Estimating The Critical GAP and FOLLOW-UP Headway at Roundabouts in Uganda

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ABSTRACT

This paper presents the findings of a research to estimate the critical gap and follow-up headway at five selected roundabouts in Uganda. Research data was collected using video technology and reduced by recording time positions of vehicles into MS Excel. Accepted and rejected gaps of individual entry drivers were determined. The maximum likelihood estimation technique proposed by Troutbeck (1992) was used to estimate the critical gap from a pair of accepted and largest rejected gaps of individual drivers. The follow-up headway was estimated assuming a log-normal distribution and the computation accomplished by MS Excel. The findings show the mean critical gap values at the all locations as 3.25, 2.67 and 3.18 seconds for vehicles, motorcycles and a combination respectively. The mean follow-up headway 1.90 seconds and standard deviation 0.60 seconds with lower and upper follow-up bound values of 1.79 and 2.01 seconds at 95% confidence level. It was observed that motorcycles consistently chose shorter gaps than vehicles although this did not significantly affect the overall critical gap values in combination with the vehicles. Drivers were found to be homogeneously aggressive; a fact explained by very short critical gaps, follow-up headway and a small coefficient of variation of 23-percent for a combination of vehicles and motorcycles. The study recommended adoption of critical gap of 3.50 seconds and follow-up headway of 2.00 seconds for operational analysis in the Uganda.

Key words: Critical gap, Follow-up headway, Log-normal, Maximum likelihood estimation, Roundabout

1.0 INTRODUCTION

The critical gap and follow-up headway are important gap acceptance parameters used in design and operation analysis of several intersection controls such as roundabouts, two-way stops, and permitted left[right]-turns at signalized intersections (Highway Capacity Manual 2000, HCM 2000). In Uganda, controls that operate on the gap-acceptance principle are roundabouts and two-way stop intersections; with roundabouts being the most significant high capacity control for major at-grade roads crossing. The basic principle of gap acceptance is that a minor stream vehicle yields to that in the major stream and merges at identified suitable gaps without interrupting the flow of the major stream. The mean gap that most minor stream drivers accept to cross or merge onto the major traffic stream is referred to as the critical gap and is expressed in seconds. However, where long gaps in the major stream exist, it is possible for several queued-up vehicles in the minor stream to use the same gap. The average headway between two successive queued-up vehicles in the minor stream using the same gap in the major stream is referred to as the follow-up headway, also expressed in seconds.

The significance of critical gap and follow-up headway is that they demonstrate the driver behavior within a given locality. In particular, how drivers choose gaps to merge onto major streams and this impacts significantly on the intersection capacity, operation and safety. In the case of roundabouts, entry traffic (minor) finds suitable gaps in circulating traffic (major) in the center of the roundabout for merger. Circulating traffic by operation has exclusive right-of-way in time and therefore should ideally not be interrupted by entry traffic.

The HCM (2000), provides an exponential model for determining the capacity of roundabouts. The model requires the critical gap and follow-up headway as input parameters. Exhibit 17-37 of the same manual recommends upper and lower bounds of the critical gap and follow-up headway of 4.10 - 4.60 and 2.60 - 3.10 seconds for design and operational analysis of roundabouts. The recommended input parameters were based on the research conducted in the United States, and therefore represent their driver behavior and gap choice characteristics. However, driver behavior is variable among countries depending on driving culture and adherence to strict driving rules. As expected therefore, the driver behavior in Uganda may be different than that in the United States because of obvious cultural, legal and behavioral differences related to the use of roads. This therefore necessitates estimation of these important gap acceptance parameters. The purpose of the study was to estimate the critical gap and follow-up headway at selected roundabouts in Kampala City, Uganda. Five roundabouts on the north-east axis of the city were selected namely: Kubiri, Mulago, Fairway, Garden City, and Wampeewo. The selection was based on approach and circulating traffic lanes, grade, traffic intensity and presence of off-peak periods where there is free-flow of traffic.

2.0 RESEARCH OBJECTIVES

The main objective of this research was to determine the critical gap and follow-up headway based on observational traffic data collected at five roundabouts in Uganda. This was achieved by: determining accepted and rejected gaps of entry traffic on a roundabout approach from observed data, estimating the follow-up headway of entry traffic using the same gap in circulating traffic stream, estimating the critical gap at each of the selected roundabouts using accepted and largest rejected gap of each queued-up entry vehicle.

3.0 LITERATURE REVIEW

Gap acceptance is used in traffic engineering to estimate the minimum gap in opposing stream required by entry traffic to complete a maneuver. It is based on the fact that minor stream traffic chooses gaps of suitable but variable sizes to merge onto a major stream. Entry traffic is presented with several gaps in opposing stream for choice before merger. The underlying principle is the existent of two traffic streams; major with exclusive right-of-way all the time and minor that is permitted to merge onto the major stream at suitable gaps without causing interruptions.

3.1. Gap Acceptance Applications

Gap acceptance has a wide range of applications in transportation engineering due to operational characteristics of traffic streams within the road system. The four main applications include: freeway merging from ramp to main freeway and lane changing in multi-lane lane highways, and freeways, un-signalized intersections, roundabouts and permitted right-turn phase at signalized intersections for countries that use keep left driving rule on the road.

3.2. Gap Acceptance Issues

The critical gap of an individual driver can not be observed in the field but rather estimated from observed accepted and largest rejected gaps of the driver as stated by researchers like Raff (1950), and Troutbeck (1992). The critical gap of individual drivers varies with the time the driver spends waiting for a suitable gap. That is, the longer a driver waits, the greater the likelihood of accepting a shorter gap (Mahmassani and Sheff, 1980; and Daganzo, 1981). Therefore, a population of drivers has variable critical gaps and this variability can be explained by a probability distribution. The above statements point to the fact that critical gap varies across drivers in a population and amongst individual drivers. Several researchers in the literature have attempted to model this variability using probability distribution functions (Mahmassani and Sheffi, 1980). Some of the more commonly used distributions include: the log-normal (Cohen *et al*, 1955; Solberg *et al*, 1966; Drew *et al*, 1967; Troutbeck, 1992); normal (Miller, 1972; Mahmassani and Sheffi, 1980; Daganzo, 1981); gamma (Blunden *et al,* 1962) and exponential (Herman and Weiss, 1961). However of the listed distributions, the log-normal distribution is preferred because of its properties such as occurrence for only positive values of the random variable and skew to the right as expected in gap distributions.

3.3. Major Research on Critical Gap Estimation

The earliest research is attributed to Raff (1950) as reported in Gerlough & Huber (1975). Raff presented a procedure to estimate the critical gap based on accepted and rejected gaps. The intersection point of cumulative curves of accepted and rejected gaps yielded the critical gap. This assumed that the critical gap was constant amongst and with individual drivers. Siegloch (1973) reported in Troutbeck and Brilon (2001) used regression for number of vehicles turning in a gap against the gap sizes to estimate the critical gap. Troutbeck (1975) after studying a procedure proposed by Ramsey and Routledge (1973) proposed the use of the maximum likelihood estimation (MLE) technique for critical gap estimation. Blumenfeld and Weiss (1978) developed heaviside step and distributed functions to measure gap acceptance parameters for a population of drivers. This procedure was cumbersome for traffic engineers to implement. Mahmassani and Sheffi (1980) assumed the critical gap varied across the population of drivers and individual drivers; defined Probit function and used a likelihood function to estimate the parameters. The model was such that the critical gap of a randomly selected driver from a population was composed of a constant term, and two random terms explaining variability across drivers and for each driver. However, too many variables meant the model was complex to solve.

Daganzo (1981) proposed a sequential estimation method and further stated that the maximum likelihood estimation technique was insufficient. The model had a constant term and two disturbance terms explaining variability across drivers and among individual drivers. The author created a likelihood function and estimated parameters by maximizing the likelihood function. He assumed a normal distribution for the critical gaps and mean acceptance threshold for each driver. Later, Horowitz (1982) compared the sequential estimation method by Daganzo and MLE by Troutbeck and concluded that MLE yielded better estimates of the critical gap subject to appropriate assumptions of the distribution than Daganzo's model. Consequently, Troutbeck (1992) proposed a procedure to estimate the critical gap based on individual drivers largest rejected and accepted gaps using maximum likelihood estimation. The procedure assumed a log-normal distribution for gaps and was computer based to ease the estimation process.

The MLE procedure by Troutbeck (1992) is extensively referred to in the literature best technique for estimating the critical gap (Tian *et al*, 1997; Brilon *et al*, 1999; Troutbeck and Brilon, 2001; Wu, 2006). However, Wu (2006) developed a macroscopic procedure based on equilibrium of probabilities using all rejected and accepted gaps to estimate critical gap parameters. He noted that the equilibrium of probabilities lies between the largest rejected and smallest accepted gaps for a population of drivers. A study by Brilon *et al*, (1999) on previous techniques to estimate the critical gap found a procedure proposed by Troutbeck (1992) yielded the most accurate results. This procedure was applied in this study to estimate the critical gap parameters.

4.0 METHODOLOGY

The methodology adopted for data collection, reduction and analysis included: literature review and data collection by video recording with a camcorder. The camcorder was positioned at an approach to capture both entry traffic queue and circulating traffic for at least two hours at each of the five roundabouts during the off-peak period. Data reduction was then accomplished by recording time positions of individual vehicles past common conflict area and entered into spreadsheets for data preparation and analysis by creating the necessary pair-wise entries of accepted and largest rejected gaps for individual drivers. The Maximum Likelihood Estimation (Troutbeck, 1992) was then used to estimate the critical gap. Follow-up headway was estimated using spreadsheets and taking a log-normal distribution.

4.1 Confidence Interval of the Mean

Values of critical gap and follow-up headway were obtained from a sample drawn from a population of drivers. It was therefore necessary to determine the confidence band for the population mean based on the sample mean using 95-percent confidence level (α=0.05). To estimate the upper and lower bounds of respective means, the authors toke a normal distribution of the logarithms and unknown population standard deviation. Then, a t-distribution is used to construct a confidence interval around respective means as in Equation 1.

$$\overline{\mu}_i = \overline{y}_i \pm t_{(\frac{\alpha}{2}, df)} \left(\frac{s_i}{\sqrt{n_i}} \right) \tag{1}$$

Where; $\overline{\mu}_i$ = Upper or Lower bound of natural logarithms of population mean, $\overline{y}_i$ = natural logarithms parameter sample mean, s_i = natural logarithms parameter standard deviation, $t_{(\frac{\alpha}{2}, df)}$ = t-distribution value corresponding to the degrees of freedom and alpha value, df = degrees of freedom (n-1), and n_i = sample size. The computed bound values are then transformed back to actual values of a lognormal distribution using Equations 2 and 3.

$$\hat{\mu}_i = \exp(\overline{\mu}_i + 0.5 s_i^2) \tag{2}$$

$$\hat{\sigma}_i^2 = \exp(2\mu_i + s_i^2)(\exp(s_i^2) - 1) \tag{3}$$

Where; $\hat{\mu}_i$ = Upper or Lower bound of the population mean, $\hat{\sigma}_i^2$ = parameter variance, and other variables as defined in Equation 1.

5.0 DATA COLLECTION AND REDUCTION

Data was collected at the five roundabouts with geometric attributes summarized in Table 1. The data was collected by video recording using a hard drive camcorder, transferred to a computer and reduced by reading vehicle positions past common conflict area into MS Excel. Two hours of video were collected at each roundabout in off-peak periods. The rear bumper was used as a common vehicle reference since it gave a complete vehicle clearance past a common conflict point. Four broad categories of vehicles were applied during data reduction: cars, buses, trucks, and motorcycles. The distinction was made to determine the proportions of heavy vehicles and motorcycles of estimated parameters. Under normal operation, traffic stream is assumed homogeneous.

Table 1: Geometric Attributes of Selected Roundabouts

No	Roundabout Name	No. of Approaches	Lanes per Approach	Approach width (m)	Circle Diameter (m)	Circulating Traffic Lanes	Circulating Traffic lane width (m)
1	Kubiri	4	2	6.0	45	2	12.0
2	Mulago	4	2	6.0	30	2	7.0
3	Fairway	4	2	6.0	40	2	11.0
4	Garden City	3	2	6.0	45	2	10.0
5	Wampeewo	4	2	6.0	45	2	9.0

6.0. FINDINGS

6.1. Estimation of Follow-up Headway

The follow-up headway of individual vehicles is the time difference between the leader and following vehicle using the same gap to merge into circulating traffic stream from a queued position. The mean of individual vehicle headways was computed for follow-up headway assuming a lognormal distribution. Values obtained from back transformations are summarized in Table 2. The mean follow-up headways range from 2.15 seconds at Wampeewo to 1.65 seconds at Garden

City roundabout showing relative homogeneity in driver behavior at five roundabouts.

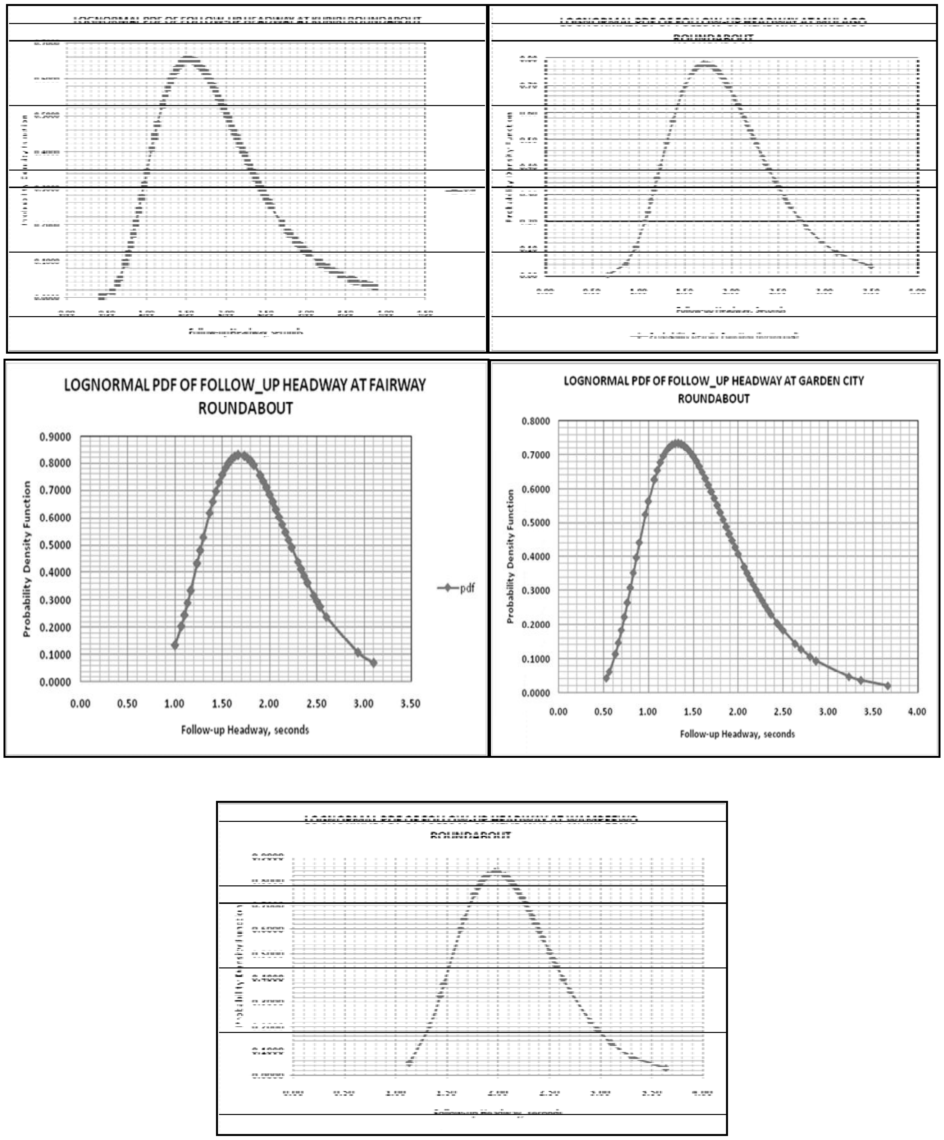

Figure 1: Lognormal Probability Density Functions of Follow-up Headways; Kubiri, Mulago, Fairway, Garden City and Wampeewo Roundabouts

6.2. Estimation of Critical Gaps

The MLE by Troutbeck (1992) was used to estimate the critical gap and standard deviation. The procedure required a pair of accepted and largest rejected gaps of a sample of individual drivers. The pair was then uploaded into a computer program outputting the mean and standard deviation summarized in Table 2. The critical gap was estimated for vehicles, motorcycles and a combination of the two categories. Although motorcycles did not significantly affect the overall critical gap with other vehicles looking at the confidence bounds, they consistently chose shorter gaps than other vehicles. Fairway registered consistently lower values due to the fact that circulating traffic goes through a positive grade, significantly lowering speeds and therefore exhibiting shorter accepted gaps. In general, the critical gap of vehicles and a combination with motorcycles is more than 3.00 seconds. Therefore for design and analysis purposes, a value of 3.50 seconds was recommended.

Table 2: Estimated Gap Acceptance Parameters at Roundabouts

GAP ACCEPTANCE PARAMETERS AT FIVE (5) ROUNDABOUTS IN UGANDA													
		Critical Gap Values						Follow-up Headway Values					
No	Name	Category	Sample Size	Mean (s)	St. Dev. (s)	95% confidence Level		Sample Size	Mean (s)	St. Dev., (s)	95% confidence Level	
						Lower Bound, (s)	Upper Bound, (s)				Lower Bound (s)	Upper Bound (s)
1	(Kubiri)	Vehicles	171	3.42	0.95	3.28	3.56	296	1.88	0.73	1.80	1.97
		Motorcycles	39	2.63	0.84	2.38	2.91					
		Combined	210	3.26	1.02	3.12	3.39					
2	Mulago	Vehicles	330	3.46	0.72	3.38	3.53	94	1.94	0.57	1.83	2.06
		Motorcycles	66	2.84	0.60	2.69	2.98					
		Combined	396	3.35	0.73	3.28	3.42					
3	Fairway	Vehicles	160	2.97	0.74	2.86	3.09	178	1.89	0.53	1.78	2.00
		Motorcycles	25	2.54	0.63	2.30	2.82					
		Combined	185	2.92	0.74	2.81	3.03					
4	Garden City	Vehicles	202	3.32	0.59	3.24	3.40	158	1.65	0.65	1.55	1.75
		Motorcycles	14	Sample Size too small								
		Combined	216	3.28	0.59	3.20	3.36					
5	Wampeewo	Vehicles	208	3.06	0.49	3.00	3.13	52	2.15	0.51	2.01	2.29
		Motorcycles	8	Sample Size too small								
		Combined	216	3.07	0.50	3.00	3.13					

6.3. Discussion of Results

The mean critical gap estimate was 3.25, 2.67 and 3.18 seconds for vehicles, motorcycles, and a combination as summarized in Table 3. The values are well below the lower bound value of 4.10 seconds recommended by the HCM 2000. This shows that the driving population in city is generally more aggressive than their counterparts in the United States. The average standard deviation is 0.72 seconds and coefficient of variation 23% for a combination indicated homogeneity in behavior that is homogeneously aggressive. The low values of critical gap however are not good in terms of traffic operation as they leave no room for error and may result in occasional hold-ups even in off-peak periods.

Table 3: Mean Critical Gap and Follow-up Headway Parameters

MEAN PARAMETER VALUES					
No	Description	Mean (Seconds)	St. Dev., (Seconds)	Lower Bound, (Seconds)	Upper Bound (Seconds)
1	Critical gap for Vehicles	3.25	0.70	3.15	3.34
2	Critical Gap for Motorcycles	2.67	0.69	2.46	2.90
3	Combined Critical gap value	3.18	0.72	3.08	3.27
4	Critical Gap (HCM 2000)			4.10	4.60
5	Follow-up Headway	1.90	0.60	1.79	2.01
6	Follow-up Headway (HCM 2000)			2.60	3.10
7	Recommended Values for Design and Operation Analysis in Uganda				
	a) Critical Gap: **3.50 Seconds**				
	b) Follow-up headway: **2.00 Seconds**				

7.0 CONCLUSION

The observed traffic composition was characterized by a high proportion of motorcycles: 19%, 17%, 14%, 7% and 4% for Kubiri, Mulago, Fairway, Garden City and Wampeewo Roundabouts respectively. The mean motorcycle volume by proportion was 12% of the total traffic volume. Motorcycles operated randomly, more aggressive, accepted very short gaps and made dangerous maneuvers. The mean of heavy vehicles was 4% indicating a predominance of passenger cars.

The mean critical gap values were: 3.25, 2.67 and 3.18 seconds for vehicles, motorcycles and a combination respectively while the recommended overall mean critical gap value of 3.50 seconds for operational analyses. The mean follow-up headway was estimated at 1.90 seconds and standard deviation 0.60 seconds and recommended mean follow-up headway value of 2.00 seconds. The low parameter values indicate that drivers are homogeneously aggressive; a major safety risk that should be addressed with appropriate enforcement to specifically compel drivers to yield on entry and restore the required patience.

Drivers were generally ignorant or disregarded the rules of use and operation of roundabouts. Entry traffic failed to yield to circulating traffic resulting in near misses and/or temporary jams. Slow exit of the vehicles in the circle and improper use of indicators were other observed operational issues. The study recommended educational/awareness campaign for drivers and enforcement on the operation and use of roundabouts with emphasis on the safety risks associated with the decision-making within the proximity of the roundabout; lane changing and choice, signs and marking interpretation, right-of-way, geometry, vehicle characteristics and gap choice.

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