{10}$$

After the actual capacity is determined, the effective occupation time is calculated using Equation (11). A comparison can be made between the capacity values measured using the conflict method and the HCM 2000 for result validation. In HCM 2000, the performance of unsignalized intersection is indicated by the control delay, which is also applicable for the conflict method (Brilon and Miltner, 2005)

$$t_{B,q,m}{}^* = \frac{3600}{C_m} \tag{11}$$

where,

$t_{B,q,m}{}^*$= Effective occupation time of movement m [s]

C_m= Capacity of movement m [veh/h]

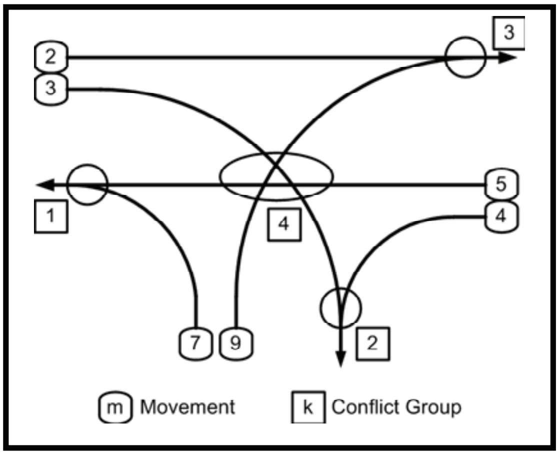

Fig. 1. Conflict groups at a T-intersection

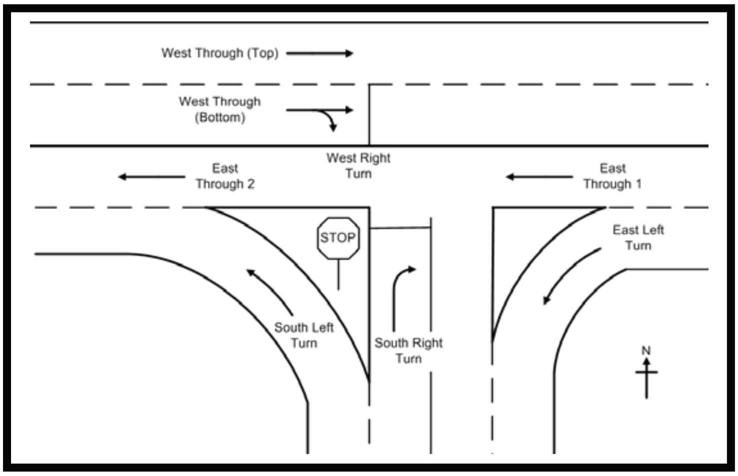

Fig. 2. Vehicular movements of intersection B

3. Results and discussion

3.1. Occupation time of vehicular movements

Intersection A. Table 1 shows the occupation time for each movement at Intersection A. South left-turning vehicles have the lowest $t_{B,q}$ for turning movement. The travel distance between the south and west approaches is the shortest. The vehicles are able to cross the intersection faster. As a result, the occupation time of this turning stream is reduced.

The west right-turning movement has conflict with two movements of higher priority. Being the high-priority movement itself, the west right-turning vehicles have a small $t_{B,q}$. However, the occupation time of this vehicular stream is higher than the south left-turning movement due to the longer travel distance between approaches. Nevertheless, the margin between $t_{B,q}$ of both movements is less significant. It indicates the high travel speed of the west right-turning vehicles when entering the south approach. This is hypothetical since there is no direct measurement of vehicular speed being taken.

Table 1. Occupation time of vehicular movement at intersection A

Vehicle Movement	Occupation Time (s)
South Left Turn	2.02
South Right Turn	4.85
West Right Turn	2.44
West Through (Bottom)	1.96
West Through (Top)	1.83
East Through	1.94
East Left Turn	1.64

Table 2. Occupation time of vehicular movement at intersection B

Vehicular Movement	Occupation Time (s)
South Left Turn	2.52
South Right Turn	4.42
West Right Turn	2.58
West Through (Bottom)	1.35
West Through (Top)	1.29
East Through 1	1.12
East Through 2	1.2
East Left Turn	2.0

The highest $t_{B,q}$ is achieved by the south right-turning movement. This movement has the lowest priority among other vehicular movements. The vehicles have to pass through two conflict areas. The conflict areas contain three major streams of different directions. The south right-turning movement also has the farthest travel distance to cross the conflict areas.

The bottom lane of the west through movement is shared with the west right-turning movement. Therefore, both lanes of the west approach are separated for data analysis. The observation of Intersection A showed the tendency of the south drivers to commit forced gap when entering the intersection. Drivers using the west through lane are cautious of the incoming vehicles from the south approach. The $t_{B,q}$ of the bottom lane indicates lower vehicular speed, contrary to the top lane of the west through movement.

The top lane of the west through movement is less affected by conflicting vehicles. This lane is located away from the conflict area. Apparently, the vehicles can travel at higher speed. However, the $t_{B,q}$ of both lanes of the west through movement is almost equal. The east through movement is located next to the west through bottom lane. Both vehicular streams are in the same conflict group. Thus, their occupation times are comparable.

On the other hand, the east left-turning movement has the lowest $t_{B,q}$ of all movements. This movement has the highest priority, and shorter crossing distance. Furthermore, the east left-turning movement has a separate lane, thus allowing the vehicles to occupy the conflict area in a small time interval only.

Intersection B. Intersection B is channelized to improve its performance, especially on turning movements. Therefore, the west right turn vehicles have a short distance to cross the conflict area. On the other hand, the south left turn vehicles have a separate lane for left turn maneuver. However, the occupation times of both vehicular streams are nearly equivalent, as shown in Table 2. Apparently, they are blocked by the same movement from the east approach.

The $t_{B,q}$ of the south left turn movement is more than the occupation time of the same movement at Intersection A. The larger conflict area at the west approach of Intersection B have caused the increase of the $t_{B,q}$ of the south left-turning movement. The channelization of traffic streams at Intersection B has no influence on the occupation time of the west right-turning vehicles. The value of its $t_{B,q}$ is almost similar to the west right-turning movement of Intersection A.

It is evident that the south right turn movement has the highest $t_{B,q}$. Compared to Intersection A, the channelization of Intersection B movements has reduced its occupation time by a small margin. Nonetheless, the south right-turning movements of both intersections are comparable due to similar traffic conflicts. The west approach has two lanes. The bottom through lane is shared with the right turn lane. However, the difference of $t_{B,q}$ values between the top and bottom lanes of the west through movement is insignificant. The shared lane does not impede the movement of the west through bottom vehicles. Similar result is achieved for Intersection A. It is due to the unsaturated condition of both intersections.

Intersection B has a divided south approach. The left turn and right turn of the south approach is separated to increase the capacity of both movements. This condition has created a space in between the turning lanes. Consequently, two streams of east through vehicles are produced. In the east approach, the second through movement has higher $t_{B,q}$ than its first through stream due to larger conflict area. It is also caused by the continuous deceleration of vehicles after leaving the intersection. The occupation times of both through streams are low due to the short travel distance between approaches.

The east left-turning movement is supposed to produce small occupation time. In the case of Intersection B, large conflict area has caused this traffic stream to produce a high $t_{B,q}$, although it has a separate lane. Besides, drivers are being cautious of the incoming vehicles from the west approach, and eventually reduced their vehicular speed.

3.2. Capacity of vehicular movements

Intersection A. Fig. 3 shows the volume and capacity of the turning movements at Intersection A. The capacity values of these movements are expected to be lower than the major stream capacities. It is due to the impeding major vehicular movements. The subject vehicles have to cross the conflict areas when entering the intersection. The volume and capacity of major movements at Intersection A are given in Fig. 4. The south left turn stream has the highest capacity among other turning movements, which is the outcome of having a separate lane. The recorded occupation time of this movement is also the lowest. As a result, the south left-turning lane is able to cater more vehicles.

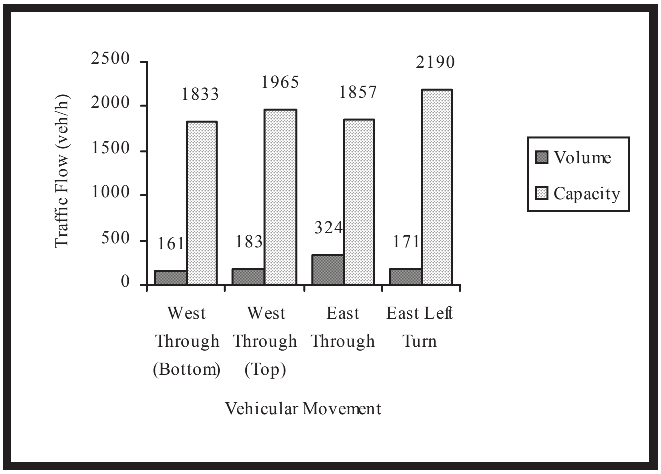

Fig. 3. Volume and capacity of turning movements at intersection A

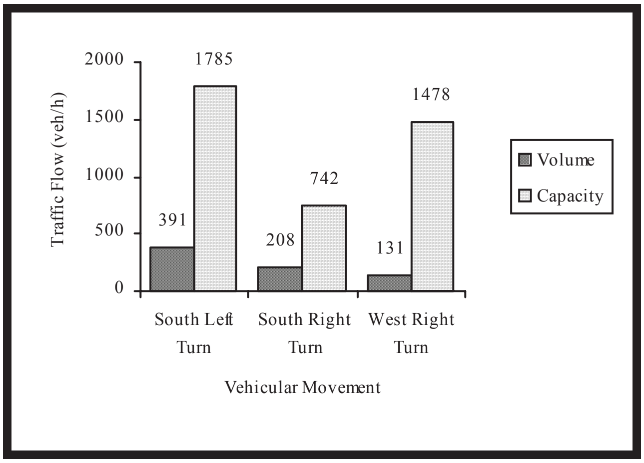

Fig. 4. Volume and capacity of major movements at intersection A

There are three impeding vehicular streams that are blocking the south right turn movement. Besides, its occupation time is the highest among other turning movements. Due to the blocking major movements and high $t_{B,q}$, the south right-turning movement has the lowest capacity. The west right turn movement has similar priority with the south left turn stream. However, there is a vast difference between its volume and capacity values.

The major movements have absolute priority over the turning streams. Conflict areas do not obstruct the major street vehicles. In addition, the major streams have low occupation time. Therefore, they are expected to have higher capacity. It is evident in Fig. 4.

The east left-turning stream has the highest capacity due to the exclusive lane. It provided more space for the vehicles, and reduced traffic conflict. The shared lane condition of the west through bottom movement has minimal impact on its capacity.

Intersection B. In Intersection A, the capacity difference between the south left turn and the west right turn streams is noticeable. However, the volume and capacity of both movements of Intersection B are almost similar. The site investigation has revealed that the south approach is leading towards schools. During peak hour, the traffic movements between the south and west approaches have produced such result, as shown in Fig. 5.

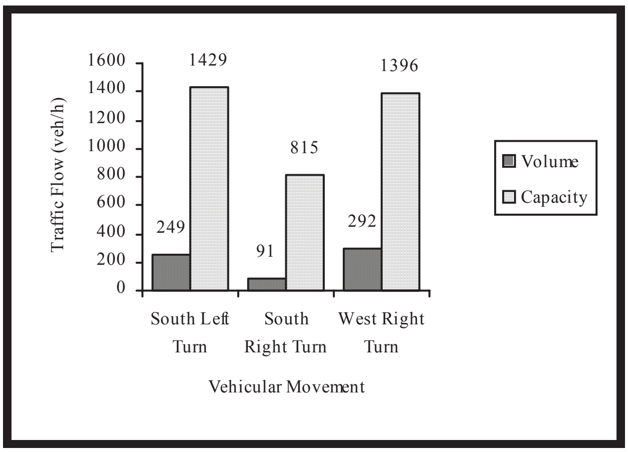

Fig. 5. Volume and capacity of turning movements at intersection B

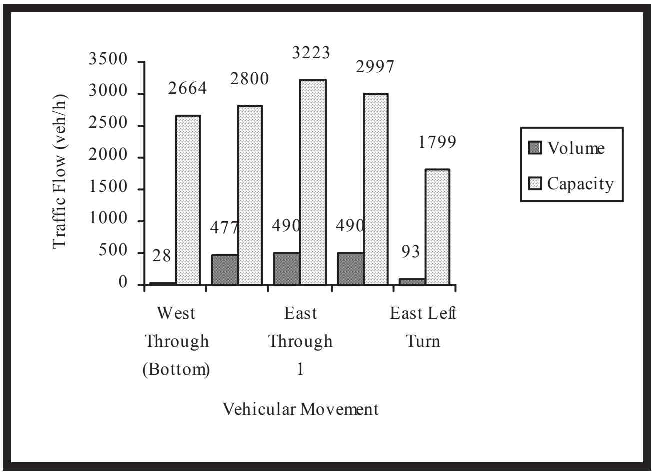

Fig. 6. Volume and capacity of major movements at intersection B

The south right turn stream is predicted to have the lowest capacity. In the case of Intersection B, there is improvement over the same movement of Intersection A. The intersection area is smaller, thus reducing the travel distance from the south approach to the east approach.

For west approach, although the bottom lane is shared, the capacity difference between west through and right turn movements is small. The traffic volume of the west through bottom lane is the lowest. This lane is mostly occupied by the west right-turning vehicles. Consequently, the drivers prefer the top lane of the west approach for through movement. Thus, the traffic volume at the top lane is more than the bottom lane, as shown in Fig. 6.

The east through stream is analyzed separately due to the geometry condition of Intersection B. In this case, the minimum capacity value is selected for the east through movement. The second through movement has less capacity than the first through stream because of its larger $t_{B,q}$. Therefore, the second capacity value of 2997 veh/h is chosen to determine the control delay of the east through movement.

The least capacity of major movement is achieved by the east left-turning stream. It is due to the larger conflict area. Similar to the west right-turning movement, the drivers of the east left turn stream are being cautious of the incoming vehicles from west approach.

3.3. Control delay and level of service (LOS)

Intersection A. In this study, every movement of Intersection A is analyzed separately. Table 3 shows the control delay and level of service of all vehicular movements at Intersection A. Based on the results obtained, the performance of each movement is satisfactory with LOS A. However, the south right turn stream has achieved LOS B. It is due to the amount of major movements that are blocking its pathway. This factor has caused the increase in control delay. There is no significant variation of control delay between other movements. The difference of control delay between the turning movement and the major streams could be apparent if the intersection is channelized.

Intersection B. Based on Table 4, the channelized Intersection B has mixed results. Obviously, the turning movements have higher control delay than the major streams. The south left turn stream and the west right-turning movement have higher control delay than their counterpart in Intersection A. On the other hand, the south right turn movement has lower control delay than similar stream of Intersection A. The channelization of vehicular movements has reduced the control delay of all major through streams. Nonetheless, all vehicular streams achieved LOS A.

Table 3. Level of service of vehicular movements at intersection A

Vehicular Movement	Control Delay (s/veh)	LOS
South Left Turn	7.58	A
South Right Turn	11.73	B
West Right Turn	7.67	A
West Through (Bottom)	7.15	A
West Through (Top)	7.02	A
East Through	7.35	A
East Left Turn	6.78	A

Table 4. Level of service of vehicular movements at intersection B

Vehicular Movement	Control Delay (s/veh)	LOS
South Left Turn	8.05	A
South Right Turn	9.97	A
West Right Turn	8.26	A
West Through (Bottom)	6.37	A
West Through (Top)	6.55	A
East Through	6.44	A
East Left Turn	7.11	A

3.4. Capacity comparison of turning movements

Intersection A. The capacity comparison between the conflict method and the HCM 2000 procedures for turning movements is shown in Fig. 7. The field data is obtained from data collection on site. The given data is based on the parameter values stated in the HCM 2000 (TRB, 2000).

Apart from the HCM 2000 with given data, the capacity values of the vehicular movements at the south approach are almost similar. However, the west right turn stream capacity has noticeable difference between each method.

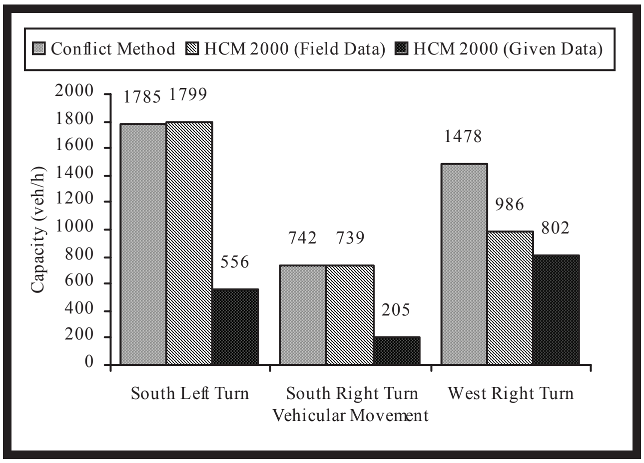

Fig. 7. Capacity comparison of turning movements at intersection A

Table 5. Comparison between tB,q and tc,field of the south movements at Intersection A

Vehicular Movement	$t_{B,q}$ (s)	$t_{c,field}$ (s)
South Left Turn	2.02	2.3
South Right Turn	4.85	3.1

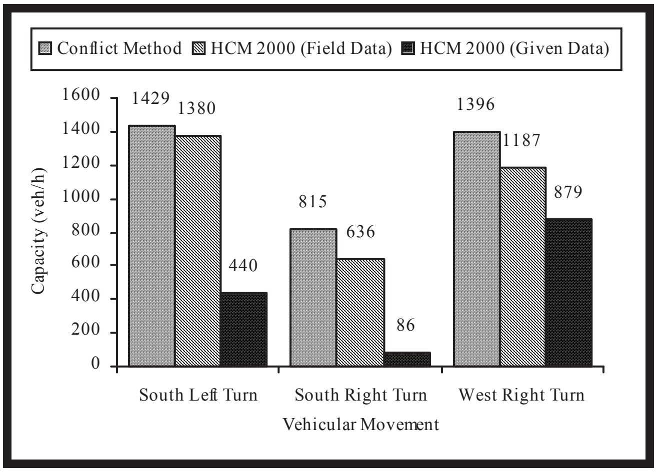

Fig. 8. Capacity comparison of turning movements at intersection B

Table 6. Comparison between tB,q and tc,field of the turning movements at intersection B

Vehicular Movement	tB,q (s)	tc,field (s)
South Left Turn	2.52	3.0
South Right Turn	4.42	3.3
West Right Turn	2.58	3.2

For the south turning streams, the comparison between the occupation time and the critical gap using field data is given in Table 5. Apparently, both the $t_{B,q}$ and $t_{c,field}$ values of the south turning movements are also comparable. In this case, both parameters are directly proportional to one another.

Intersection B. As in intersection A, the HCM 2000 method using given data has underestimated the turning stream capacity values, according to Fig. 8. The south right-turning movement has the worst capacity of 86 veh/h, which is illogical. This anomaly is likely due to software issue during data analysis. The $t_{B,q}$ and $t_{c,field}$ values obtained with both methods are compared in Table 6. The occupation time and the critical gap are shown to be inversely proportional to the capacity, except for the south right turn movement. Small value of $t_{B,q}$ indicates that more vehicles can cross the conflict area, thus increasing the capacity. Similarly, the capacity values are also raised when vehicles have small critical gap.

3.5. Control delay and LOS comparison of turning movements

Intersection A. The control delays analyzed with different methods are shown in Figure 9. The LOS comparison for turning movements is given in Table 7. Apparently, the worst control delay is determined by HCM 2000 with given data. The control delay readings obtained using the conflict method and the HCM 2000 with field data is almost equal. Thus, the south turning movements have similar LOS.

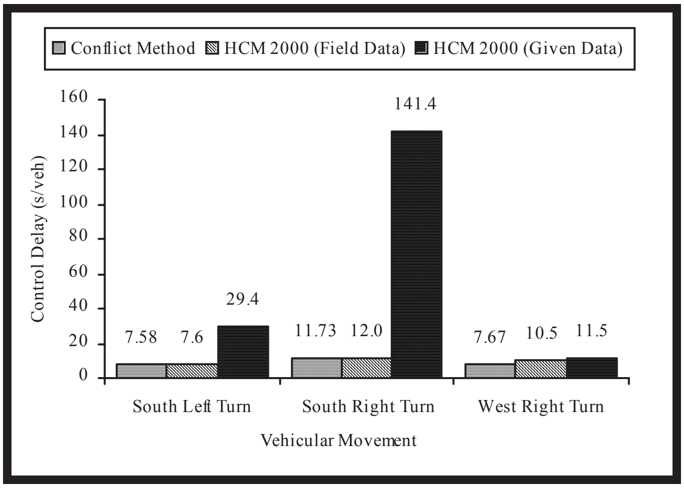

Fig. 9. Comparison of control delay between turning movements at intersection A

Table 7. LOS comparison for turning movements at intersection A

Vehicular Movement	LOS		
	Conflict Method	HCM 2000 (Field Data)	HCM 2000 (Given Data)
South Left Turn	A	A	D
South Right Turn	B	B	F
West Right Turn	A	B	B

Intersection B. The conflict method and the HCM 2000 with field data have provided control delay with comparable values for the turning movements. The HCM 2000 with given data has clearly overestimated the control delay of the south right turn vehicular stream. It is shown in Fig. 10. The conflict method indicates that all turning movements at Intersection B have the highest performance with LOS A. It almost matches the performance level indicated by the HCM 2000 with field data, as presented in Table 8.

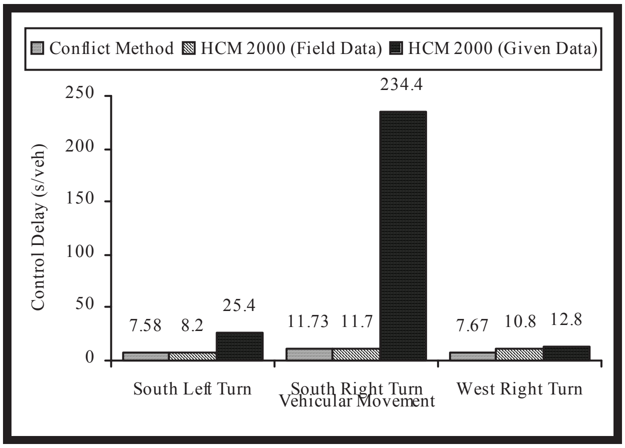

Fig. 10. Comparison of control delay between turning movements at intersection B

Table 8. LOS comparison for turning movements at intersection B

Vehicular Movement	LOS		
	Conflict Method	HCM 2000 (Field Data)	HCM 2000 (Given Data)
South Left Turn	A	A	D
South Right Turn	A	B	F
West Right Turn	A	B	B

4. Conclusions

Different methods have been developed to analyze the unsignalized intersection. Among them, the gap-acceptance method is the dominant approach. It is adopted by many countries in their capacity manuals. The gap-acceptance method has a simple concept. It depends on the driver's decision to accept or reject a gap before committing the vehicular manoeuvre.

However, there are drawbacks to this approach, such as non-compliance to the priority rules. Efforts have been made to improve the reliability of the unsignalized intersection analysis. Conflict method is proposed to assist the current methods available. It is based on the interaction between vehicular movements that created conflict areas in the intersection. According to the results from the data analysis, the following conclusions can be made:

The occupation time is inversely proportional with the capacity of the vehicular movement. Small occupation time indicates that more vehicles are able to cross the conflict area in a given time period, and vice-versa. It can also provide the estimation of the vehicular speed when crossing the intersection.

Long duration of occupation time is achieved due to slow-moving vehicles, large intersection area, and multiple blocking major streams. It increases the delay of the vehicular movement, thus degrades its LOS.

Based on the results obtained from the analysis of the intersections, their performance can be concluded as follows:

Both intersections are indicated as undersaturated, which conform to the field observation.

The exclusive lane for turning movement is capable to reduce the delay of vehicular stream. However, it still depends on the vehicular speed, and the traffic volume. On the other hand, the shared lane does not always impede the movement of turning streams, provided that the traffic volume is low.

Comparison with the HCM 2000 by using field data has shown promising outcome. The conflict method is verified as capable to assist the gap-acceptance approach. With data calibration, better results can be expected.

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