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Field study on the behavior of right-turning vehicles in Malaysia and their contribution on the safety of unsignalized intersections

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ABSTRACT

Behavior of right turning vehicles in the context of safety is characterized by their use of turning indicators and compliance with the stop rule. They are influence by the width of the carriageway and the variation in volume on the major road with respect to the traffic moving in the near and far side direction. Other factors affecting the behavior are the speed and spacing between vehicles moving on the major road. Lack of adequate past knowledge on the effect of geometric variation in terms of road width and directional variation in volume on the safety of unsignalized intersections have provided the motivation for this study. This paper focuses on the many factors that affect the behavior of right-turning vehicles resulting into conflicts. A brief account of the unique indigenous maneuver termed as the "Weaving Merging Right Turn" (WMRT) is provided and its effectiveness with respect to conventional right turn is evaluated. Data of 39,016 vehicles collected on 10 sites between January and June 2014 was analyzed. Multiple accidents were observed only on sites which had near side traffic volume greater than far side traffic volume. This result remains consistent with sites having single as well as multiple lanes per direction on the major roads. The number of conflicts for vehicles performing the WMRT was 2.5 times less as compared to the conventional right turn. Moreover WMRT was found to be the maneuver of choice for right turning motorcyclists with 60% of them opting for it over the conventional right turn on intersections having major road width less than 9 m. None of the motorcyclists, which were involved in a traffic conflict, were observed to use their turning indicator. Moreover none of the motorcyclists, which experienced a traffic conflict, were found to comply with the stopping rule at sites with major road width less than 9 m. On sites with major road width greater than 9 m, 45% of motorcyclists, involved in a traffic conflict, complied with the stopping rule as compared to 79% by vehicles other than motorcycles.

1. Introduction

Behavior of vehicles making a right-turn (or left-turn in countries where traffic follows the right-hand rule) onto the major road in particular, and any other maneuver in general, at unsignalized intersections is characterized by their compliance with the stop rule (Kodsi & Muttart, 2009; Kosaka et al., 2007; Muttart et al., 2011; Pradhan et al., 2005), use of turning

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indicator (Abdul Manan, 2014a), aggressive driving or force merging (Kaysi & Abbany, 2007; Kaysi & Alam 2000) and making indigenous maneuvers such as the Opposite Indirect Right Turn (Abdul Manan, 2014a). Their safety is often measured in terms of conflicts occurring between them and the major road vehicles (Abdul Manan, 2014b; Caliendo & Guida, 2012; Li et al., 2011; Sayed & Zein, 1999; Sayed, Brown, & Navin, 1994).

Unsignalized intersections in Malaysia are the probable sources where accidents occur. A study on primary roads of Malaysia has identified the number of access points or unsignalized intersections per kilometer to be one of the factors affecting motorcycle fatalities per kilometer (Abdul Manan, Jonsson, & Várhelyi, 2013). They pose threats to both minor as well as major road traffic because of their general poor visibility, inappropriate sight distance, lack of traffic control devices, and illegal encroachment by mobile car shops and vendors. Most of them lie on single carriageways at unsuitable locations like adjacent to bus bays, point of activities and other signalized intersections. This makes them the most potential spots for incidents to occur. They are more hazardous as compared to signalized intersections because of their higher fatality rates (Subramanian & Lombardo, 2007). Anomalous behaviors of minor road vehicles contribute further in the reduction of safety.

This paper sets out to investigate the many factors affecting the behavior of right turning vehicles and to evaluate their contribution to the safety of unsignalized intersections in the context of geometric and traffic variations. Lack of adequate past knowledge on the effect of difference in volume moving in opposite direction and difference in road width along the major approach on the safety of unsignalized intersections and the behavior of right turning vehicles provided the motivation for this study. The primary objective of this paper is to report the naturalistic behavior indigenous to Malaysian right-turning vehicles. First the anatomy of the unique right-turning maneuver termed as the "Weaving Merging Right Turn (WMRT)" is explained. Then the effect of traffic characteristics such as volume, speed and gap between vehicles in the context of variation in major road width pertinent to Malaysian traffic conditions is analyzed. The approach proposed by Abdul Manan (2014a) is adopted for investigating the behavior of right-turning vehicles. Their safety, measured in terms of number of conflicts, is explored with respect to two different domains. The first is the movement type which is the conventional right-turn and the weaving merging right-turn and the second is the major road width which is less than 9 m and greater than 9 m.

1.1. Previous work

Traffic behavior has intrigued many researchers and dates as far back as the 1930s (Greenshields, 1934). Past researches related to the behavior of traffic at unsignalized intersections were primarily focused toward the context of gap acceptance. Probit analysis of lag or gap acceptance by minor road drivers' was performed by Solberg and Oppenlander (1965). The effect of major road speed was explored by Hansson et al. (1978). Increase in the number of accepted lags and gaps at stop controlled as compared to yield controlled intersections were identified as the probable cause of increase in the number of accidents observed with the change of control levels by Polus (1985). Later investigations reported that the decision to accept or reject a gap was dependent upon traffic volume and the arrival pattern of vehicles on the major road (Akcelik, 1994). Effects of number of lanes and the presence of median on the major road for the estimation of intersection mean critical gap was presented by Hamed, Easa, and Batayneh (1997). Stopping behavior of motorcycles and car drivers was reported by Muttart et al. (2011). In a heterogeneous traffic environment the behavior of traffic is characterized by non-lane-based car following (Gunay, 2007) with no lane discipline (Arasan & Koshy, 2005). The vehicles move freely on any available part of the carriageway cutting the corners, creating negligible lateral and longitudinal spacing between vehicles. Thus the parameters such as lateral and longitudinal gap between vehicles serve as a parameter for the measurement of traffic heterogeneity (Arasan & Koshy, 2005).

The concept of 'Traffic Conflicts' was introduced in 1960s by Perkins and Haris (1967) as a surrogate measure of safety. The technique was extensively explored by Hydén (1987) who suggested 'Time to accident' and 'Conflicting speed' for the measurement of traffic conflicts while Parker Jr. and Zegeer (1989) suggested a simpler definition in which an evasive maneuver made by a road user to avoid a collision is recorded as a conflict. It has been reported in the literature that Traffic conflicts have been simulated (Cooper & Ferguson, 1976; McDowell, Wennell, Storr, & Darzentas, 1983; Sayed et al., 1994; Caliendo & Guida, 2012) as well as measured in the field (Abdul Manan, 2014a; Sayed & Zein 1999) at unsignalized intersections by previous researchers. A very detailed analysis of the influence of speed on crashes and conflicts occurring at unsignalized intersections was presented by Spek, Wieringa, and Janssen (2006). Volume and Speed have been reported as important factors affecting safety at unsignalized intersections in past studies (Haleem & Abdel-Aty, 2010; Haleem, Abdel-Aty, & Mackie, 2010). It was found in a recent study (Abdul Manan, 2014a) that vehicles that make a right-turning maneuver from minor to major road, at unsignalized intersections in Malaysia, experience more conflicts as compared to left turning vehicles (Note: Malaysians drive on the left side of the road). Being more prone to accidents, the behavior of right turning vehicles are greatly influenced by the volume of traffic of the major road traffic stream. A study on 1036 junctions in Denmark has proven volume to be the most significant parameter influencing number of accidents on signalized as well as unsignalized intersections (Greibe, 2003). Although extensive work has been done on examining the effect of volume on the safety of unsignalized intersections but the variation in volume with respect to near and far side has been neglected and the effect of this variation on crash frequency has not been explored. Analysis of major road width has also been seldom evaluated in previous behavioral studies. In a recent research by Ahmed, Sadullah, and Shukri Yahya (2014) it has been identified as a very important geometric parameter responsible for the reduction of safety at unsignalized intersections.

2. Method

The procedures and methods used in this study are presented in this section. The first subsection explains the procedure of site selection for traffic data collection. The subsequent subsections explain how traffic data was collected and behavioral observations were made respectively.

2.1. Site selection

This study was conducted in the state of Penang located in the North West part of Peninsular Malaysia. The sites selected for this study were based on their geometrical conformity and accident history. All sites selected for data collection were three-leg uncontrolled intersections located on undivided roadways with no median or channelizing islands and experienced at least one crash during the last ten years that is from 2006 to 2015. The crash data was obtained from Malaysian Institute of Road Safety Research (MIROS). Since observing the effect of geometric variation was part of the objectives of the study, therefore the total width of the major approach carriageway varied between 7 and 15 m. All sites selected conform to the criteria of having equal number of lanes in each direction on the major approach. The major road contained painted single or double line lane marking in the middle to separate the traffic moving in the opposite direction. All sites selected were of uniform traffic control with the major and minor road vehicles being able to make both left and right turns. Each site selected represented a "typical" unsignalized intersection in Malaysia, with no channelizing islands or auxiliary lanes to restrict the movement or guiding the path of the turning vehicles respectively. The traffic mix was diversified containing different percentages of motorcycles and other vehicles. Table 1 shows the details of the 10 sites selected. All sites conform to the characteristics previously explained.

2.2. Traffic data collection

Traffic data at all sites was collected using MetroCount® MC5600 data loggers. All data collected was with respect to the direction of travel of vehicles near or far from the minor road. The data was collected during peak hours from 6:30 a.m. to 9:30 a.m. on all sites. The volume, speed and longitudinal gap size of vehicles whose direction of travel is near to the point where the minor road merges with the major road were classified as near side volume, speed and longitudinal gap sizes respectively. The traffic parameters for the vehicles travelling in the opposite direction of near side vehicles were classified as far side volume, speed and longitudinal gap sizes respectively. The major roads on all sites had either single lane per direction or multilane per direction. Therefore, the data was segregated further with respect to road width and traffic mix. Fig. 1(a) shows the layout of typical intersections on sites with major road widths less than 9 m and greater than 9 m respectively. Fig. 1(b) shows the location of traffic camera and the rubber tubes fixed on the road to record the behavioral and traffic data simultaneously.

The data recorded by MetroCount® MC5600 data loggers were transferred to the computer. The software accompanied with the equipment delivers the output in the form of a spread sheet containing the time stamp, type of vehicle, direction of travel, speed and distance from the preceding vehicle (that is the longitudinal gap) for each vehicle crossing the tube. The equipment was placed in such a manner that it captures the speed of the turning vehicles exactly at the point when they clear the conflict area of the intersection. Mean speed, volume and longitudinal gap between vehicles for all sites were calculated and statistically analyzed.

2.3. Behavioral observations

Behavioral observations were made with respect to the movement of minor road vehicles using video camera. Their movement was recorded as they complete their maneuver from the beginning of their entrance onto the major road to

Table 1
Site characteristics.

Site number	Speed limit (km/h)	Total road width (m)	Lane marking	Traffic mix (%)		Collision type	Vehicles involved
				Motorcycle	Others		
1	70	15	Single	21	79	4(1)	Motorcycle and car
2	70	14.5	Single	21	79	2(1), 4(2), 12(1)	Motorcycle and car in all collision types
3	70	14.5	Double	23	77	4(1)	Motorcycle and lorry
4	70	13.5	Double	39	61	4(1)	Motorcycle and car
5	70	12	Double	28	72	4(1)	Motorcycle and car
6	70	11	Single	39	61	1(1)	Motorcycle and car
7	60	13.4	Single	33	67	1(1), 3(1), 4(2)	Motorcycle and car in all collision types
8	60	7.5	Single	51	49	5(1)	Motorcycle and Motorcycle
9	70	8.3	Single	28	72	4(2)	Motorcycle and car
10	60	7.1	Single	66	34	4(1)	Motorcycle and car

The numbers in the brackets represent accident frequency (from 2006 to 2011).
Collision type: 1 = Head On, 2 = Rear End, 3 = 90°, 4 = Angular or Side, 5 = Side Swipe and Out of Control.

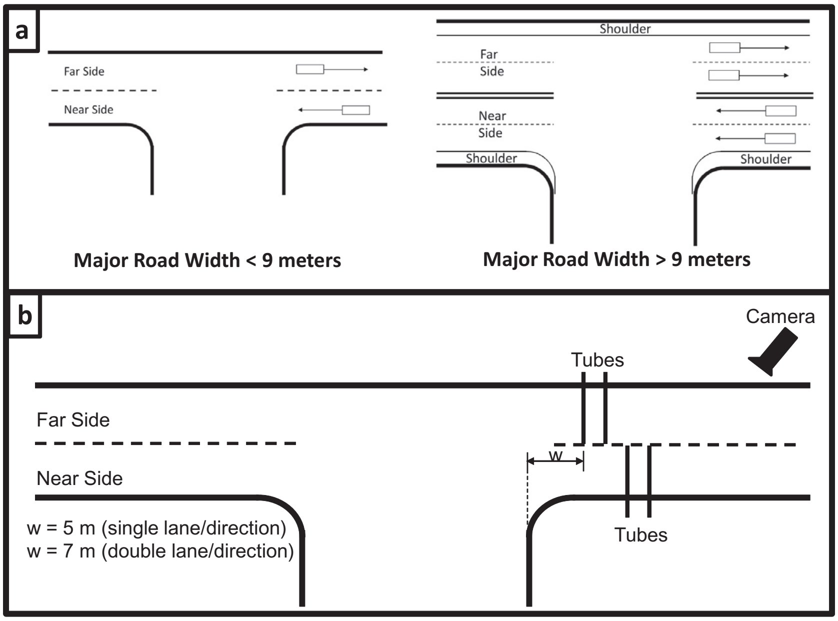

Fig. 1. (a) Typical layout of Intersections having major road width less than nine meters and greater than nine meters (note: Malaysia is a country with left-hand traffic), (b) location of road tubes and camera for data recording.

the point where they merge with the major traffic stream. The video recordings were made during peak hours from 6:30 a.m. to 9:30 a.m. for all sites. A total of 30 h of data was recorded. The camera was located at such a position so as to capture the movement of minor road vehicle from the start of its trajectory, before leaving the stop line, to the end of its maneuver when it finally merges with the major road traffic. The movement of major road traffic with respect to the turning vehicles was also recorded.

Eight different behavioral observations were made on six sites. These observations were made specifically for vehicles involved in a traffic conflict. First the stopping behavior of minor road vehicles was observed. All minor road vehicles are required to stop before entering the major road as per traffic rules. Stopping at the stop line, whether it is present or not, helps assess the situation at the intersection. It enables a driver to make a better judgment regarding major stream vehicles' speed, gap availability and size. Therefore, it was important to observe whether turning vehicles were stopping or not, before making a maneuver. The second behavior observed was the use of turning indicator. Turning indicators send message to approaching major road vehicles about the maneuver that the turning vehicle is about to make. It makes the major stream driver cautious and helps reduce accidents. It was observed whether the minor vehicles switched on their indicators before the start of their trajectory and kept them flashing until they complete their maneuver. A gap accepted by the minor road vehicle was the third behavior to be observed. Fourth behavioral observation was the 'gap' immediately rejected by the vehicle before the one accepted. The speed of the minor vehicle as soon as it clears the conflict area of the intersection and the speed of the major vehicle following it were the fifth and sixth behavioral observations respectively.

The minor road vehicles were found making a unique right turning maneuver that involved turning onto the major road and travelling further in the direction of turning until they merge with the major stream traffic. This particular maneuver, which was very different from the conventional right turn, was named as the "Weaving Merging Right Turn (WMRT)". Fig. 2 illustrates the difference between WMRT and conventional right-turn. In a conventional right-turn the driver performs three tasks simultaneously. It turns, accelerates the vehicle rapidly and looks behind. While in WMRT these three tasks are performed stepwise. The driver first turns, then accelerates while he moves in the direction of turning and then merges with the main stream traffic by looking back. By making WMRT the complex task of making a right-turn is converted into a simple merging task. This gives WMRT preference over conventional right-turn in terms of driver comfort.

The seventh observation was related to the vehicles making or not making the WMRT. The final behavior which was observed was the 'conflict' between a minor road vehicle and the major road vehicle(s). A similar study on unsignalized intersections (Caliendo & Guida, 2012) has strongly highlighted the effectiveness of traffic conflicts over traffic volume in the prediction of actual accidents. A conflict is defined as "…. an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision." (Parker & Zegeer, 1989). The Swedish traffic conflict technique (TCT) (Hydén, 1987) was referred for the classification of conflicts. For the purpose of this study all incidents in which one of the two road vehicles involved was required to stop, to avoid a collision, were termed as serious conflicts. The rest of the incidents in which the major road vehicle slowed down, applied brakes, or changed its course to avoid collision were classified as potential conflicts.

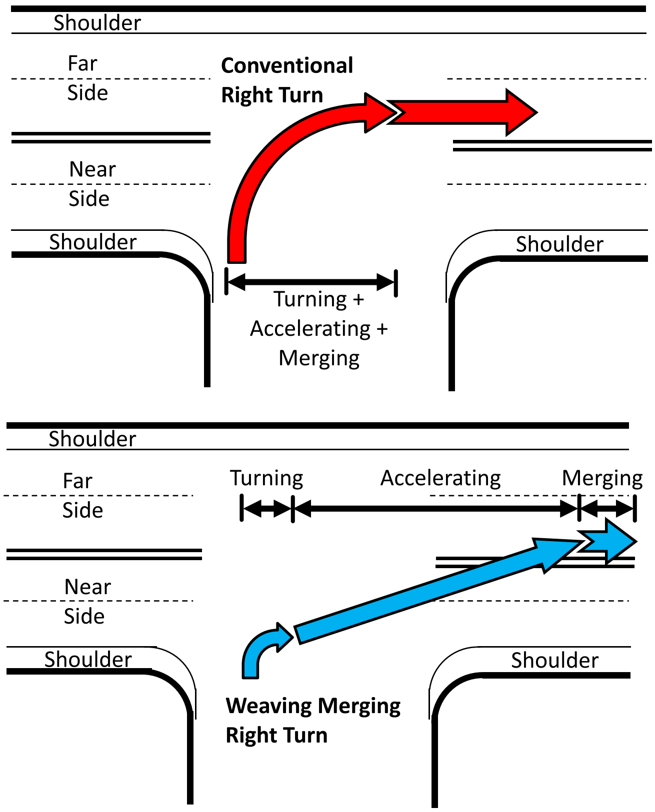

Fig. 2. Weaving Merging Right Turn (WMRT) and Conventional Right Turn.

3. Results

3.1. Volume

Volume is a measure of exposure and therefore quite significant in influencing the number of accidents occurring at any intersection. For this study through volume was classified with respect to its proximity to the minor road. The direction of flow near to the minor road was termed as 'near side' volume while the other one, which is in opposite direction, was termed as 'far side' volume. The ratio between the near and far side volume, for all sites, was calculated and classified with respect to major road width. Multiple accidents were observed only on sites having near/far ratio greater than one. This result remained consistent for all sites irrespective of their width classification as shown in Table 2.

Further analysis of the traffic mix of vehicles on all sites was performed. The volume was broadly classified into two groups, namely motorcycles and other vehicles. Independent sample *t*-test of all sites having width less than 9 m showed no significant difference between the volume of motorcycles and other vehicles (p-value > 0.05). Contrary to it sites having width greater than 9 m indicated significant difference between the volume of motorcycles and other vehicles (p-value < 0.01). The total volume of other vehicles on sites with wider major roads was almost three times higher as compared to motorcycles as shown in Table 3. On sites with narrower major roads the difference in total volume between motorcycles and other vehicles was only 0.03 times, that is, other vehicles were almost equal in numbers as compared to motorcycles. On an average sites on wider major roads had more volume as compared to sites on narrower major roads. As a result higher numbers of accidents were observed on sites having wider major roads as compared to sites having narrower major roads, as shown in Table 2.

3.2. Speed

Speeds of all vehicles travelling on the 10 sites were recorded. Their average is shown in Table 4. On all sites the mean speeds of vehicles were found to be lower than the speed limit except motorcycles travelling on the far side of site 8. Even on this site the mean speed is almost equal to the speed limit mentioned on the road. The difference in the mean speeds between motorcycles and other vehicles was found to be statistically insignificant as per the results of independent sample *t*-test ($p > 0.05$). These findings remained consistent on all sites irrespective of their major road widths and direction of

Table 2
Near/far volume ratio with respect to major road width.

Major road width	Site number	Volume		Minor	Total	Near/far ratio	No. of accidents
		Near side	Far side				
Greater than 9 m	1	4287	2251	96	6634	1.90	1
	2	3860	2271	81	6212	**1.70**	**4**
	3	2409	4171	27	6607	0.58	1
	4	1984	1304	24	3312	1.52	1
	5	1761	2491	253	4505	0.71	1
	6	1612	1842	51	3505	0.88	1
	7	1450	1337	14	2801	**1.08**	**4**
Less than 9 m	8	992	2322	10	3324	0.43	1
	9	712	354	80	1146	**2.01**	**2**
	10	446	521	3	970	0.86	1

Note: The values represent the total volume collected during peak period i.e. from 6:30 to 9:30 a.m.
Multiple accidents observed only on sites having near/far ratio greater than one.

Table 3
Volume with respect to type of vehicle.

Major road width	Site number	Volume motorcycle			Volume others		
		Near side	Far side	Total	Near side	Far side	Total
Greater than 9 m	1	211*	256*	468	539*	1173*	1712
	2	179*	257*	436	578*	1029*	1607
	3	224*	277*	502	579*	1113*	1692
	4	193*	238*	431	242*	423*	665
	5	156*	241*	397	431*	590*	1021
	6	234*	219*	453	380*	319*	699
	7	137*	166*	303	309*	317*	626
	Total	1334	1655	2990	3057	4963	8022
	Average	191	236	427	437	709	1146
Lesser than 9 m	8	409	160	569	365	171	536
	9	62	36	98	176	82	257
	10	116	95	211	58	54	111
	Total	586	291	878	599	306	904
	Average	195	97	293	200	102	302

* Statistically significant difference between the volume of motorcycles and other vehicles, according to *t*-test ($p < 0.01$).

Table 4
Mean speeds (km/h) of different vehicles on all sites.

Site number	Near side		Far side		Overall		Average
	MC	Others	MC	Others	MC	Others	
Speed on sites less than 9 m major road							
8	54.9	56.4	60.61	58.31	57.76	57.36	57.56*
9	27.35	33.78	31.14	30.95	29.25	32.37	30.81*
10	20.47	17.93	27.86	23.05	24.17	20.49	22.33*
Speed on sites greater than 9 m major road							
1	40.61	34.12	39.96	38.12	40.29	36.12	38.20*
2	39.71	40.84	45.78	50	42.75	45.42	44.08*
3	42.68	42.62	44.78	43.83	43.73	43.23	43.48*
4	32.66	33.56	34.77	36.19	33.72	34.88	34.30*
5	26.02	22.25	31.46	28.6	28.74	25.43	27.08*
6	43.47	46	37.3	37.87	40.39	41.94	41.16*
7	38.35	43	38.24	39.87	38.3	41.44	39.87*

* Statistically significant difference between the average speeds on sites less than 9 m and greater than 9 m, according to *t*-test ($p < 0.05$).

travel. This indicates that the speeding behavior of motorcycles remain uninfluenced by other vehicles on all types of roads. This also indicates that the direction of travel has no effect on the motorcycle speeds on all sites. Comparing the average speeds of all vehicles among narrower and wider roads, that is, between sites having major road width less than 9 m and greater than 9 m; it was found that vehicles tend to travel on higher speeds on wider roads as compared to narrower roads. The difference was statistically significant as per the results of independent sample *t*-test ($p < 0.05$). This indicates that wider roads encourage the vehicles to travel faster as compared to narrower roads.

Fig. 3 shows the speed profile of motorcycles with respect to the direction of travel for all sites having width greater than 9 m. The 85th percentile speeds of motorcycles on all sites were found to be lower than the speed limit imposed at the major road. This result remains valid irrespective of the direction of travel. A maximum of 1.2% of all motorcycles were found to be travelling above the speed limit on all sites except site 2 and 7 at which only 2% and 3% of motorcycles exceeded the speed limit of 70 km/h and 60 km/h respectively. The difference in slope between the near side and far side directions of the cumulative curve shown in Fig. 3 was found to be varying for almost all sites except site 5. On this site the mean speed of motorcycles travelling on the far side was found to be 5.4 km/h higher than the near side. The probable reason for this anomaly is the market entrance being served by the minor road which constantly attracts major road vehicles to stop for shopping. The difference between the lowest and the highest overall mean speeds of motorcycles was only 15 km/h indicating less variation in average speeds among motorcyclists on all sites. Among all sites the average variations in speed of motorcycles travelling in opposite directions were 3.2 km/h. The mean of average speeds on all sites on wider roads, for motorcycles travelling in both directions, was found to be 38 km/h.

The speed profile of 'Other vehicles' with respect to the direction of travel for all sites having width greater than 9 m is shown in Fig. 4. Unlike motorcycles 'Other vehicles' displayed a distinctive profile for each site. The reason for this variation could be the significant difference in traffic volume between motorcycles and other vehicles as discussed in Section 3.1. Less than 1.1% of all other vehicles were found to be travelling above the speed limit on all sites except site 2 at which only 2.9% of other vehicles exceeded the speed limit of 70 km/h. The 85th percentile speeds of other vehicles on all sites were found to be lower than the speed limit imposed at the major road. This result remains valid irrespective of the direction of travel. More variation was observed among the speed profile of other vehicles as compared to motorcycles. Because of the high variation in volume among vehicles travelling in the near and far side directions, as shown in Table 2, their speed profiles were not identical to each other. Among all sites the average variations in speed of vehicles travelling in opposite directions were 5 km/h. The difference between the lowest and the highest mean speeds of other vehicles was 28 km/h. This result indicates that there is more variation in average speeds among other vehicles, as compared to motorcycles, on all sites having major road width greater than 9 m. Surprisingly the mean of average speeds on all sites on wider roads, for other vehicles travelling in both directions, was also found to be 38 km/h.

Analogous to sites on wider roads, the mean speeds of motorcycles on sites having major road width less than 9 m were also found to be within the limits imposed on the major road. Site 8 had a distinctive speed profile as compared to the other

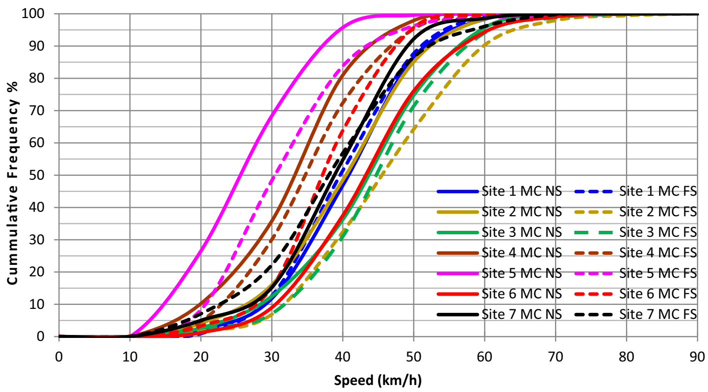

Fig. 3. Speed profile of Motorcycles (MC) travelling near/far side on greater than 9 m roads (NS: Near Side, FS: Far Side).

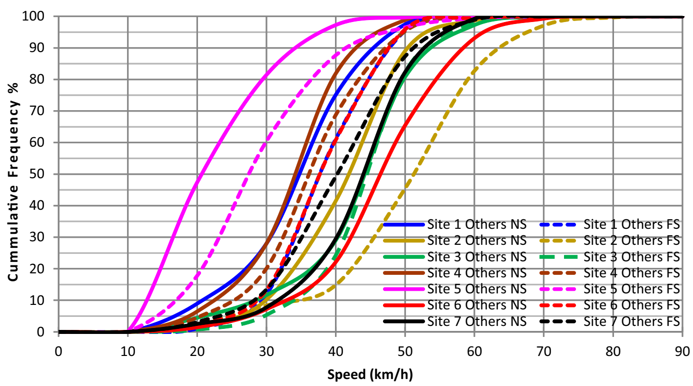

Fig. 4. Speed profile of 'Other vehicles' travelling near/far side on greater than 9 m roads (NS: Near Side, FS: Far Side).

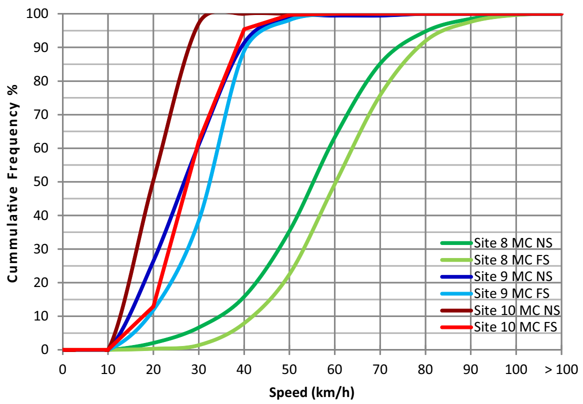

Fig. 5. Speed profile of Motorcycles (MC) travelling near/far side on less than 9 m roads (NS: Near Side, FS: Far Side).

two sites among all intersections having major road width less than 9 m, as shown in Fig. 5. The reason for this change could be the higher traffic volume as compared to the other two sites as per Table 3. Moreover there was extensive variation in traffic mix on site 8 where motorcycles constitute 51% of the total volume as shown in Table 1. This could be the other cause for higher motorcycle speeds. The cumulative speed profile of motorcycles shown in Fig. 4 indicates that the 37–51% of all motorcycles travel above the speed limit of 60 km/h on site 8. On the other two sites, 99.5% of motorcycles were found to be travelling below the speed limit. The mean of average speeds on all sites on narrower roads, for motorcycles was found to be 37 km/h which is similar to 36.25 km/h found in a study conducted in Central London (Lee, Polak, Bell, & Wigan, 2012).

Unlike motorcycles, other vehicles had three distinctive speed profiles for sites 8, 9 and 10. The probable reason for vehicles travelling at higher speeds on site 8 as compared to other vehicles could be the difference in volume. From Table 3 it can be deduced that the volume of other vehicles on site 8 was 52–80% higher as compared to site 10 and site 9 respectively. As shown in Fig. 6, the speeds of most vehicles travelling in the near side were, to a great extent, identical to the ones travelling in the far side. Dissimilar to wider roads, the speed profile of motorcycles and other vehicles, on sites with major road widths less than 9 m, were found to be identical to each other. This indicates that narrower roads provide better interrelation among vehicles as compared to wider roads. Similar to motorcycles, the mean of average speeds on all sites on narrower roads for other vehicles travelling in both directions, was also found to be 37 km/h.

3.3. Gap between vehicles

In a heterogeneous traffic environment, where the vehicles move freely along the entire width of the roadway in each direction, the longitudinal gaps between particular types of vehicles characterize their behavior. Aggregate analysis of gap size between vehicles, among sites having major road width greater than and less than nine meters, indicated that the average gap between vehicles is 5.0 s and 17.3 s respectively. The higher percentage of gap between vehicles on narrower roads is due the fact that the volume on such roads was less as compared to wider roads. To investigate further the gap sizes between vehicles were divided into two categories, which are less than or equal to 0.5 s and less than 4 s. The percentage of vehicles travelling with an average gap less than 4 s was found to be higher for sites on major roads having width greater than nine meters. This indicates that the density of vehicles is higher on wider roads as compared to narrower roads. Disaggregate

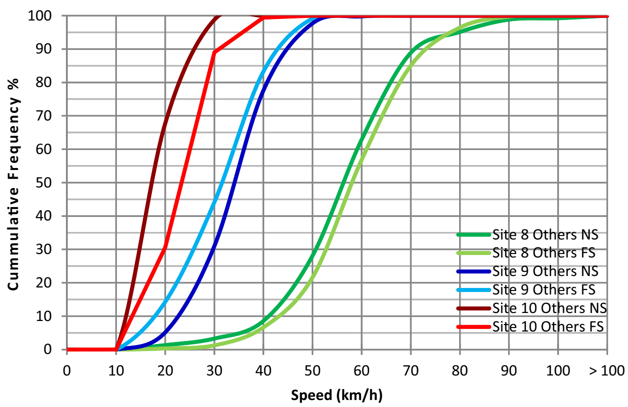

Fig. 6. Speed profile of 'Other vehicles' travelling near/far side on less than 9 m roads (NS: Near Side, FS: Far Side).

analysis with respect to vehicle type show that the gap size between motorcycles and their preceding vehicles is higher on narrower roads as compared to wider roads. It was further established that on an average motorcycles tend to keep a higher gap between them and their preceding vehicles as compared to all other vehicles. This was a contradictory finding. Therefore, analyzing further with respect to the percentage of vehicles that travel with gaps lower the 0.5 s, between them and their preceding ones, it was found that motorcycles have a higher percentage as compared to other vehicles. The result was consistent for sites with major road width less than 9 m as well as greater than 9 m as shown in Table 5. Further disaggregation with respect to travel direction indicated that the percentage of motorcycles having longitudinal gaps less than 0.5 s vary within the same site with respect to travel direction. This indicates that the car following behavior of motorcycles not only vary with respect to the width of the carriageway but also with respect to the direction of travel as shown in Fig. 7. This is an important finding. It indicates that the 'nature' of motorcyclists is to travel more close to their preceding vehicles.

3.4. Behavioral observations

3.4.1. Right turning behavior of vehicles entering the major road

Statistically significant difference was found among types of vehicles performing WMRT with respect to major road width. The percentage of motorcycles performing WMRT on narrower roads was found to be 30 times higher as compared to other vehicles, as shown in Table 6. Because of less space available on major roads having width less than 9 m, other vehicles found it difficult to perform WMRT, therefore preferred the conventional right-turn. Opposite behavior was observed on wider roads, where motorcycles preferred conventional right-turn over WMRT. As wider roads require more time to clear the

Table 5
Gap size (seconds) with respect to type of vehicles and road width.

Major road width	Site number	Motorcycle			Others			All	
		Average	% ⩽ 0.5 s	% < 4 s	Average	% ⩽ 0.5 s	% < 4 s	Average	% < 4 s
Greater than 9 m	1	3.85	7.9	73	2.8	4.5	82	3.03	80
	2	4.1	7.5	67	3.24	6.8	78	3.4	76
	3	3.95	6.9	68	2.96	5.7	80	3.2	77
	4	7.5	2.5	44	6	2	54	6.5	50
	5	6.4	2	57	4.6	1.5	69	5	66
	6	6.8	4.1	49	5.7	2.4	56	6.2	53
	7	8.95	2.4	42	7.22	3.1	52	7.8	49
	Average	5.9	4.8	57.1	4.6	3.7	67.3	5.0	64.4
Less than 9 m	8	6.78	5.23	55	6.58	3.4	55	6.68	55
	9	22.35	0.7	23	21.35	0.4	19	21.6	20
	10	24.14	0.5	28	22.12	1.1	29.1	23.5	30
	Average	17.8	2.1	35.3	16.7	1.6	34.4	17.3	35.0

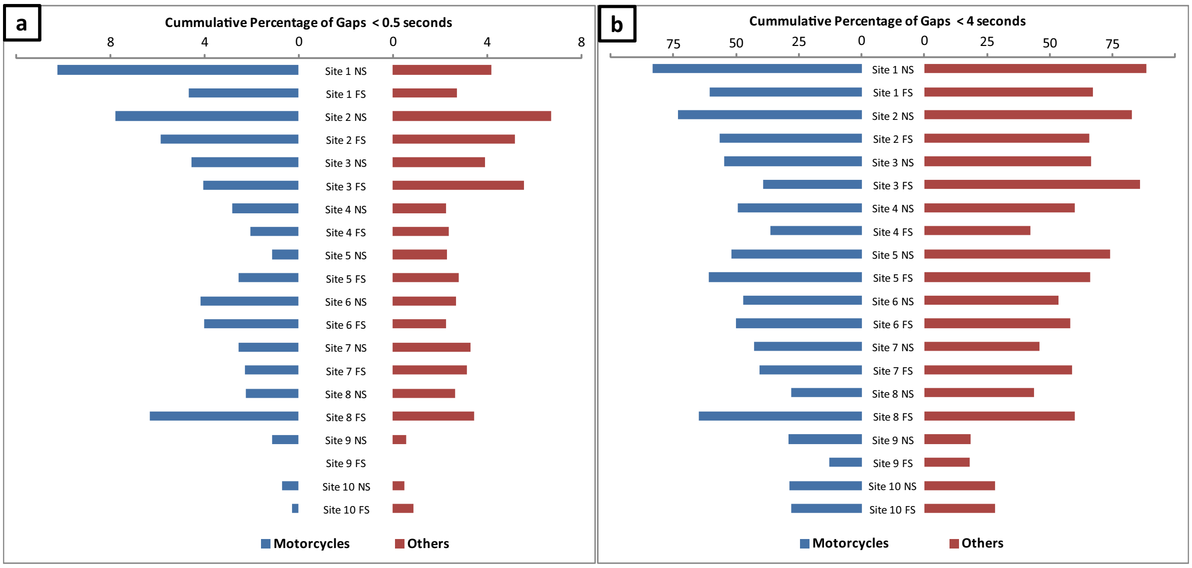

Fig. 7. (a) Cumulative percentage of longitudinal gaps less than 0.5 s between motorcycles and other vehicles in each direction (b) Cumulative percentage of longitudinal gaps less than 4 s between motorcycles and other vehicles in each direction (NS: Near Side, FS: Far Side).

Table 6
Percentage of vehicles performing WMRT and Non-WMRT maneuver.

Major road width	WMRT		Non-WMRT	
	Motorcycles	Others	Motorcycles	Others
0–9 m	60	2	18	20
Greater than 9 m	11	13	20	56

Significant difference among vehicle type and road width as per χ^2-test ($p < 0.001$).

conflict area, motorcyclists tend to perform the Non-WMRT maneuver to quickly pass through it. The results also support the evidence of driver comfort in performing the WMRT as compared to the conventional right-turn.

3.4.2. Traffic conflicts with respect to movement type of vehicles entering the major road

Of all the accidents recorded on the sites under consideration, angle collisions were found to be the highest as shown in Table 1. This result is conformal to the accident statistics mentioned in previous studies conducted in Malaysia (Abdul Manan, 2014; Abdul Manan & Várhelyi, 2012). In a similar study involving data from 38 counties in Georgia, USA; angle crashes were found to be the highest among all types of accidents occurring at unsignalized intersections (Kim, Lee, Washington, & Choi, 2007). Since right turning movement influences such type of collisions most, therefore, it was decided to concentrate on right turning movements only. The vehicles performing Weaving Merging Right Turn (WMRT) had fewer conflicts as compared to the vehicles that did not perform the WMRT as shown in Table 7. A total of 23 conflicts were observed for Non-WMRT maneuver as compared to only 9 for the WMRT maneuver. This indicates that vehicles that did not perform the WMRT maneuver experienced 2.5 times more conflicts as compared to the ones performing it. The numbers of serious conflicts encountered by vehicles performing Non-WMRT were twice as high as compared to potential conflicts. Relatively the vehicles performing the WMRT had half the number of serious conflicts as compared to potential conflicts. The involvement of motorcycles was lower as compared to other vehicles in both potential as well as serious conflicts. This result remains valid for vehicles performing WMRT and Non-WMRT maneuver.

Speed analysis revealed that vehicles making the WMRT were able to achieve 42% higher turning speeds as compared to those who followed the conventional Non-WMRT maneuver. While no significant difference in speeds of major vehicles following the turning minor vehicles were observed as shown in Table 8. This ability to achieve better speeds by driving further and then merging into the main traffic stream as compared to the conventional right turning vehicles enabled them to accept comparatively shorter gaps with respect to Non-WMRT vehicles. It also increases the risky attitude of 'Other' vehicles as turning indicators were used only by 33% of those performing WMRT as compared to 64% by Non-WMRT and only 67% of them stopped at the stop line as compared to 86% by Non-WMRT. None of the motorcyclists, involved in conflicts, used their turning indicators and only 33–44% of them stopped at the stop line before making a right turn. This result is similar to a previous study in which it was reported that 39% of the motorcyclists stopped at the stop sign (Muttart et al., 2011). The number of conflicts could have been reduced further by improving the use of turning indicators and stopping at the stop line.

3.4.3. Traffic conflicts with respect to major road width

Significant difference between numbers of conflicts was found among roads having different widths. Only two conflicts were observed on narrower roads, that is, the ones having widths less than nine meters. While 30 conflicts were observed on roads having widths greater than nine meters, as shown in Table 9. Similar to the results of conflicts with respect to movement type, the number of motorcycles involved in 'Total' conflicts was less as compared to other vehicles. In terms of severity motorcycles experienced only 36% serious out of the total conflicts that occurred on sites having major road width greater than nine meters. Contrary to it other vehicle had 68% serious conflicts out of the total conflicts occurring on sites with wider major roads.

Significant differences in speeds of major vehicles following the turning minor vehicles were observed as shown in Table 10. Following vehicles were faster on wider roads as compared to narrower roads resulting into more conflicts.

Table 7
Conflicts with respect to movement type.

Movement type	Vehicle type	Conflict type	
		Potential	Serious
WMRT	Motorcycle	2	1
	Others	4	2
	Total	6	3
	All	9	
Non-WMRT	Motorcycle	5	4
	Others	3	11
	Total	8	15
	All	23	

Table 8
Traffic parameters of conflicts with respect to movement type.

Movement type	WMRT		Non-WMRT	
Vehicle type	Motorcycle	Others	Motorcycle	Others
Average speed				
Turning	–	28.1	–	19.72
Major	29.7	39.3	38.22	31.8
Average gap				
Accepted	3.7	4.33	3.9	5.6
Rejected	3	1.6	1.2	1.9
Turning indicator				
On %	0	33	0	64
Off %	100	67	100	36
Stopping behavior				
Stop %	33	67	44	86
Did not Stop %	67	33	56	14

Table 9
Conflicts with respect to road width.

Major road width	Vehicle type	Conflict type		Total
		Potential	Serious	
0–9 m	Motorcycle	0	1	1
	Others	1	0	1
>9 m	Motorcycle	7	4	11
	Others	6	13	19

Table 10
Traffic parameters of Conflicts with respect to road width.

Major road width	<9 m		>9 m	
Vehicle type	Motorcycle	Others	Motorcycle	Others
Average speed				
Turning	35.1	–	–	22.6
Major	10	12.4	36.2	35.15
Average gap				
Accepted	4	13	3.81	4.8
Rejected	3	–	1.1	1.8
Turning indicator				
On %	0	100	0	53
Off %	100	0	100	47
Stopping behavior				
Stop %	0	100	45	79
Did not stop %	100	0	55	21

Shorter gaps available to turning vehicles, on sites having major road width greater than 9 m, increased their risky behavior. It encouraged them to accept smaller gaps as compared to turning vehicles on sites having major road width less than 9 m. All 'Other' vehicles stopped at the stop line and used turning indicators while making a right turn on sites having narrower major roads. Contrary to it only 79% of 'Other' vehicles stopped and 53% used turning indicators while making a right turn on sites having wider major roads. This result is conformal with previous researches which reported that drivers stopped 73.4%, 76.9%, 66% and 61% at different intersections (Kodsi & Muttart, 2009; Kosaka et al., 2007; Muttart et al., 2011; Pradhan et al., 2005). This also supports the findings presented in Table 8 in which sites with wider major roads were found to have 94% more accidents as compared to sites with narrower major roads. Similar to the results presented in Table 7, none of the motorcyclists, involved in conflicts, used their turning indicators. Furthermore none of the motorcyclists stopped at the stop line before making a right turn.

4. Discussion

Among the important findings was the effect of difference in volume moving in opposite direction on the number of accidents. Multiple accidents were observed only on sites where the volume of traffic moving near side was higher than the far side. Lower far side volumes negatively affected the behavior of right turning vehicles. It encouraged them to take the risk of turning, as they found lower ongoing traffic, ignoring the higher volume of incoming traffic resulting into more accidents. This effect remained consistent with sites having major road width less than 9 m as well as greater than 9 m. Variation in speeds of all vehicles travelling in opposite direction was observed at all sites. Differences in speed coupled with differences in volume makes the task of completing the maneuver for turning vehicles more mentally challenging. It has been reported in a study conducted in UK, that the severity of accidents involving motorcyclists increase with the increase in speed limit (Pai & Saleh, 2007). The 85th percentile speed of all vehicles at all sites was observed to be less than the speed limit except site 8. The probable cause of this deviation could be the abnormal traffic mix. Only on site 8 and 10 the percentage of motorcycles was higher than other vehicles. But due to the presence of a speed hump just before the intersection at site 10, the speed of vehicles was within limits. Otherwise similar to site 8, the speed of vehicles on site 10 would also have been greater than the speed limit of 60 km/h. It has been reported that an increase in approach speed by 10 km/h can increases the motorcycle accidents by 26% (Harnen, Umar, Wong, & Hashim, 2003a, 2003b). Since the difference in speed between motorcycles and other vehicles observed on all sites was less than 10 km/h, therefore, both motorcycles and other vehicles were equally vulnerable to accidents. This claim was supported by the results of the conflicts analysis. The mean of average speeds on all sites on narrower roads, for motorcycles was found to be 37 km/h which is similar to 36.25 km/h found in a study conducted in Central London (Lee et al., 2012).

The reason for the average longitudinal gap between Motorcycles and other vehicles being higher on wider roads was the higher volume of other vehicles as compared to motorcycles. This variation of volume also affected the speed with which vehicles travel on wider roads resulting into higher differences among the mean speeds of motorcycles and other vehicles. Higher longitudinal spacing and lower speeds of motorcycles tend to segregate them from the rest of the traffic on wider roads making them more vulnerable to accidents. Table 1 provides the evidence for this finding, as all accidents recorded involved at least one motorcycle. Contrary to it on narrower roads the overall volume analysis reveals that there is no significant difference between volume of motorcycles and other vehicles. Further analysis with respect to speed shows that motorcycles tend to travel with almost the same average speed as compared to other vehicles resulting into equal average gaps between them. This proves that narrower roads prevent motorcycles from segregating from the rest of the platoon and provide more cohesion among vehicles as compared to wider roads. But the higher percentage of motorcycles having longitudinal gaps less than 0.5 s as compared to other vehicles is conformal with their 'nature' of driving close to their preceding vehicles (Abdul Manan, 2014a) as they can manage to weave quickly (Hussain, Umar, & Sadullah, 2011) and move within the spaces between vehicles (Lee et al., 2012).

None of the motorcyclists, involved in conflicts, used their turning indicators and only 33–44% of them stopped at the stop line before making a right turn. This result is similar to a previous study in which it was reported that 39% of the motorcyclists stopped at the stop sign (Muttart et al., 2011). The number of conflicts could have been reduced further by improving the use of turning indicators and stopping at the stop line. All 'Other' vehicles stopped at the stop line and used turning indicators while making a right turn on sites having narrower major roads. Contrary to it only 79% of 'Other' vehicles stopped and 53% used turning indicators while making a right turn on sites having wider major roads. This result is conformal with previous researches which reported that drivers stopped 73.4%, 76.9%, 66% and 61% at different intersections (Kodsi & Muttart, 2009; Kosaka et al., 2007; Muttart et al., 2011; Pradhan et al., 2005). This also supports the findings presented in Table 9 in which sites with wider major roads were found to have 94% more conflicts as compared to sites with narrower major roads.

WMRT is a more comfortable maneuver for drivers because they do not have to exert the extra force on the steering wheel which is required in the conventional right turning maneuver. The results supplement this finding, as the numbers of conflicts for vehicles performing the WMRT were 2.5 times less as compared to the vehicles not performing the WMRT. Moreover, the WMRT enables the drivers to accelerate further, as compared to Non-WMRT, before merging with the main traffic stream. At the same time it gives an indication to the preceding major road vehicle that another vehicle is about to merge, therefore the driver becomes more cautious and gives way to the merging vehicle. This reduces the number of serious conflicts for WMRT vehicles, despite the fact that shorter gaps were accepted by vehicles performing WMRT in relation to Non-WMRT, as supported by the results. This result is also conformal with the findings of Abdul Manan, 2014a which indicated that vehicles making indigenous maneuvers such as the 'Opposite Indirect Right Turn' experienced less serious conflicts as compared to the ones which opted for the conventional right-turn. Since, number of conflicts is a function of exposure, therefore, the number of motorcycles involved in both WMRT and Non-WMRT conflicts were relatively lower due to their lesser volume. Wider roads cater higher volumes thus resulting into more conflicts on sites having major road width greater than 9 m. The involvement of other vehicles in both serious and total conflicts was high because of their higher volume as compared to motorcycles on wider roads. More conflicts were observed on sites that had near side traffic flow greater then far side. This supports the evidence of higher number of accidents on sites having higher near to far volume ratio.

Taking into consideration the findings of this study it is recommended that travel demand modeling and better landuse planning should be sought as the way forward to mitigate traffic congestion. The option of 'Road Widening' to resolve the issue of traffic jams should be considered as the last choice. The gap size among vehicles on wider major roads become shorter and the waiting time for minor vehicles, to find a suitable gap, become longer. Wider major roads subsequently increase the time to complete the turning maneuver of minor road vehicles. All the above parameters supplement each other in increasing the risky behavior of minor road vehicles resulting into more accidents. This result is conformal with the study conducted by Hamed et al. (1997) in which the number of lanes in the major approach were shown to have a positive effect on the mean critical gap indicating that intersections with wider major road width require greater gap size to be accepted.

The results of this study should be utilized with caution due to under representation of 'other' vehicles in performing the WMRT on sites having major road width less than 9 m because of low traffic volume on minor approaches. Similarly the number of conflicts on sites having road width less than 9 m was underrepresented due to low traffic volume on minor approaches. The procedure presented in this study, to observe the behavior of vehicles, can be extended to roundabouts, signalized intersections, highway ramps, entry/exit points and merging sections to evaluate their safety.

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