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ESTIMATION OF A CRITICAL GAP/ LAG IN UNCONTROLLED INTERSECTIONS IN SRI LANKA

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ABSTRACT

The critical gap/lag value for an uncontrolled intersection is an important parameter in estimating highway traffic capacity and developing micro stimulations of traffic movements. In manoeuvring an intersection, drivers decide to accept or reject the gap, based on several considerations. However, only a few studies have been carried out to estimate the critical gap on Sri Lankan roads; meanwhile, estimates of external factors are rare. This study found the influence of external factors on drivers' gap acceptance decision and estimated the critical gap/ lag values using the Binary Logistic model. Analysis considered 4,233 gap acceptance decisions taken by drivers on minor roads. These were collected at three four-way and two three-way intersections and analysed across three vehicle categories: Motorcycle, Three-wheeler, and Car/Van. Among the external factors studied, vehicle type, intersection type, size of the available gap, and type of traffic manoeuvre were found to have a significant influence on gap acceptance. Critical gap/lag values found in this study can be used for capacity estimation of three-way and four-way intersections in Sri Lanka.

Keywords: *Critical Gap, Uncontrolled Intersection, Gap acceptance, logit model*

1. INTRODUCTION

Estimation of the Critical Gap and study of the gap acceptance behaviour of uncontrolled intersections are important considerations in determining intersection capacity and understanding local driver behaviour. Driver behaviour in an uncontrolled intersection is affected by several factors. For example, vehicles that approach a T-junction/ three-way intersection have to perform a left turn or a right turn. At a four-way intersection, these turns are performed by manoeuvring. In these scenarios, drivers of vehicles coming from the minor road (minor stream) should estimate whether there is a sufficient gap between two successive vehicles in the major road (major stream) in deciding whether to enter the intersection or not. The Highway Capacity Manual defines Gap as the space or time between two vehicles, measured from the rear bumper of the first vehicle to the front bumper of the second vehicle [1]. The critical gap is the gap size that is equally likely to be accepted or rejected by the driver. Many deterministic and probabilistic methods have been used to determine critical gaps. The Raff's method which has been used in many studies determines the value of the critical gap by taking the gap value corresponding to the 50^{th} percentile of the gap-accepting probability distribution. This concept has been used to estimate the critical gap values of uncontrolled intersections in developing countries by Serg [2].

Past studies have shown that gap acceptance behaviour is affected by several factors, which may be related to the driver, vehicle, or some other external factors. Thus, the gap acceptance behaviour would vary with the situation, and thus, different behaviours can be expected in the context of different countries. While there are some studies estimating the critical gap values in other countries, those related to Sri Lankan roads are rare to the best of the author's knowledge. Capacity estimation at uncontrolled intersections is a frequent requirement for transport planners around the world. However, the absence of critical gap values for Sri Lanka has compelled transport planners to rely on less accurate (often conservative) gap estimates. To address this problem faced by transport planners in Sri Lanka, this research attempts to estimate the critical gap values based on Sri Lankan driver behaviour data while giving due consideration to external factors.

Thus, this research intends to estimate the critical gap for an uncontrolled intersection while giving due consideration to the external factors that affect gap values based on Sri Lankan driver behaviour. Specifically, the research intends to achieve the following three research objectives.

- **Objective A:** Identify different external factors affecting the critical gap based on the literature review.
- **Objective B:** Determine the factors that are significantly influential on the critical gap based on field data in the Sri Lankan context.
- **Objective C:** Estimate the critical gap by considering the influential factors in the Sri Lankan context.

2. LITERATURE REVIEW

2.1. Determinants of critical gap

Past studies have investigated the effect of different factors that affect the critical gap and gap acceptance behaviours in an uncontrolled intersection. These include intersection geometry, vehicle, and driver characteristics as well as other factors such as vehicle and driver characteristics. Evidence from previous research is discussed.

Several research papers have provided supporting evidence related to the potential effects of intersection geometry. When the number of legs at the intersection increases, the lane's critical gap value will also increase due to the increasing complexity of the manoeuvre. Smaller gaps can be accepted in the presence of smaller turn angles of intersection than larger turning angles. Previous research [3] has identified several major factors affecting critical gaps which include intersection geometry (e.g., multi-lane or single lane, three-way or four-way), approach grade, vehicle type, movement type, and vehicle delay. Further, the same study found that with the increase of major stream volume or minor stream vehicle delay, drivers tend to accept smaller gaps. Multiple researchers have identified vehicle types to influence the critical gap [4 – 8]. This may have resulted from larger vehicles requiring more space and time to make a manoeuvre than smaller vehicles. The above research confirms the need to develop critical gap/ lag estimates that are specific for different vehicle types and intersection configurations (three-way or four-way).

At the personal factor level, the driver's age and gender, the driver's psychology and aggressiveness, and the presence of passengers may affect the critical gap. For the effect of gender, one previous research [4] has found that male drivers are more aggressive in gap acceptance than female drivers. However, another work [5] found that the driver's gender is a less significant factor affecting the critical gap. The age of the driver is a factor that is identified as affecting gap acceptance. Further, notable differences in critical gap values have been found between teens and adult drivers. In terms of passenger presence, drivers tend to accept higher gap values and behave less aggressively in the presence of passengers [4], [5]. Previous work has also found that when the drivers were involved in a phone conversation their gap acceptance rate decreased. On the other hand, those who had the music player turned on while driving, had their gap acceptance rate increased [3 – 6], [9]. Vehicle delay, type of manoeuvre, number of rejected gaps, time of the day and day of the week, weather, presence of vehicles queued behind the turning vehicle, distractions by phone conversations and the music player are some additional factors that may affect the critical gap. Previous work [5] found that drivers are more aggressive in gap accepting (leading to smaller critical gaps) during the peak traffic periods in both morning and evening. Further, the presence of vehicles queued behind the turning vehicle was found to be more influential leading to accept shorter gaps because drivers are pressured by the vehicles behind them. They tend to accept a gap smaller than a regular scenario. Considering the effect of weather, the critical gap linearly increases with the increasing rain intensity [10]. Research conducted using a driver simulator has also shown that less experienced drivers are more likely to accept shorter gaps [11]. In a study to evaluate the effects of stress and time pressure on gap acceptance, authors found that drivers under pressure may accept smaller gaps [12]. In the presence of varying evidence related to personal factors, there is a need for a complete study focusing on the effects of one or more personal factors. However, the effect of gap size has been highlighted as important in several studies.

In summarising the above, type of manoeuvre and vehicle type can be identified to have a strong influence on the value of the size of gap/ lag.

2.2. Data Collection Methods and Approaches for Critical Gap Estimation

Studies for the estimation of critical gaps have used either field observations or simulation methods to collect data for gap performances [7]. Often field data collection is based on extracted data from video recordings in an intersection. Some of the studies considered the arrival and passing of vehicles to the common area of the intersection while some other studies have defined a specific zone in the intersection and recorded time instances for that zone. Studies [9, 13] considered that "a vehicle can be assumed to have cleared the intersection when it crosses the influence area which has a rectangular shape and reach a point where it requires only to merge in the next stream. For each type of movement based on the influence area defined for it, clearing time is observed as the time taken by a lower priority vehicle from the instant it moves from its stopped position". Figure 1 describes the gap and lag as described by Dutta and Ahmed [9].

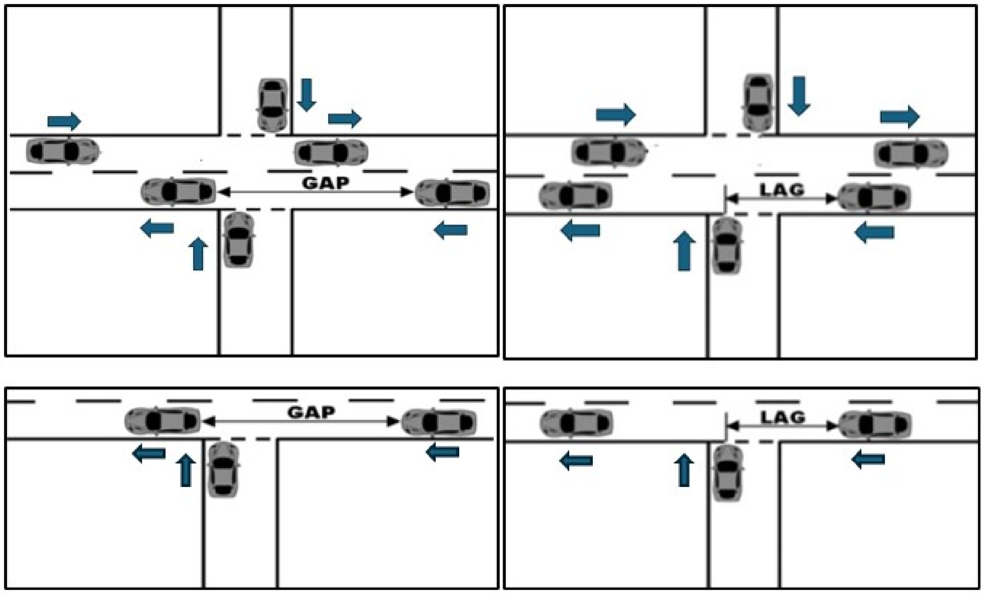

Figure 1: Definition for Gap and Lag for intersections based on illustrations of Dutta and Ahmed [9]

Many techniques have been used to estimate the critical gap based on gap acceptance data at intersections. Deterministic, Probabilistic, Stochastic, or Fuzzy Logic approaches are the methods used. Examples of deterministic methods are Raff's method and Greenshields' method. The probabilistic method involves discrete choice models that predict the likelihood of accepting different gaps. Examples are the logit model, Probit Model, and Neural Networks. Bayesian Approach and Bootstrap are stochastic approaches and the uncertainty of affects gap-acceptance decision process can be properly determined using fuzzy logic which is based on the conditional process of decision making [9], [14]. In addition to these conventional methods, a deterministic graphical method which estimates the Critical gap through the clearing behaviour of drivers at un-signalized intersections has also been proposed [13]. As discussed below graphical methods using probabilistic estimates have been selected to reflect the effects of multiple factors.

2.3. Critical gap values from past studies and Applications of Critical Gap

Critical gap values in the range of 2.93 – 4.79 s for non-aggressive drivers, and 2.02 – 2.40 s for aggressive drivers were found at uncontrolled three-way intersection under mixed traffic conditions using a Binary logit model [9]. Further, critical gap values in the range of 2.80 – 4.09 s were found by drivers excluding aggressive drivers [14]. Based on a study in Egypt, the smallest critical gap of 4.18 s and the largest of 5.46 s in uncontrolled intersections were proposed for developing countries [2]. The

2010 edition of Highway Capacity Manual (HCM) of the Transportation Research Board has used a deterministic model to determine the critical gap [14]. Accordingly, it recommends a 4.5 s critical gap for left-turn drivers at signalised intersections with a permitted left-turn phase.

However, driver behaviour may vary based on other factors; so, the critical gap values specific to such factors should be estimated. Such estimation of critical gap values should be based on data from respective contexts such as for a particular country. Thus, as an alternative approach to HCM estimations, other researchers have proposed probabilistic methods which can model drivers' gap acceptance behaviour [8]. According to previous observations, the critical gap which is typically set equal to the 50th percentile value observed in field studies, has been estimated to be 5.0 s [15]. These probabilistic methods use multiple factors to model the gap acceptance. Effects of gap duration, the number of rejected gaps, the mean and total time interval of the rejected gaps and the gender of the driver on the gap acceptance have been successfully studied previously [8].

Research to estimate the critical gap in the Sri Lankan context is rare although the values are important for highway capacity estimations. Even among these studies, estimates which are specific to external factors are not available to the best of the authors' knowledge.

2.4. Application of Critical Gap estimation and relevant research for Sri Lankan roads

Critical gap values for an uncontrolled intersection are taken into account in calculating the capacity of minor streams [8], [14], [15]. When traffic flow at uncontrolled intersections is interrupted or controlled, risk of traffic hazards may be high [4], [5]. The accuracy of capacity estimates obtained by micro-simulation models depends on the critical gap values. Estimates based on values from developed countries may not be suitable for others [2]. Therefore, studies on critical gaps and the factors affecting gap acceptance are useful in determining the intersection capacity and planning future traffic control mechanisms according to the capacity.

In the absence of such studies conducted based on Sri Lankan drivers and road context, the research attempts to estimate the critical gap values for uncontrolled intersections by giving due consideration to relevant external factors.

3. METHODOLOGY

By referring to the approach adopted in a similar in Malaysia [2], this study used the Binary Logistic model to determine the critical gaps in an uncontrolled intersection since the driver must make a decision of whether to accept or reject a gap. For the analysis, several external factors which are determined by external observations were considered. The study was carried out by observing the traffic flow at uncontrolled four-way and three-way- intersections located in suburban areas in Sri Lanka.

3.1. Data Collection

Traffic recordings were done to observe the gap acceptance behaviours of vehicles in different scenarios in the Sri Lankan context. The study intended to get the critical gap/ lag values for different Types of uncontrolled intersections (IT) {Four-way (4W) and T-intersections or three-way intersections (3W)}, Vehicle types (VT) { Motorcycle (MC), Three-wheeler (TW), Car /Van/Jeep (CVJ) and Heavy vehicles (HV)} and Manoeuvre types (MT) { Right Turn (RT), Left Turn (LT), and Flow Through(TH)}. For this purpose, below data related to the gap acting below were also collected.

- Type of the performance; gap or lag, (GL);
- Size of the considered gap or lag, (SZ);
- Whether the gap or lag was accepted or rejected, (AR);
- Whether the major stream approaching vehicle yielded or not yielded, (YN);
- Clearance Time to complete the total gap performance (CT).

For the collection of gap acceptance data, video recordings of traffic flow at uncontrolled intersections were recorded during weekdays in typical morning peak hour periods (0800 - 1100) under normal weather conditions. Five locations were selected; three four-way intersections and two three-way intersections located in semi-urban areas in Puttalam District, Sri Lanka. All the locations had almost level terrain without any sightline restrictions or traffic interruptions nearby area. In each location, two hours of traffic data was recorded using a mobile phone camera. The camera was placed at an angle that could capture the whole approaching stream to the intersection. Special care was taken to minimise the parallax error by taking the time when the vehicle would pass reference points that were visible.

3.2. Data Extraction and Analysis

For the extraction of the necessary data, the recorded videos were played in the desktop video player applications reducing the speed by 50% as the original, to have better observations on gap performances. Each gap performance was observed to record the data under the factors considered. 4,462 gap performances were extracted from the collected videos but the collected data for the heavy vehicle category were excluded they composed only 5.2% of the total data set.

Following time instants were recorded to obtain the gap-related parameters.

- T_0 – Time instant when the minor stream vehicle approaches the Intersection.
- T_n – Time instant the n^{th} major stream vehicle approaches the intersection after the minor stream vehicle has approached the intersection. (n = 1, 2, 3…)
- T_{n+1} – Time instant the first major stream vehicle approaches the intersection after the minor stream vehicle accepts the gap to proceed. (n= 1, 2, 3…)
- T_c – Time taken by minor stream vehicle fully completes the maneuver.

The time difference between T_0 and T_n is the first gap, or the lag experienced by the minor vehicle while approaching the intersection, while the difference between T_n and T_{n+1} is the lag experienced by the vehicle in a minor stream. Values are recorded starting from the first vehicle (T_n) on the major road until the last major vehicle (T_{n+1}) crosses the intersection when the minor vehicle finally accepts the gap and moves ahead.

When performing a manoeuvre in an intersection, drivers only have two decisions to make over a Gap or Lag which are to either accept (A) or reject (R). This type of decision-making can be identified as a binary choice. The likelihood of making a decision is based on the utility of the choice [2]. In this study, the likelihood of deciding on accepting or rejecting is predicted by adopting the probabilistic Binary Logistic (BL) model using the utility function. The utility functions are as follows,

$$u_i = v_i + e_i \tag{1}$$

$$v_i = \beta_0 + \beta_1 x_i + \beta_2 x_2 + \cdots + \beta_n x_n \tag{2}$$

where v_i - binary choice of accepting or rejecting (AR) the gap/lag; u_i - total utility; e_i - the error term; B_n - constant parameters; x_n - independent variables (affecting factors).

Pearson correlation tests were performed to identify the significantly influential factors for the gap acceptance decision-making. To derive the utility function logistic regression was performed. In the analysis, the gap acceptance decision was taken as the dependent variable while the factors that had a significant influence were used as independent variables. Distinct models were derived separately for different intersection types and different vehicle categories. The derived models were used to calculate the critical gap or lag values using the Binary Logistics Method (BLM). Further for each case, average values of clearance times were also calculated. These are presented as values using the Clearance Time Method (CTM).

4. RESULTS AND DISCUSSION

In the analysis, 4,233 gap performance data were analysed, leading to 2,769 and 1,464 gap performance data at 4W and 3W intersections respectively.

4.1. Gap Acceptance Model

Table 1 shows the results of Pearson Correlation tests conducted to identify the significance of the selected external factors to the decision of gap acceptance. As demonstrated in Table 1, all the factors were significant in the decision of gap acceptance in all the cases.

Table 1: Results of Pearsons Correlation test for different vehicle types

IT	External Factor	Vehicle Type					
		MC		TW		CV	
		PC	Sl	PC	Sl	PC	Sl
Four Way (4W)	SZ	0.383**	0	0.399**	0	0.528**	0
	CT	-0.219**	0	-0.218**	0	-0.170**	0
	GL	-0.397**	0	-0.412**	0	-0.397**	0
	YN	0.299**	0	0.286**	0	0.311**	0
	MT	0.105**	0	0.144**	0	0.174**	0
Three Way (3W)	SZ	0.318**	0	0.364**	0	0.428**	0
	CT	-0.187**	0	-0.196**	0	-0.160**	0
	GL	-0.440**	0	-0.446**	0	-0.411**	0
	YN	0.181**	0	0.200**	0	0.219**	0
	MT	0.279**	0	0.256**	0	0.234**	0

PC - Pearson Correlation Coefficient; Sl - Significance level of 2-tailed test; **Correlation is significant at the 0.01 level (2-tailed). * Correlation is significant at the 0.05 level (2-tailed).

According to the regression coefficient values shown in Table 2, the gap acceptance decision was found to be influenced by the factors in different ways as follows. The likelihood of gap acceptance increases, with the increase of the available gap/lag size, or when a major stream vehicle is yielding. It was also influenced by the manoeuvre type. Also, the likelihood of gap acceptance was high when the time to clear was low. As discussed in the literature review, similar observations have been found in the studies conducted for Egyptian [2] and Indian intersections [6] related to influential factors on gap acceptance.

Table 3 shows the critical gap/ lag values calculated using the BLM and CTM. The values obtained from CTM were somewhat higher than those obtained from BLM for both critical gap and lag values. Nevertheless, for both gap and lag values, those values calculated from BLM and CTM showed similar trends for different cases presented in Table 3. Key trends observed for gap acceptance behaviour are therefore discussed using the BLM estimates.

Table 2: Coefficient for factors affecting gap acceptance for logistic regression

IT	External Factor	Vehicle Type					
		MC		TW		CV	
		P value	C	P value	C	P value	C
Four Way	SZ	0.000	0.601	0.000	0.581	0.000	0.676
	CT	0.000	-0.372	0.000	-0.35	0.000	-0.272
	GL	0.000	-2.17	0.000	-2.073	0.000	-1.792
	YN	0.995	-	0.995	-	0.005	0.699
	MT	0.004	0.279	0.001	0.309	0.001	0.351
	Const.	0.010	0.399	0.003	0.308	0.004	0.269
Three Way	SZ	0.001	0.318	0.000	0.465	0.000	0.543
	CT	0.000	0.000	0.000	-0.215	0.000	-0.234
	GL	0.000	-2.103	0.000	-2.026	0.000	-1.784
	YN	0.306	0.163	0.996	-	0.006	0.35
	MT	0.000	0.566	0.000	0.445	0.000	0.431
	Const.	0.023	0.400	0.057	0.014	0.004	-0.262

C - External Factors/ constant for regression

The critical gap values vary across vehicle type, manoeuvre type and yield behaviours.

In comparison to previous studies, this study has found the critical gap/lag values for three different vehicle categories, two intersection types and all three manoeuvre types (two in the case of three-way intersections). Further, since the CVJ category shows different behaviours for yielding and non-yielding cases of mainstream vehicles, separate critical gap/lag values were obtained for these two cases.

The critical gap values for three-way intersections were higher than those for four-way intersections among both motorcycles and three-wheelers. This shows extra caution exercised by drivers of these two vehicle categories in three-way intersections as these drivers wait more in three-way intersections than in four-way intersections. As expected for the manoeuvre type, the critical gap values increased in the order of left turns, through movement and right turns for both intersection types and for consistently all vehicle categories. In terms of vehicle categories lowest critical gap values were observed for the CVJ category when mainstream vehicles yielded. For the remaining vehicle categories, critical gap values increased in the order of motorcycles, three-wheelers, and CVJ category when mainstream vehicles did not yield. This shows that while smaller vehicles have lower waiting time well-mannered driving can lead to lesser waiting time and thus greater time saving. This indicates that well-mannered behaviour by major stream vehicles can improve the traffic flow of minor stream vehicles and increase the capacity of the minor stream as well in four-way intersections.

The average critical gap/lag of 4.35 s was obtained in that study for left turns in four-way intersections for cars. The estimate of the current study for this scenario stood at 4.38 s for non-yielding cases which were again closer to the estimates of the Egyptian study [2]. However, the present study reported a critical gap value of 1.92 s when the mainstream vehicles yielded. This shows that well-mannered driving behaviour can increase the confidence of vehicles in minor streams and lead to time savings for them.

In a different study in Silchar and Guwahati cities in Assam, India, the authors [9] estimated the critical values for right turns in three-way intersections as 3.37 s for two-wheelers and 4.79 s for four-wheelers. The corresponding values for this study were 4.33s and 4.44s. The values related to four-wheelers/ CVJ are similar for both studies. However, the value for two-wheelers/MC reported in the present study is higher than the value of the Indian study showing more waiting time by Sri Lankan Motorcyclists at three-way intersections. HCM recommends a 4.5 s critical gap for left-turn drivers at signalised intersections with a permitted left-turn phase. The values of the present study are in the same range as the HCM recommendations. Further, the right turn critical gap values of the present study are closer to the range of 4.5s - 5s as defined in the "Highway Capacity Manual" [14] for the right turns. Another study [4] conducted in India has evaluated the critical gap values using multiple methods. Those results have shown lower critical gap values. The authors have attributed this devotion to an assumption of homogeneity under mixed traffic conditions. They have suggested in the same study the results obtained based on clearing behaviour to produce more suitable results. The clearing time data of their study is closer to the critical gap data in this study.

It can be observed that in taking Left turns, Motorcycles have accepted relatively lower gaps for both three-way and four-way intersections. This may reflect the smaller size of the motorbike. Critical lag values for most of the cases remained below 2 s, further, these were smaller than critical gap values in all cases.

The estimated critical gap and lag values can be used as input parameters for highway capacity estimations, especially for microsimulations in uncontrolled intersections in Sri Lanka. Recently there has been an interest in automated driving systems (ADSs) operating in real life in mixed traffic [16]. The estimated gap values would form a good reference in calculating the gap values under such conditions. Gap acceptance behaviour affects both the network capacity and road safety [17], [18]. The nature of gap acceptance behaviour found in this research has implications for road safety improvement measures.

Table 3: Gap acceptance values calculated based on the Binary Logistics Method (BLM) and Clearance Time Method (CTM)

Four-way (4W) intersections					
VT	**MT**	**Gap(s)**		**Lag(s)**	
		BLM	**CTM**	**BLM**	**CTM**
MC	RT	3.99	4.00	1.44	2.00
	TH	3.47	4.00	1.00	2.02
	LT	1.00	1.70	1.00	1.75
TW	RT	5.20	5.25	1.63	1.95
	TH	4.66	4.80	1.10	1.95
	LT	4.13	4.30	1.00	1.50
CV (YN=0)	RT	5.31	5.40	1.70	1.75
	TH	4.84	5.15	1.23	1.80
	LT	4.38	4.60	1.00	1.40
CV (YN=1)	RT	2.96	3.10	1.00	1.90
	TH	2.44	3.05	1.00	1.95
	LT	1.92	2.02	1.00	1.35
Three-way (3W) intersections					
VT	**MT**	**Gap(s)**		**Lag(s)**	
		BLM	**CTM**	**BLM**	**CTM**
MC	RT	4.33	4.30	1.23	2.10
	LT	3.09	3.10	1.00	1.75
TW	RT	5.45	5.75	1.09	2.02
	LT	4.49	4.75	1.00	1.40
CV (YN=0)	RT	4.33	4.35	1.09	1.95
	LT	3.09	3.80	1.00	1.40
CV (YN=1)	RT	4.44	4.60	1.00	1.75
	LT	3.64	3.85	1.00	1.50

Previous research in Egypt showed that the behaviour of drivers in developing countries is riskier with a reluctance to follow traffic rules [2]. As discussed above comparing the outcomes of this study with those from developing countries and those reflected in the Highway Capacity Manual does not reflect significant differences. In other words, the outcomes of this present study conducted in a developing country did not yield significantly lower gap acceptance values that may indicate risk-taking behaviour. On the other hand, the lowest critical gap values estimated for the CV category when major stream traffic was yielded indicate that possible time savings can be yielded through well-mannered behaviours. These results could be useful in designing interventions. If the mainstream drivers of three-way intersections can be educated to improve their yielding behaviour, the critical gap values for three-way intersections could also be brought down. However, since excessive yielding of mainstream vehicles may bring down the network capacity, such interventions should be done only if the whole network would benefit from time savings.

5. CONCLUSION

The critical gap is an important parameter that is applied in highway capacity calculations. In this research, was aimed to develop the critical gap/ lag estimates of an uncontrolled intersection based on three external factors namely the vehicle type, intersection type and yielding behaviour. Vehicle category-specific Probabilistic Binary Logistic models were developed and used to estimate the critical gap values for both intersection types and for the cases where major stream vehicles yielded or not.

In consistent with similar previous studies done for developed countries, findings indicated that gap/lag values would increase with the available gap/lag size, and when a major stream vehicle is yielding for cars or vans. Further gap/lag values increased in the order of left-turn, flowing through, and right-turn.

The majority of obtained results are in the range of the overall values given by [15] as defined in the "Highway Capacity Manual" [12] and those obtained by [9] focusing on T intersections of Indian streets. The estimated critical gap and lag values can be used as input parameters for highway capacity estimations for uncontrolled intersections in Sri Lanka.

Further studies can help to improve these findings related to Sri Lankan roads to study the critical gap considering other factors such as the number of lanes in the stream, waiting time of drivers, and the geometrical differences in the intersection.

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