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COMPARISON OF PROCEDURES TO ESTIMATE CRITICAL HEADWAYS AT ROUNDABOUTS

ABSTRACT

The capacity analysis of roundabouts in Portugal is mostly done using the UK regression method. Due to its empirical and non-explanatory nature, this method has some limitations, particularly for studying innovative layouts, which has recently motivated research in Portugal into the use of capacity methods based on gap-acceptance theory. This paper describes the results of a related project: the estimation of critical headways and follow-up times at Portuguese roundabouts. For this study, gap-acceptance data were collected at six roundabouts, in two cities, and used to estimate the parameters at each entry, for the left and right entry lanes independently. Several estimation methods were used (Siegloch, Raff, Wu, Maximum Likelihood and Logit). The results have revealed important specificities of the methods that have significant effects on the results and therefore on the capacity estimate exercises. The comparison of the estimates with reference values from several countries indicates significant differences, suggesting the existence of relevant driving style differences, which implies that locally calibrated, country-specific, parameters are required for capacity calculations.

KEY WORDS

roundabout, critical headway, follow-up time, capacity estimation, gap acceptance

1. INTRODUCTION

Roundabouts are becoming extremely popular in the world and widely used in urban and suburban areas. In Portugal, the current state of practice regarding roundabout design and capacity analyses is loosely based on the United Kingdom experience, with most practitioners relying on the Transportation Research Laboratory (TRL) capacity method [1]. This is an empirical method, based on linear regression over empirical data sets, that produces accurate estimates for roundabouts with standard geometric and traffic conditions. However, it is not suitable for studying innovative traffic solutions where a lane-by-lane analysis is required [2]. This limitation has recently motivated new research works in Portugal into the use of capacity methods based on gap-acceptance theory, in particular by focusing on the calibration of the headway distribution parameters [3], and on alternative methods for estimating the critical headways at unsignalized intersections [4].

This paper describes a related research that looks at the direct estimation of critical headways and follow-up times at one-lane and two-lane conventional roundabouts. The parameters were estimated independently for each entry lane, having in mind their use with the currently more powerful gap-acceptance capacity model – the Hagring's generalization of Tanner's formula [5]. This model is very flexible, allowing accurate capacity predictions even at non-conventional geometries, such as turbo-roundabouts [2, 6] or flower-roundabouts [7].

A dedicated data-collection and estimation process was preferred to the use of parameters from the specialized literature. The three main reasons for this are: a) critical headways and follow-up times depend on driver behaviour which is known to vary from country to country; b) the parameters used by some authors/institutions were not estimated from direct observations of driver's accept/reject decisions – they are, instead, the values that provide the best fit to a series of capacity measurements. This means that they come to depend on the assumptions and modelling simplifications used in the capacity calculations, and so they should not be used in other formulations; c) the study involved a comparative analysis of a number of different reference estimation techniques that help to complement the findings from a reference research article [8] on this subject, based on synthetic data (generated by randomized procedures).

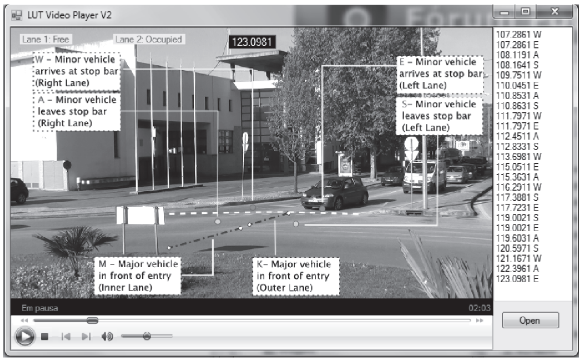

Figure 1 - A screenshot of the LUT|$_{VP2}$ application

2. DATA COLLECTION AND ANALYSES

2.1 Sample

Video recordings were made at six different roundabouts in the cities of Coimbra and Viseu, Portugal. Two of these are single-lane roundabouts (*Rainha Santa* and *Choupal*), one has two lanes at the entry and three in the circle (*VR Taveiro*), the remaining are standard two-lane roundabouts (two lanes at each entry, at each exit and at the circulatory ring). With the exception of the *Nelas Rbt*, a single entry was observed at each roundabout. The selection criteria were: a) existence of periods of continuous queuing (allowing the application of Siegloch's method), b) simple operations, uninterrupted by traffic lights or pedestrians, c) standard geometric design. At one of the sites (*Palmeiras Rbt.*, in Coimbra), an upstream pelican crossing was responsible for some traffic platoons; the corresponding periods were removed from the data file. The observation time ranged between 53 and 99 minutes per roundabout entry.

2.2 Data conversion

The collection and analysis of gap-acceptance data based on the stopwatch method is time consuming. Considering the large number of locations and estimation methods used in this study, a fully manual process was not an option. Therefore, a semi-automatic tool - LUT|$_{VP2}$ - was developed to facilitate this task. This tool was programmed in VB.NET and is essentially a video player application with full motion control, to which was added the possibility of marking specific events using the keyboard (*Figure 1*). Specifically, the user should press a key when a vehicle arrives at the stop bar (W – right lane, E – left lane) and when the same vehicle enters the roundabout (A – right lane, S – left lane), clearing the entry for new vehicles. Likewise, the user should mark the instants when the major vehicles are passing in front of the entry (M – inner lane, K – outer lane). Each of these events is associated with the corresponding instant and saved to a text file. The X key can also be pressed to indicate that the previous entry was incorrect and should be erased from the log. A new version (LUT|$_{VP3}$) of this application has recently been developed [4]. The main improvement is that time tagged points can be placed at specific locations on the screen via mouse input so that vehicle trajectories and speed profiles may be recorded.

The next step is to convert the raw data in the text file into a format suitable for the various gap-acceptance methods. To be consistent with similar projects in the USA [9] and Germany [10] it was decided to include only observations that contain at least one rejected lag, defined as the time from the arrival of the entering vehicle at the roundabout entry to the arrival of the first conflicting vehicle. The conversion was done using VBA macros in Excel. The set of reject / accept decisions and the corresponding explanatory variables (lane, headway, lanes used by the major vehicles and waiting time at the stop bar) were recorded for each minor vehicle. An example of these data is presented in *Table 1*.

The individual headways were calculated assuming that the entering vehicles yield to conflict vehicles both in the inner and outer lanes (superposed arrivals). This approach assumes that all conflicting vehicles have the same influence on the entering drivers' behaviour, which will be true for the left lane and generally conservative for the right lane [9]. The alternative approach – assuming that entering vehicles in the right lane yield only to traffic in the outer lane – was tried in an early stage, but abandoned after confirming that it would predict an unrealistic number of rejections of very large headways (more than 10 seconds).

3. ESTIMATION METHODS

The critical headway was estimated at each entry, using different methods (Siegloch, Raff, Maximum Likelihood, Wu and Logit). The following points give brief descriptions of these methods.

3.1 Siegloch

This method [11] is the only one directly connected with the capacity formulations [8]. It is also the only

Table 1 - Example of gap-acceptance data of a multilane roundabout

Minor ID	Decision	Major vehicles					Minor vehicles (left lane)		
		Leader		Follower		Headway	Arrival	Event time	Wait time
		Time	Lane	Time	Lane				
L1	ACCEPT	38.47	INNER	40.79	INNER	2.31	37.36	38.72	1.36
L2	REJECT	40.79	INNER	42.04	INNER	1.25	39.46	40.79	1.33
L2	ACCEPT	42.04	INNER	52.02	INNER	9.99	39.46	43.71	4.25
L5	ACCEPT	52.02	INNER	57.86	INNER	5.84	50.47	53.34	2.87
L6	REJECT	57.86	INNER	61.14	INNER	3.28	54.92	57.86	2.95
L6	ACCEPT	61.14	INNER	81.59	INNER	20.45	54.92	62.71	7.79
L10	REJECT	118.11	OUTER	119.39	INNER	1.28	118.06	118.11	0.05
L10	ACCEPT	119.39	INNER	126.96	INNER	7.57	118.06	120.67	2.61
L13	REJECT	126.96	INNER	128.55	INNER	1.60	125.76	126.96	1.20
L13	ACCEPT	128.55	INNER	133.80	INNER	5.24	125.76	130.27	4.51
L14	ACCEPT	133.80	INNER	138.40	INNER	4.60	132.32	134.87	2.55
L15	REJECT	138.40	INNER	139.92	INNER	1.52	137.83	138.40	0.57
L15	ACCEPT	139.92	INNER	143.40	OUTER	3.48	137.83	140.83	3.00

one that returns both the critical headways and follow-up times and requires the observation of saturated conditions (continuous queuing on the minor street). There is no universal criterion to define "continuous queuing". In the NCHRP Report 572 [9] it was assumed that a move-up time (time the next vehicle takes to move into entry position) of less than 6s indicates a queue condition. In this study, considering the congestion levels of most roundabouts, an additional threshold was used (4s) thus enabling the collection of more homogeneous data.

The estimation procedure is simple and does not require iterative calculations: for each gap *h* (headway, in recent publications) in the major stream one counts the number of minor vehicles *n* that enter the intersection. The observations are plotted in a graph, which allows the construction of an *h-n* regression line (see *Figure 2*, corresponding to Rainha Santa Rbt.). Before starting the regression the individual headways should be averaged for each occurrence of *n*, otherwise the numerous observations for the smaller headways would govern the whole result.

The follow-up headway (t_f) is taken directly from the graph and corresponds to the regression line *slope*. The critical headway (t_c) is given by the following equation:

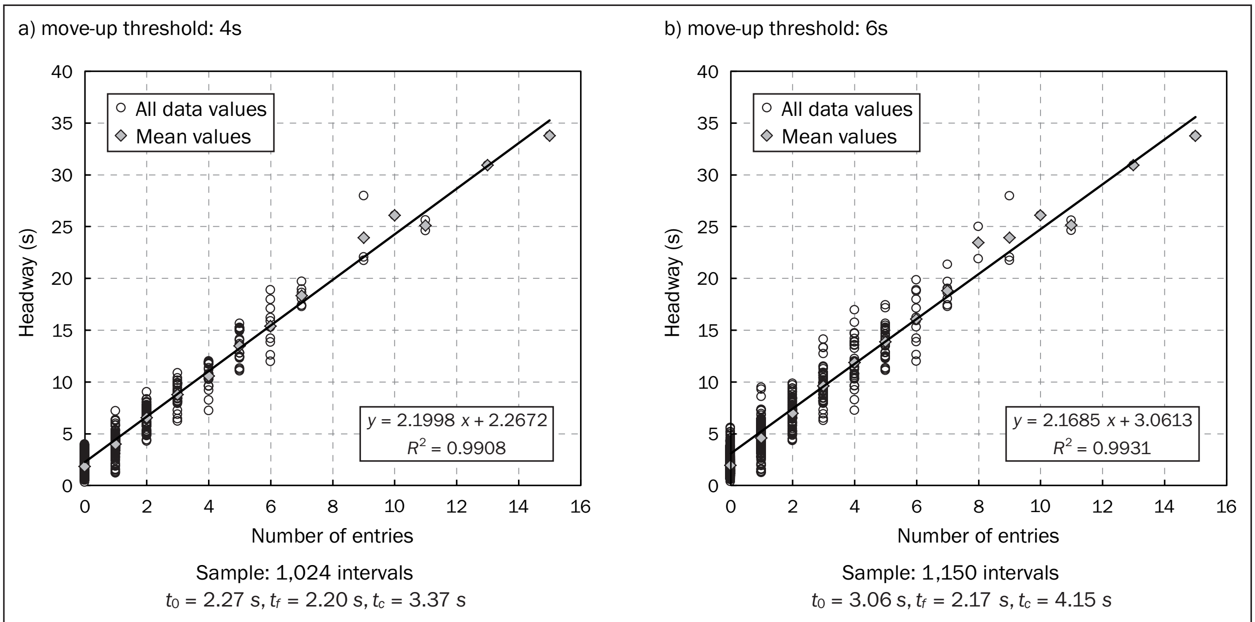

Figure 2 - Result of Siegloch's method at Ponte Rainha Santa Rbt.

$$t_c = t_0 + \frac{t_f}{2} \quad (1)$$

where t_0 is the *intersection* of the regression line ($h|_{n=0}$).

The choice of the move-up threshold, as discussed above, has a significant effect on the estimate of the critical headway (4 s → t_c = 3.37 s, 6 s → t_c = 4.15 s). The estimates of the follow-up time, on the contrary, are relatively stable (4 s → t_f = 2.20 s, 6 s → t_f = 2.17 s).

3.2 Raff

According to Raff's method [12] the critical headway is the value of t at which the functions $1 - F_r(t)$ and $F_a(t)$ intercept, where $F_a(t)$ and $F_r(t)$ are, respectively, the cumulative density functions (CDF) of the accepted and rejected (see *Figure 3*). Actually, according to Wu [13], this point does not correspond to the average of the critical headway distribution, but to its median. The $F_a(t)$ curve is based on the drivers who rejected at least one lag; regarding the $F_r(t)$ distribution, in order to be consistent with the other methods and to reduce the weight of the cautious drivers in the model, only the maximum rejected headway of each driver was considered.

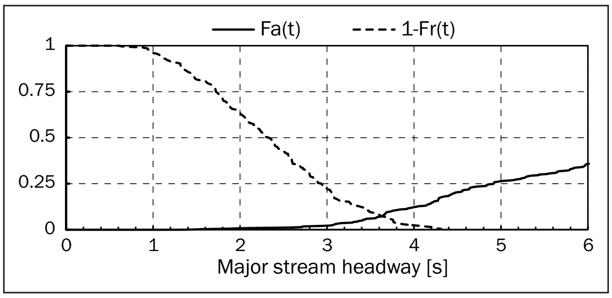

Figure 3 - Result of Raff's method at Ponte Rainha Santa Rbt. (t_c = 3.65 s)

3.3 Maximum likelihood

Maximum likelihood (ML) technique for the estimation of critical headways was originally suggested by Miller and Pretty [14] and described in detail by Troutbeck [15]. It is based on the decisions of those drivers that rejected one or more gaps. For each minor driver d it is necessary to record the accepted headway a_d and the largest rejected headway r_d. Drivers are assumed to be consistent and homogeneous, therefore the cases where $a_d < r_d$ must be excluded from the sample. The user must specify the general form of distribution $F_{tc}(t)$ of the critical headways (the log-normal distribution is often used). The likelihood that a driver's critical headway is between a_d and r_d is given by $F_a(a_d) - F_r(r_d)$. The optimal parameters of the distribution (location, μ and scale, σ) are those that maximize the likelihood function $\mathcal{L}^*$ for the sample of n observed drivers – Eq. (2). It is usually preferable to maximize the likelihood logarithm $\mathcal{L}$- Eq. (3), which provides more efficient calculations [16].

$$\mathcal{L}^* = \prod_{d=1}^{n} [F_a(a_d) - F_r(r_d)] \quad (2)$$

$$\mathcal{L} = \sum_{d=1}^{n} \ln[F_a(a_d) - F_r(r_d)] \quad (3)$$

Finally, the critical headway is calculated from the calibrated parameters as follows:

$$t_c = e^{\mu + \frac{1}{2}\sigma^2} \quad (4)$$

This method is often used under the assumption that opposing traffic at multilane intersections is superposed in a single lane. It has recently been adapted to enable estimation of the different critical gaps when a roundabout has two major lanes [17, 18].

3.4 Wu

Wu's method [13] is based on the equilibrium probability of the rejected and accepted headways. It does not require the predefined distribution function of the critical gaps, or assumptions about the consistency or the homogeneity of drivers. It yields the cumulative density function (CDF) of the critical gaps directly. The method can be easily implemented into a spreadsheet:

1. insert all measured and relevant (depending on whether all or only the maximum rejected gaps are taken into account) gaps t in the major stream into column 1 of the spreadsheet;
2. in column 2 mark the accepted gaps with "a" and the rejected gaps with "r";
3. sort all gaps (together with their marks "a" and "r") in ascending order;
4. calculate the accumulated frequencies of the rejected gaps, n_{rj}, in column 3 (that is: for a given row j, if mark = "r" then $n_{rj} = n_{rj} + 1$, otherwise $n_{rj} = n_{rj}$, with $n_{a0} = 0$)
5. calculate the accumulated frequencies of the accepted gaps, n_{aj}, in column 4 (that is: for a given row j, if mark = "a" then $n_{aj} = n_{aj} + 1$, otherwise $n_{aj} = n_{aj}$, with $n_{a0} = 0$)
6. calculate the CDF of the rejected gaps, $F_r(t_j)$, in column 5 (that is: for a given row j, $F_r(t_j) = n_{rj}/n_{r,max}$ with $n_{r,max}$ = number of all rejected gaps)
7. calculate the CDF of the accepted gaps, $F_a(t_j)$ in column 6 (that is: for a given row j, $F_a(t_j) = n_{aj}/n_{a,max}$ with $n_{a,max}$ = number of all accepted gaps)
8. calculate the CDF of the estimated critical gaps, $F_{tc}(t_j)$, in column 7: for a given row j, $F_{tc}(t_j) = F_a(t_j)/[F_a(t_j) + 1 - F_r(t_j)]$
9. calculate the frequencies of the estimated critical gaps, $p_{tc}(t_j)$, between row j and $j - 1$ in column 8, that is: $p_{tc}(t_j) = F_{tc}(t_j) - F_{tc}(t_{j-1})$
10. calculate the class mean, $t_{d,j}$, between row j and $j - 1$ in column 9 (that is: $t_{d,j} = (t_j + t_{j-1})/2$)

11. calculate the average value of the estimated critical gaps (that is: $t_{c,avg} = \text{sum}[p_{tc}(t_j) \cdot t_{d,j}]$)

In this application the same sample as in Raff's method was used: each driver who rejected one or more headways contributes with one or two values: his accepted headway and his maximum rejected headway (if any). In most cases the CDF estimated from Wu's model is comparable to the log-normal CDF of the Maximum Likelihood method.

3.5 Logit

In this method the gap-acceptance behaviour is described as a binary logit model in which the probability of a driver choosing alternative *i* (accept or reject a gap) is given by:

$$p(i) = \frac{e^{V_i}}{\sum_{i \in L} e^{V_i}} \tag{5}$$

where *L* is the set of available alternatives and V_i is the systematic component of the utility, defined as:

$$V_a = \beta_0 + \beta_1 v_1 + \ldots + \beta_n v_n \qquad V_r = 0 \tag{6}$$

where V_a and V_r are respectively the deterministic components of the utility of accepting or rejecting a gap, $v_0, \ldots, v_n$ are explanatory variables such as the gap size or waiting time, and $\beta_0, \ldots, \beta_n$ are parameters.

Combining equations (5) and (6) yields:

$$p_a = \frac{e^{V_a}}{1 + e^{V_a}} = \frac{1}{1 + e^{-(\beta_0 + \beta_1 v_1 + \ldots + \beta_n v_n)}} \qquad p_r = 1 - p_a \tag{7}$$

The parameters are estimated using the maximum likelihood method. The objective is to find the optimal values of $\beta_0, \ldots, \beta_n$ that maximize the log-likelihood function for the set of *N* observations:

$$L = \sum_{i=1}^{N} [y_A \ln(p_A) + (1 - y_A) \ln(p_R)] \tag{8}$$

where y_A takes the value 1 if the gap was accepted or 0 if it was rejected. The optimization can be done easily with the Solver tool in Excel or with statistical packages such as SPSS.

This method has been used to identify the influence of other independent variables in the critical headway, such as the waiting time, speed in the major road or even the rain intensity [19-21]. In the current project, two explanatory variables were used at first to define the systematic utility of accepting a gap – the headway in the major stream (t_h) and the waiting time of the entry vehicle at the stop bar (t_w):

$$V_a = \beta_0 + \beta_1 t_h + \beta_2 t_w \tag{9}$$

It should be noted that with this formulation a driver who accepts a gap smaller than one previously rejected cannot be defined as "inconsistent", since the waiting time can explain that behaviour. Therefore, all gaps should be included, not only the maximum one rejected by each driver.

It was found that, at most roundabouts, the ratio of the odds for the variable t_w had a 95% confidence interval that included the value 1. This means that, at $\alpha = 0.05$, the influence of the waiting time has no statistical significance and a simple model can be used. In this model the headway is the only explanatory variable and drivers are assumed to be consistent. The data sample was the same as that used in Raff's method – all accepted gaps and the largest rejected gap of each driver. The critical headway is that which returns a 50% acceptance probability [22].

3.6 Summary of results and discussion

The results of the estimation procedures are summarized in *Table 2*. Several conclusions can be drawn:

- The results are reasonably consistent for all methods. The estimates from Siegloch's are very dependent on the move-up time threshold used to classify the saturation periods. The 6 seconds threshold results in estimates that are, in global terms, similar to the ones from the remaining methods. However, this threshold is not small enough to guarantee samples constituted only by unperturbed entry manoeuvres, which results in some inconsistent estimates (as, for example, in *Pedrulha Rbt.*, left lane, where lane change manoeuvres are frequent);
- At one of the roundabouts (*Choupal*) the estimate from Maximum Likelihood method is considerably higher than the rest. A similar result is reported by Luttinen [23] and that is because, under very low opposing flows, the information about the drivers' availability to accept shorter gaps is missing from the sample (the method discards drivers who have not rejected at least one gap);
- At multilane roundabouts, the critical headway is usually smaller at the right-lane entry. The south entry of the *Nelas Rbt.* is an exception, which may be explained by the similar traffic pattern at the left and right entries - most drivers take the north exit and very few turn right;
- For the *VR Taveiro Rbt* the estimates from the Logit method are clearly the lowest.
- Wu and ML methods produce very similar estimates.

4. CAPACITY ESTIMATIONS

The estimation of the critical headways and follow-up times should be seen not as an end in itself but as an intermediate step towards more accurate capacity estimations. Therefore, it is natural to ask "which are the methods that result in the best capacity estimates?". This question is not easy to answer because these parameters, associated with a simple gap-acceptance model, can explain only part of the variation

Table 2 Critical and follow-up headways times for the complete sample

Round-about	Entry	Lane	Sample data			Method / Sample Set							
						Siegloch / A				Raff	Wu	Trout.	Logit
						MUT(*): 4 s		MUT(*): 6 s		B	B	C	B
			Length	Entries	Oppos.	t_c	t_f	t_c	t_f	t_c	t_c	t_c	t_c
			(min)	(veh)	(veh)	(s)	(s)	(s)	(s)	(s)	(s)	(s)	(s)
Choupal	N	--	54	1053	246	3.76	2.18	4.27	2.08	3.90	3.75	4.28	3.54
R. Santa	E	--	99	1181	1245	3.37	2.20	4.15	2.17	3.65	3.56	3.73	3.54
Nelas	W	L	53	524	756	3.14	1.94	3.72	1.99	3.40	3.55	3.63	3.26
Nelas	W	R	53	721	756	3.11	1.95	3.33	2.11	3.11	3.22	3.31	3.07
Pedrulha	W	L	76	819	553	2.95	2.42	4.46	2.33	3.09	3.98	3.88	3.59
Pedrulha	W	R	76	1137	553	2.52	2.32	3.19	2.42	3.57	3.68	3.75	3.31
Nelas	S	L	54	489	664	3.06	2.25	3.78	2.26	3.28	3.30	3.37	3.11
Nelas	S	R	54	671	664	3.02	2.16	3.38	2.64	3.39	3.46	3.60	3.33
Palmeiras	S	L	59	252	977	2.96	2.35	3.55	2.78	3.65	3.68	3.56	3.49
Palmeiras	S	R	59	421	977	2.62	2.36	3.12	2.56	3.30	3.20	3.29	3.07
VR Taveiro	W	L	73	1198	931	3.19	2.16	3.43	2.13	3.03	3.15	3.25	2.75
VR Taveiro	W	R	73	1165	931	2.69	2.37	2.88	2.38	2.97	3.02	3.19	2.56

Sample sets: A: all gaps (saturated conditions); B: accepted gaps and largest rejected gap of each minor vehicle; C: accepted gap and largest rejected gap of drivers that rejected at least one headway.
(*) MUT: move-up threshold

observed in capacity measurements. For example, Siegloch's formula (used in HCM 2010) assumes exponential arrivals in the major stream and only one circulatory lane. If this formula is to be used under different traffic conditions, the parameters that result in the best estimates will, most probably, be biased from the real ones because they have the additional role of counterbalancing the model specification errors.

In order to minimize the influence of the specification errors, a generalized Tanner's formula [5], was used to estimate the capacity at the roundabout entries identified in the previous section. This formula yields the capacity for a minor stream crossing or merging independent major streams, each having a Cowan's M3 headway distribution:

$$C_k = \frac{e^{-\sum_{i\in I_k}\lambda_i(t_{c,i}-\Delta_i)}\sum_{i\in I_k}\lambda_i}{1-e^{-\sum_{i\in I_k}t_{f,i}\lambda_i}}\prod_{i\in I_k}\frac{\phi_i}{\phi_i+\lambda_i\Delta_i} \tag{10}$$

where k is the minor stream index, I_k is the set of major streams i conflicting with the minor stream k, ϕ_i, Δ_i and λ_i are the parameters of the headway distribution for each of the opposing lanes, and $t_{c,i}$ and $t_{f,i}$ are, respectively, the critical headway and the follow-up headway for each opposing lane i at entry lane k.

Assuming that at two-lane roundabouts both circulatory lanes of a given entry have the same gap-acceptance parameters ($t_{c,1} = t_{c,2}$ and $t_{f,1} = t_{c,2}$), the particular models for one and two opposing lanes are given, respectively, by Eq. (11) and Eq. (12).

$$C = \frac{q\phi\exp[-\lambda(t_c-\Delta)]}{1-\exp(-\lambda t_f)} \tag{11}$$

$$C = \frac{\exp[-(\lambda_1+\lambda_2)(t_c-\Delta)](\lambda_1+\lambda_2)}{1-\exp[-t_f(\lambda_1+\lambda_2)]}\cdot \cdot\frac{\phi_1\phi_2}{(\phi_1+\lambda_1\Delta)(\phi_2+\lambda_2\Delta)} \tag{12}$$

The first relation between the three Cowan M3 parameters (ϕ, λ and Δ) stems from the method of moments - Eq. (13) which ensures that the mean of the estimated distribution is equal to flow q.

$$\lambda = \frac{\phi q}{1-\Delta q} \tag{13}$$

The second relation is required to solve the remaining indetermination. This relation, also known as a 'bunching model', indicates the proportion of free vehicles in the traffic stream (not driving in platoons) and can take different shapes such as linear, bi-linear, or exponential [24-26]. A bi-linear relation calibrated in a previous work for another set of roundabouts was used for this analysis [3]:

$$\phi = \begin{cases} 1 & \text{if } q < 0.178 \\ 1.553(1-2q) & \text{if } 0.178 < q \le 0.5 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

The above bunching relation was calibrated assuming an intra-platoon headway parameter $\Delta = 2s$. Therefore, the model predicts null capacity when one or more opposing lanes have flows above $1/\Delta$ (0.5 veh/s or 1,800 veh/h).

At each roundabout entry, the capacities were estimated using the parameters given by the different methods and then compared against observed capacities. These observed capacities were calculated for the

1-minute aggregation periods that fulfilled the continuous demand criteria (move-up threshold < 6s), once again keeping consistency with the NCHRP 572 report methodology. The adoption of such short intervals results in larger samples but also leads to increased variation due to the random nature of the gap-acceptance process. The results are presented in *Figure 4* for the six entries where at least 20 congested periods were observed. It can be concluded that while capacities estimated using parameters from the different methods are generally within the range of observed capacities, at two sites (Rainha Santa Rbt. And VR Taveiro - R) the

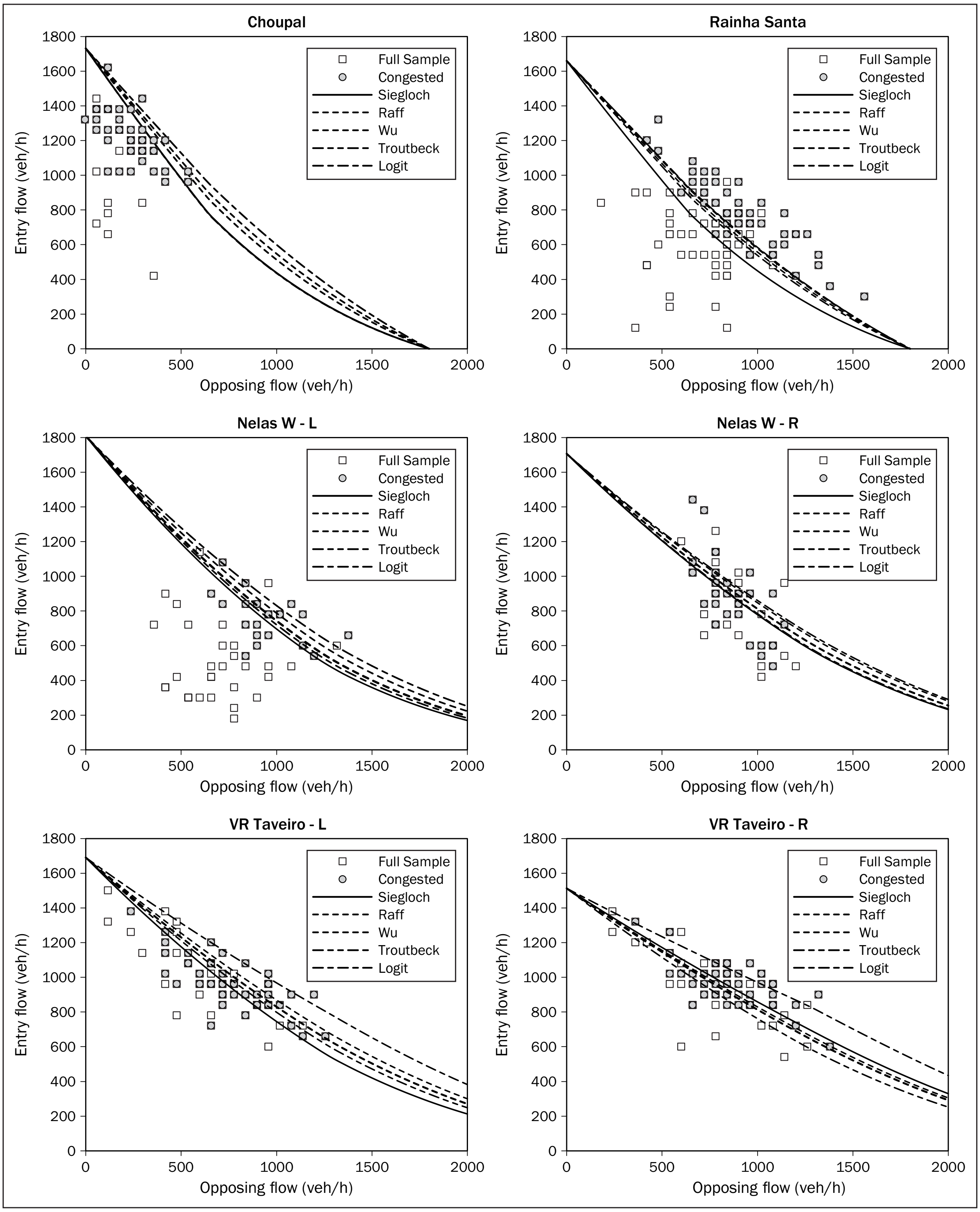

Figure 4 - Comparison between observed and estimated capacities

Siegloch and Logit methods performed less satisfactorily. Conversely, capacity estimates using parameters form Raff, Wu or Troutbeck methods are consistently accurate, without a clear advantage of each one.

5. REFERENCE VALUES

The roundabout sample used in this study is limited and thus cannot be taken as fully representative of Portuguese roundabouts. However, the results indicate a trend. Disregarding extreme cases, and taking the more traditional methods (Raff and Maximum Likelihood) as reference, the critical headway at the sample roundabouts varies between 3.2 and 3.7 seconds. The follow-up time, from Siegloch's method, varies between 2.1 and 2.3 seconds. These results can be compared with reference values used in other countries, as presented in *Table 3*.

It can be seen that the critical and follow-up headways in Portugal and Spain are remarkably similar and smaller than those in northern and eastern European countries (Denmark, Sweden and Germany and

Table 3 - Summary of critical and follow-up headways

Country	Critical headway, t_c (s)	Follow-up time, t_f (s)	Observations
AUSTRALIA			Model based on conflicting flow, number of lanes, diameter, and entry width [27] (cited in [9])
1-lane	1.4 – 4.9 (2.9)	1.8 – 2.7	
2-lane (dominant lane)	1.6 – 4.1 (2.9)	1.8 – 2.2	
2-lane (subdominant lane)	--	2.2 – 4.0	
DENMARK			Parameters estimated by regression [28]
1-lane, urban	5.1	3.0	
1-lane, rural	4.7	3.0	
2-lane, rural	4.0	2.6	
GERMANY			[x/y]: number of lanes: entry/circle; In the original only final capacity formulas are provided. These are the parameters that provide the best fit using Siegloch's capacity formula [29]
[1/2] 40 ≤ DCI ≤ 60 m	5.6	2.5	
[2/2] compact 40 ≤ DCI ≤ 60 m	5.2	2.2	
2/2 large DCI > 60 m	4.4	2.9	
ISRAEL			Logit method with waiting time as independent variable. Value for a 10s waiting time [20]
1-lane, urban/sub-urban	4.0		
POLAND			Parameters estimated by regression [30]
Medium 2-lane (L)	4.3	3.3	
Medium 2-lane (R)	4.6	3.6	
Large 2-lane (L)	3.8	2.6	
Large 2-lane (R)	4.2	2.9	
Semi 2-lane	4.7	2.8	
SLOVENIA	4.8	2.9	Data collected from Seven single-lane roundabouts across the country [31]
PORTUGAL	3.2 – 3.7	2.1 – 2.3	Maximum Likelihood, Raff , other methods (from current limited observations)
SPAIN	3.3 – 3.5	≈ tc / 2	[32]
SWEDEN			Maximum Likelihood method generalized for multilane roundabouts [17]
2-lane roundabouts (L)	4.4 – 4.6		
2-lane roundabouts (R)	4.0 – 4.3		
UNITED STATES			(*) Maximum Likelihood method [9]
HCM 2000	4.1 – 4.6	2.6 – 3.1	
NCHRP 572 (*)			
1- lane roundabouts	4.2 – 5.9	2.6 – 4.3	
2- lane roundabouts (L)	4.2 – 5.5	3.1 – 4.7	
2- lane roundabouts (R)	3.4 – 4.9	2.7 – 4.4	

Poland), supporting the view that these parameters should not be directly transferred from other countries with significant cultural differences.

The variability of the parameters within each country is also significant suggesting that there is scope for an attempt to create a more generalized estimation approach. This might be done namely by taking advantage of the potential presented by the logit method to take into consideration the influence of different explanatory variables, as might be some related to the geometry of each roundabout and not only ones related with waiting time. There is also scope for new estimation methods, based on microscopic modelling of vehicles, which can lead to accurate estimates based on measurable variables such as the geometric characteristics and vehicle dynamics.

6. CONCLUSION

In many countries, most operational analyses of roundabouts are performed using the TRL regression method. The limitations of this model motivated the research team to study and improve the capacity models based on gap-acceptance theory and this paper describes a fundamental task within this project – the estimation of local values for critical and follow-up headways. Five methods were used, all based on observations. These methods have some specific characteristics that should be noted:

- Siegloch's method requires the observation of saturated conditions, i.e. continuous queuing on the minor road, but it is the only one that also yields the follow-up headway; its estimates are highly dependent on the follow-up time used to identify the saturated periods;
- Raff's method is extremely simple and no iterative calculations are required;
- Wu's method is similar to Raff's. It has the advantage of returning the true average of the critical headway (Raff's method returns the median). It addition, this method yields the empirical distribution of the critical headways, which may be useful for microscopic simulation;
- Maximum likelihood or Troutbeck's method is considered a reference by major transportation agencies. It is highly data-demanding because it only uses the accepted headway and the largest rejected headway of the drivers who rejected at least one gap. Therefore, it produces biased estimates when the opposing flow is very low (cf. *Table 4* – Choupal Rbt.);
- The Logit method allows the explicit use of independent variables other than the headway; in this application, the waiting time at the stop bar was used but its effect was not statistically significant for most roundabouts.

From a limited sample (seven entries at six roundabouts) it was found that the results are consistent for the methods studied. The parameters are usually slightly lower for the right entries and significantly lower for the three-lane roundabouts. The comparison between estimated and observed capacities, based on a limited sample size, suggest that Raff, Wu and Troutbeck methods are the more reliable.

The comparison of these results with reference values from other countries strongly suggests that Portuguese (and Spanish) drivers are more aggressive than northern/eastern European drivers, which supports the need to use locally calibrated parameters in capacity formulas.

Finally, it is worthwhile noting that the data collection and estimation of these parameters is a complex and time-consuming task, even with the aid of automatic procedures, and it is unrealistic to expect to have locally calibrated parameters for every geometric and operational scenario. Therefore, there is scope for new auxiliary methods that can help with the adjustment of these reference values to take into consideration the influence of different explanatory variables, such as special geometric configurations, demand patterns or driver/vehicle dynamics.

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RESUMO

COMPARAÇÃO DE MÉTODOS DE ESTIMAÇÃO DE INTERVALOS CRÍTICOS EM ROTUNDAS

A análise de capacidade de rotundas em Portugal é feita essencialmente com base no método de regressão do Reino Unido. Devido à sua natureza empírica, este método tem algumas limitações, particularmente quando está em causa o estudo de geometrias inovadoras. Neste âmbito, foi recentemente iniciada em Portugal uma linha de investigação que visa a transição para métodos baseados na teoria de gap-acceptance. Este artigo descreve uma das vertentes dessa investigação: a estimação de intervalos críticos e mínimos *em rotundas portuguesas. Para o efeito, foram recolhidos dados de tráfego – fluxos e decisões de aceitação/rejeição de intervalos – em seis rotundas de duas cidades, independentemente para a via da esquerda e da direita. A estimação dos intervalos críticos e mínimos baseou-se em diversos métodos (Siegloch, Raff, Wu, Máxima Verosimilhança e Logit). Os resultados demonstraram que os métodos têm várias especificidades que afetam as estimativas dos intervalos e consequentemente das capacidades. Foi também feita uma comparação com valores de referências de outros países, tendo-se constatado diferenças significativas, o que sugere a efetiva existência de diferenças comportamentais e reforça a necessidade de calibrar os parâmetros de gap-acceptance para as condições locais.*

PALAVRAS-CHAVE

rotunda, intervalo crítico, intervalo mínimo, estimação de capacidade, gap-acceptance

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