Performance of Non-priority Intersections Under Mixed Traffic Conditions Based on Conflict Streams Analysis

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Abstract Conflict method is regarded as a viable solution for the drawbacks in the gap-acceptance approach. It has been used for the capacity analysis of unsignalized intersections, which includes the two-way stop-controlled, and the all-way stop-controlled types. This method is now applied for the capacity estimation of vehicular streams at a non-priority intersection, where gap-forcing, poor lane discipline, violation of priority rule, and heterogeneous traffic co-exist. However, there are some issues encountered when applying the conflict method for non-priority intersection analysis, particularly with the occupation time and heterogeneous traffic. The concepts developed for capacity estimation have considered the blocking effect from all possible conflicting streams. Therefore, the additional concept with volume portion, $P_{n,i}$ is introduced. The probability of non-blocking traffic streams and the portion

of consumed shared capacity by the subject stream are analyzed. The portion concept, $P_{n,i}$ provided a more realistic estimation. The proposed approaches generated high capacity values, even though the observed intersections have near-saturation traffic. A high percentage of small vehicles occupied the lateral lane space, which is permitted by gap-forcing and poor lane discipline, apart from their smaller footprint.

Keywords Mixed traffic · Unsignalized intersection · Conflict streams · Capacity

Introduction

The capacity estimation of unsignalized intersection is based on several rules related to gap acceptance and empirical approaches [1], which are the main components in the Highway Capacity Manual (HCM 2000) [2]. These approaches are valid for traffic condition where stream hierarchy exists, and the drivers comply with the enforced rules. This condition does not necessarily exist in developing countries (e.g. Indonesia). The efficiency of the unsignalized intersection is hampered by poor lane discipline with the presence of heterogeneous traffic [4].

Therefore, the shortcomings of the previous methods led to the development of the conflict method. Wu [6] applied this new approach for all-way stop-controlled (AWSC) intersections, hence negated the need for iterative steps of computation. It was later modified by Brilon and Wu [7] for two-way stop-controlled (TWSC) intersections, which expanded the probability concept of non-blocking vehicular streams within conflict groups. Further research by Li et al. [8] had incorporated mixed traffic condition into the intersection analysis. Based on previous findings [8], the

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effect of blocking streams in multilane approaches have also been explored [9]. However, current studies conduct the analysis based on the common rules of priority that does not exist in most developing countries.

Therefore, by using occupation time, Prasetijo et al. [5] had established the relationship between capacity and vehicular speed under the heterogeneous traffic with no-priority. The current conflict method developed by Wu [1] is used for intersections where priority rule exists, and under non-saturated traffic condition. Furthermore, this study utilized the streams behavior of intersections where a vehicular stream can be blocked by all possible conflicting streams under near-saturation traffic condition. The portion of shared capacity was also introduced. This scenario caused actual traffic conflicts between vehicles, which produced the actual total volumes. Thus, this study considers such situation in its attempt to apply the conflict method for capacity estimation under mixed traffic conditions of non-priority intersections.

Traffic Condition at Non-priority Intersections

In developing countries, the first-in-first-out (FIFO) intersection is widely used. Without absolute stream priority, it is considerably similar to AWSC operation [4]. Congestion will occur when traffic streams with high volumes approach the intersection simultaneously. In heterogeneous traffic, motorized vehicles such as two-wheelers, rickshaws, cars, buses, and light and heavy trucks are mixed with non-motorized vehicles that include bicycles, pedicabs, and pushcarts.

The motorized and non-motorized vehicles have different static and dynamic characteristics [10]. Traffic conflicts that are incurred by these vehicles can decrease the intersection capacity. The near-saturation traffic condition impedes vehicular speed between vehicle modes, although motorized vehicles are typically fast-moving. Reduced gap between vehicles is expected under this occurrence.

Some drivers are intimidated by the combination of high traffic volume and slow-moving vehicles. It creates the urgency to cross the intersection quicker to avoid being trapped in a long delay. Therefore, these drivers will attempt to leave the conflict areas faster. This behavior promotes gap-forcing, especially among aggressive road users [11]. While there are various levels of gap-acceptance, drivers are willing to accept smaller gaps in near-saturation traffic conditions. In fact, a previous study on traffic condition in Indonesia revealed that two-thirds of vehicles crossed the intersection without waiting for gaps, and the average critical gap was less than two seconds [13].

Vehicles are typically driven closer to the center of the road lane to avoid collision with other vehicles on the adjacent lane. This circumstance is almost non-existent in heterogeneous traffic, resulting in poor lane discipline. It is caused by factors such as uneven lateral positioning of vehicles across the carriageway, partial usage of road shoulder as traffic lane, poor road surface and markings, and inadequate lane width [3].

However, if small vehicles utilize the lateral lane space, near-saturation traffic condition could have adverse effect on intersection capacity. Contrary to homogeneous traffic, heterogeneous traffic can occupy the lane space and road geometric efficiently (Figs. 1, 2, 3 and 4). Ironically, this situation can only be permitted by the lack of lane discipline in heterogeneous traffic. The combination of gap-forcing behavior with poor lane discipline could allow higher traffic volume and capacity, even though these factors may disrupt the rhythm of traffic streams. On the downside, the drivers do not always remain in a particular lane. Therefore, it is difficult to analyze each lane in multilane approaches.

Basic Concept of Conflict Method

In an AWSC intersection, all vehicular streams have equal priority in departure sequence in Fig. 5. On the other hand, the major streams have higher priority over the minor streams in a TWSC intersection [12]. Vehicles of different streams shall cross the intersection alternatively. These streams create a conflict area (Fig. 5). Each vehicle will take an amount of time to cross the conflict area. This time period is known as occupation time, $t_{o,i}$. It is a key parameter in the conflict method. The occupation time is defined as the period whereby a vehicle occupies the

Fig. 1 Three-legs intersection 1

Fig. 2 Layout intersection 1 **Fig. 3** Three-legs intersection 2

conflict area. It was measured by counting the time arrival between consecutive vehicles at the arrival lines (reference lines at every leg of intersections).

A vehicular stream may be blocked by different streams (Fig. 5). The conflicting streams not only increase the $t_{o,i}$ of the subject stream, but they also reduce its capacity.

Therefore, the probability of conflicting streams not blocking the subject stream, $P_{u,i}$ must be considered.

Capacity Analysis for Non-priority Intersections

Generally, the operation of a non-priority intersection is similar to AWSC intersection in terms of stream hierarchy, which is equal for all vehicular streams. In the case of a non-priority intersection, more than one vehicular stream cross the intersection simultaneously. This study presents two possible concepts to estimate the capacity values of all streams at the intersection.

Probability Concept for Non-priority Intersection Analysis

The first concept is based on the idea of probability by Li et al. [8]. The blocking effect of conflicting streams at the entry, center, and exit of conflict areas are considered. The layout of the conflict areas are shown in Fig. 5. Table 1 shows the interaction between vehicular streams. In a

Fig. 4 Layout intersection 2

Fig. 5 Layout of a four-leg intersection

situation where there is no waiting vehicle at the intersection (vehicles are constantly moving), the blocking effect due to approaching vehicle is not present.

The uninterrupted subject traffic stream has a maximum capacity, $C_{\max,i}$. A subject vehicle can only cross the conflict area if it is not occupied by other vehicles from

conflicting streams. The actual capacity of the subject stream is determined by considering the non-blocking proportion of the conflicting streams. A general expression of capacity is shown as follows:

$$C_i = C_{\max,i} \cdot P_{u,i} \quad (1)$$

Table 1 Interaction of vehicular streams in conflict groups

Subject stream	Entry Streams involved	Center Streams involved	Exit Streams involved
1	2,3	–	5,9
2	1,3	5,9,11,12	6,10
3	1,2	5,6,8,12	7,11
4	5,6	–	8,12
5	4,6	2,3,8,12	1,9
6	4,5	3,8,9,11	2,10
7	8,9	–	3,11
8	7,9	3,5,6,11	4,12
9	7,8	2,6,11,12	1,5
10	11,12	–	2,6
11	10,12	2,6,8,9	3,7
12	10,11	2,3,5,9	4,8

(–) No vehicular stream involved

where C_i = Capacity of stream i (veh/h), $C_{\max,i}$ = Maximum capacity of stream i (veh/h), $= \frac{3600}{t_{o,i}}$, $t_{o,i}$ = Occupation time of stream i (s), and $P_{u,i}$ = Proportion of non-blocking stream i .

The proportion of conflicting stream not blocking the subject stream is shown as follows:

$$P_{u,i} = 1 - \left(\frac{Q_i \cdot t_{o,i}}{3600} \right) \quad (2)$$

where $P_{u,i}$ = Proportion of non-blocking stream i , Q_i = Traffic volume of stream i (veh/h), and $t_{o,i}$ = Occupation time of stream i (s).

By taking into consideration the non-blocking streams at the entry, center, and exit conflict area, the general expression of capacity of the subject stream can be derived as follows:

$$C_i = C_{\max,i} \cdot \prod_{i \in D_{k,E_i}} P_{u,E_i} \cdot \prod_{i \in D_{k,C_i}} P_{u,C_i} \cdot \prod_{i \in D_{k,F_i}} P_{u,F_i} \quad (3)$$

where P_{u,E_i} = Proportion of unblocking stream i at entry conflict area, P_{u,C_i} = Proportion of unblocking stream i at center conflict area, P_{u,F_i} = Proportion of unblocking stream i at exit conflict area, k = Number of conflict group pertaining to stream i , and D_k = Set of conflicting streams in the conflict group k .

Therefore, the actual capacity can be determined for the respective vehicular streams.

$$C_1 = C_{\max,1} \cdot \{ (P_{u,E2} \cdot P_{u,E3}) \cdot (P_{u,F5} \cdot P_{u,F9}) \} \quad (4)$$

$$C_2 = C_{\max,2} \cdot \{ (P_{u,E1} \cdot P_{u,E3}) \cdot (P_{u,C5} \cdot P_{u,C9} \cdot P_{u,C11} \cdot P_{u,C12}) \cdot (P_{u,F6} \cdot P_{u,F10}) \} \quad (5)$$

$$C_3 = C_{\max,3} \cdot \{ (P_{u,E1} \cdot P_{u,E2}) \cdot (P_{u,C5} \cdot P_{u,C6} \cdot P_{u,C8} \cdot P_{u,C12}) \cdot (P_{u,F7} \cdot P_{u,F11}) \} \quad (6)$$

$$C_4 = C_{\max,4} \cdot \{ (P_{u,E5} \cdot P_{u,E6}) \cdot (P_{u,F8} \cdot P_{u,F12}) \} \quad (7)$$

$$C_5 = C_{\max,5} \cdot \{ (P_{u,E4} \cdot P_{u,E6}) \cdot (P_{u,C2} \cdot P_{u,C3} \cdot P_{u,C8} \cdot P_{u,C12}) \cdot (P_{u,F1} \cdot P_{u,F9}) \} \quad (8)$$

$$C_6 = C_{\max,6} \cdot \{ (P_{u,E4} \cdot P_{u,E5}) \cdot (P_{u,C3} \cdot P_{u,C8} \cdot P_{u,C9} \cdot P_{u,C11}) \cdot (P_{u,F2} \cdot P_{u,F10}) \} \quad (9)$$

$$C_7 = C_{\max,7} \cdot \{ (P_{u,E8} \cdot P_{u,E9}) \cdot (P_{u,F3} \cdot P_{u,F11}) \} \quad (10)$$

$$C_8 = C_{\max,8} \cdot \{ (P_{u,E7} \cdot P_{u,E9}) \cdot (P_{u,C3} \cdot P_{u,C5} \cdot P_{u,C6} \cdot P_{u,C11}) \cdot (P_{u,F4} \cdot P_{u,F12}) \} \quad (11)$$

$$C_9 = C_{\max,9} \cdot \{ (P_{u,E7} \cdot P_{u,E8}) \cdot (P_{u,C2} \cdot P_{u,C6} \cdot P_{u,C11} \cdot P_{u,C12}) \cdot (P_{u,F1} \cdot P_{u,F5}) \} \quad (12)$$

$$C_{10} = C_{\max,10} \cdot \{ (P_{u,E11} \cdot P_{u,E12}) \cdot (P_{u,F2} \cdot P_{u,F6}) \} \quad (13)$$

$$C_{11} = C_{\max,11} \cdot \{ (P_{u,E10} \cdot P_{u,E12}) \cdot (P_{u,C2} \cdot P_{u,C6} \cdot P_{u,C8} \cdot P_{u,C9}) \cdot (P_{u,F3} \cdot P_{u,F7}) \} \quad (14)$$

$$C_{12} = C_{\max,12} \cdot \{ (P_{u,E10} \cdot P_{u,E11}) \cdot (P_{u,C2} \cdot P_{u,C3} \cdot P_{u,C5} \cdot P_{u,C9}) \cdot (P_{u,F4} \cdot P_{u,F8}) \} \quad (15)$$

Portion Concept for Non-priority Intersection Analysis

The shared lanes capacity of each stream at unsignalized intersections are determined by using capacity of shared lane, C_{sh} that was developed by Wu [6]. However, this considers that the traffic flows are saturated, which does not exist in non-priority intersections. Therefore, the second concept of analysis was introduced as another possible way to evaluate the intersection. At non-priority intersections, vehicles tend to shift lanes via gap-forcing, which causes poor lane discipline. It is not possible to analyze lanes individually. Thus, vehicular streams in the subject approach are treated as sharing streams (Fig. 6). The portion of subject stream at the entry of the conflict area is then considered. For example, the shared lane capacity, C_{sh} at Conflict Group 1 is distributed among the three sharing streams before the subject stream 2 passes through the other conflicting streams (Fig. 7).

The equation to determine the shared lane capacity is based on the case study by Wu [6], is given as follows:

$$C_{sh} = \frac{Q_L + Q_T + Q_R}{X_L + X_T + X_R} \quad (16)$$

where C_{sh} = Capacity of shared lane (veh/h), Q_L = Traffic volume of left-turning stream (veh/h), Q_T = Traffic volume of through stream (veh/h), Q_R = Traffic volume of right-turning stream (veh/h), x_L = Degree of saturation for left-turning stream, x_T = Degree of saturation for through stream, and x_R = Degree of saturation for right-turning stream.

Equation 16 provides the maximum capacity to be distributed among the sharing streams. Before determining the capacity of the subject stream, its portion from the shared lane capacity should be calculated. It is simply determined as follows:

$$P_{n,i} = \frac{Q_i}{Q_{sh}} \quad (17)$$

where $P_{n,i}$ = Volume portion of subject stream i , Q_i = Volume of subject stream i (veh/h), and Q_{sh} = Total volume of the sharing streams (veh/h).

To compute the subject stream capacity, C_i , Eq. 3 can be modified to take into account the shared lane condition, as follows:

$$C_i = C_{sh} \cdot P_{n,i} \cdot \prod_{i \in D_{k,C_i}} P_{u,C_i} \cdot \prod_{i \in D_{k,F_i}} P_{u,F_i} \quad (18)$$

Data Collection and Capacity Comparison

Data Collection

The concepts developed for capacity estimation were applied to two T-intersections with single lanes in Pontianak, Indonesia. Video camcorders were used to observe the traffic streams, as well as driver behavior. For each T-intersection, observations were made during peak hours within a one-hour period. These intersections were similar in terms of traffic performance and geometric design.

Fig. 6 Sharing streams at the subject approach

Fig. 7 Subject stream (Stream 2) with its sharing and conflicting streams

Pedestrians were not considered in this studies because the numbers were very low and in most of the cases, pedestrians crossed the intersection from any section of the lanes only when appropriate gaps were available. Therefore, a subject vehicle is more likely to be blocked by other vehicles instead of pedestrians. The arrival and departure points at the respective exit and entry of each approach were marked beforehand for occupation time measurement. Recorded videos were analyzed with a time-code machine to obtain the arrival and departure times of vehicles at the marked points. For comparison purpose, the Indonesian Highway Capacity Manual (IHCM) [13] was utilized as the baseline for capacity estimation. The IHCM evaluates traffic performance based on the total capacity values of all streams only.

Capacity Comparison

Traffic compositions at Intersection 1 and 2 are shown in Table 2. It shows eight categories of vehicles that consist of motorized and non-motorized transport, with motorcycles making up the highest portion. The capacity values of Intersection 1 are presented in Table 3, while Table 4 shows the capacity values of Intersection 2. It should be noted that before the passenger car unit (PCU) conversion, Intersection 1 and Intersection 2 had a total volume of 4902 veh/h (vehicles per hour) and 3725 veh/h, respectively. Based on the comparison of results, the probability concept yielded higher capacity values than the portion concept. This outcome is due to the difference in the consideration of conflicting streams. For the first approach, all traffic streams were assumed to have equal blocking effect. In this regard, the sharing streams at the subject

Table 2 Traffic composition

Traffic composition	Intersection 1 (veh/h)	Intersection 2 (veh/h)
Truck 2 axle	49	30
Minibus	20	–
Car	358	238
Motorcycle	4260	3285
Bicycle	201	160
Rickshaw	10	–
Tricycles	–	3
Pushcart (2-wheels)	5	3

Table 3 Capacity values of intersection 1

Stream	Volume (pcu/h)	Capacity (pcu/h)		
		Concept 1	Concept 2	IHCM
2	1300	2538	2139	–
3	351	757	396	–
4	227	1211	988	–
6	61	530	128	–
7	59	1493	150	–
8	643	1444	1373	–
Total	2642	7973	5174	3393

(–) Data unavailable

Table 4 Capacity values of intersection 2

Stream	Volume (pcu/h)	Capacity (pcu/h)		
		Concept 1	Concept 2	IHCM
2	377	1705	1309	–
3	108	713	251	–
4	124	1489	554	–
6	373	1771	1267	–
7	474	2082	1205	–
8	516	1685	1085	–
Total	1972	9445	5671	2704

(–) Data unavailable

approach have no significance over the conflicting streams from other approaches.

However, the second concept acknowledged the blocking effect of the sharing streams. Since lane discipline was poor, the subject stream was already in conflict with its sharing streams. This was reflected by the reduction in the total capacity of both intersections. On the other hand, the capacity estimation using IHCM provided degrees of saturation of 0.78 and 0.73 for Intersection 1 and Intersection 2, respectively. While IHCM has the likely results when compared with field observations, the method is still

based on priority rule, which has been violated by the drivers. Therefore, after considering the traffic condition at these intersections, the capacity values obtained using Concept 2 seems more realistic. The results showed that both concepts produced high capacity values for the vehicular streams, although the traffic observed is almost saturated. This is caused by the high percentage of small vehicles crossing the intersection (above 90 %).

Occupation Time of Vehicular Streams

The value of $t_{o,i}$ is recorded based on the uninterrupted stream of the subject stream. It is essentially the time taken to cross the conflict areas without any blocking stream. After the probability values of non-blocking streams are accounted, the actual stream capacity is produced. Thus, the actual occupation time can be determined by a simple equation as follows:

$$t_{oA,i} = \frac{3600}{C_i} \quad (19)$$

where $t_{oA,i}$ = Actual occupation time of stream i (s), and C_i = Capacity of stream i (veh/h).

The $t_{oA,i}$ obtained from Eq. 19 is true if the volume, Q_i of a vehicular stream reaches its C_i . It is also indicated as the delay at the first position in the queue [4]. The $t_{o,i}$ and the $t_{oA,i}$ values for vehicular streams of both intersections are given in Tables 5, 6. Obviously, each vehicular stream in the observed intersections has different values of occupation time. Thus, a set of values for occupation time that can represent the streams in general, as proposed by Brilon and Miltner [12] cannot be suggested. In fact, the variation of $t_{o,i}$ values between the through and turning streams proves the absence of absolute priority at these intersections. The through streams do not necessarily produce small occupation time, and the turning streams occasionally cleared the conflict areas faster. The occupation time generated depends on the vehicular speed, and the amount of vehicles that enter the intersection within a time interval.

Table 5 Occupation time of streams at intersection 1

Stream	$t_{o,i}$ (s)	$t_{oA,i}$ (s)	
		Concept 1	Concept 2
2	1.12	1.42	1.68
3	1.87	4.76	9.09
4	2.01	2.97	3.64
6	2.02	6.79	28.13
7	1.38	2.41	24.0
8	1.68	2.49	2.62

Table 6 Occupation time of streams at intersection 2

Stream	$t_{o,i}$ (s)	$t_{oA,i}$ (s)	
		Concept 1	Concept 2
2	1.72	2.11	2.75
3	2.43	5.05	14.34
4	1.71	2.42	6.5
6	1.17	2.03	2.84
7	1.29	1.73	2.99
8	1.36	2.14	3.32

Issues with Occupation Time and Estimated Capacity

Previous findings [5] have given insight on the occupation time. It is deemed as not practical to measure $t_{o,i}$ values directly from field observations, due to the uncertainty of the starting and ending points of each vehicle's occupation time. This study has proven that although the conflict areas have been defined, it is difficult to determine the exact spot where traffic conflict occurs. It is possible for the subject vehicle to be blocked suddenly while crossing the intersection. Consequently, a range of occupation time values is produced.

The occupation time is recorded when the subject stream is not blocked by vehicles from different streams. However, in a near-saturation traffic condition at non-priority intersections, all vehicular streams are already obstructing each other. In other words, when attempting to collect the data of occupation time, the blocking effect of the conflicting streams has been accounted. The $t_{o,i}$ values obtained from the observed intersections could actually be used directly in the capacity estimation. This is possible without considering the probability of non-blocking streams, $P_{u,i}$ and calibration of $t_{o,i}$. The results from capacity estimation without the $P_{u,i}$ component are presented in Tables 7, 8. Evidently, higher capacity values were obtained when $P_{u,i}$ was not included in capacity calculation.

From the series of capacity analyses, two aspects have influenced the outcome of this study, which are:

- The product of traffic volume and occupation time for all vehicular streams can potentially surpass the restriction posed by Brilon and Wu [1]. In an hour, all vehicles are able to consume more than 3600 s of crossing time when using the intersection. This is possible if the lane discipline is poor, and the lateral lane space is occupied by small vehicles. Two-wheelers such as motorcycles can travel side-by-side in the same time interval. This

Table 7 Capacity values of intersection 1 without probability component

Stream	Volume (pcu/h)	Capacity (pcu/h)		
		Concept 1	Concept 2	IHCM
2	1300	3214	2215	–
3	351	1925	599	–
4	227	1791	1412	–
6	61	1782	377	–
7	59	2609	183	–
8	643	2143	1992	–
Total	2642	13,374	6778	3393

(–) Data unavailable

Table 8 Capacity values of intersection 2 without probability component

Stream	Volume (pcu/h)	Capacity (pcu/h)		
		Concept 1	Concept 2	IHCM
2	377	2093	1490	–
3	108	1481	427	–
4	124	2105	688	–
6	373	3077	2071	–
7	474	2791	1299	–
8	516	2647	1415	–
Total	1972	14,194	7390	2704

(–) Data unavailable

occurrence explained the abnormally high capacity values obtained from the capacity estimation.

- When analyzing mixed traffic conditions, there are different types of vehicles that require specific PCU. For this study, the IHCM provided the PCU for both motorized and non-motorized vehicles. Apparently, vehicles of the same class may have different sizes and occupied areas, thus making the PCU values generalized. Moreover, the PCU stipulated in most capacity manuals are derived based on homogeneous traffic concepts [14].

Conclusions

This paper presents the concepts that are possible for the analysis of unsignalized intersections with no priority rule, poor lane discipline, and gap-forcing behavior among drivers in a heterogeneous traffic condition. The first approach considers the probability of non-blocking vehicles of sharing and conflicting streams. In the second concept,

portion of shared lane capacity at the subject approach is determined before considering the probability of non-blocking vehicles from conflicting streams. The latter concept is found to be more suitable for capacity estimation in near-saturation traffic condition. Both concepts produced high capacity values, although the traffic is almost saturated. This is due to violation of lane discipline and forced gap, which allowed small vehicles such as motorcycles to occupy the lateral lane space. The occupation time caused problems in the capacity estimation, apart from the PCU values used. It is measured under the condition where the blocking effect took place when the vehicles cross the intersection. In addition, it is difficult to identify the exact point where traffic conflicts actually occur, due to multiple streams being mixed together in the conflict areas simultaneously. Therefore, the conflict method requires some modifications before it can be utilized for unsignalized intersections without priority control. For future research, the interval between arrival times of vehicles at the intersection can be used to replace the occupation time. The arrival time is marked when the sharing streams are about to exit the subject approach before moving to their destination approaches. Furthermore, it is suggested to use PCU that is derived based on heterogeneous traffic concepts, such as the occupied area by vehicle.

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