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Variable's prediction of gap acceptance roundabout capacity model – Critical gap

Predicción de variables del modelo de capacidad indirecta de aceptación de brechas – Brecha

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ABSTRACT

Introduction: The research relevance is determined by the assessment of the capacity of roundabouts and their efficiency are extremely important topics in transport engineering research. As road networks are constantly growing in size and complexity, congestion and insufficient flow capacity are becoming serious problems for traffic. The research aims to determine the critical interval at a certain roundabout using several statistical methods and to compare the results obtained by each of them, respectively. **Material and Methods:** The statistical methods used in the study included the Ruff, Wu, Troutbeck, Ashworth, and standard deviation methods. **Results and Discussion:** The results of the study show that the difference between the five methods is minimal, although each method has its characteristics. The analysis of the critical interval for the left and right bands showed that different methods may vary in their estimates, but the overall picture remains within acceptable convergence. The difference between the Wu method and the other methods was found to be negligible, except for the Ashworth method, which has a significant difference in the definition of the critical interval. **Conclusion:** Thus, all five methods can generally be used to calculate the critical interval at roundabouts. However, due to its simplicity and reliability, the Wu method was recommended for use. The practical significance of the study is that the results provide important guidance and information for the design and management of roundabouts. Estimation of the critical spacing is key to determining the optimal traffic flow regime, which affects safety, flow capacity and convenience for drivers.

Keywords: Transport engineering; Traffic flow; Road networks; Critical interval; Congestion.

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INTRODUCTION

In the context of intensive development of transport infrastructure and growing traffic volumes, an important task is to ensure the safety and efficiency of road traffic. One of the key components of this task is the analysis and modelling of intersections, including roundabouts. Roundabouts have gained popularity due to their ability to optimise traffic flow and reduce congestion, but their effectiveness is highly dependent on understanding and modelling the key parameters that determine their capacity. An important aspect that affects the capacity of roundabouts is understanding the behaviour of drivers entering and exiting the junction (1). Over the past two decades, roundabouts have seen rapid adoption worldwide, with over 60.000 currently in use across the globe. Analysis of data from the UK, Australia, Canada, and other countries finds that the number of roundabouts has often doubled or even tripled within 10-15-year periods. For example, the United Kingdom has implemented over 10.000 roundabouts to date. Germany has seen its roundabout total rise from under 100 in the early 1990s to approximately 3.000 by 2015. And numerous cities globally from Bellingham, Washington to Carmel, Indiana in the United States have embraced aggressive roundabout installation campaigns. With enhanced understanding of roundabout capacity and performance, transportation departments can facilitate their burgeoning popularity (2).

In this context, the concept of critical interval is key, as it defines the minimum time a driver can safely enter a roundabout between two vehicles. Understanding and accurately estimating this parameter is critical to developing traffic models and adapting them to real-world traffic conditions. The "critical gap" in traffic engineering is a crucial concept for modeming the capacity of roundabouts, representing the minimum time gap a driver needs to safely enter a roundabout. Its importance lies in directly affecting the roundabout's efficiency and safety, where a smaller gap suggests higher traffic flow and capacity, while a larger gap indicates lower efficiency (3,4). Various methods like the Raff, Wu, Troutbeck, and Ashworth methods estimate this gap, considering factors like driver behaviour, road conditions, and vehicle interaction. Accurately determining the critical gap is essential in traffic management, as it influences roundabout design, traffic flow optimization, and congestion reduction.

According to H.A. Al-Jameel and A.J. Kadhim (2), a detailed review of various methods for determining the critical interval in the context of traffic research is a key stage of analysis. The variety of methods available allows researchers to choose the most appropriate approach for a particular situation or task. A detailed review of different methods helps to improve understanding of their advantages, limitations, and differences. Following H. Muslim and M. Itoh (5), the analysis of the interaction of different types of vehicles on the critical interval is also one of the important aspects in the study of traffic on roads and intersections. The interaction between different road users can affect the traffic flow, speed, and therefore the determination of the critical interval. Since different types of vehicles have different driving characteristics and behaviour, their interaction can create complex situations that need to be considered in research.

L.Q. Shadhan and Z.A. Alkaissi (6) studied an aspect that is sometimes overlooked in research, namely the impact of weather conditions on critical intervals. Their study highlights changes in atmospheric conditions, such as rain or snow, as factors that can make significant changes to driver behaviour and safety. Considering the influence of weather conditions can make a significant contribution to the determination of the critical interval and provide more accurate and practically applicable recommendations for road safety in different weather conditions. The results of the study of K.H.H. Shubber (7) are also essential for understanding the impact of modern technologies on the determination of the critical interval on roads. This study demonstrates the capabilities of intelligent transport systems to effectively manage traffic and reduce the negative impact on traffic flow. Particular attention is focused on the ability of such systems to optimise traffic at intersections and coordinate traffic lights. Automatic traffic control is important since it can respond to changes in real-time and consider traffic dynamics, which helps to avoid congestion and reduce waiting time on the road (8,9).

Y.A. Mansoor Al- Al-Kubaisy (10) focused on the difference in driver behaviour in different regions and its impact on critical intervals. According to the conclusions, a more aggressive driving style is prevalent in some areas, where drivers tend to take risky manoeuvres and drive faster. Considering such behavioural characteristics becomes an important aspect when determining the critical interval, as it affects the safety and prediction of drivers' actions while driving. A.A. AbdulMawjoud (11) determined that comparing the results of the critical interval with the standards and recommendations that determine traffic safety and efficiency is a necessary step to assess the compliance of research findings with industrial standards and requirements. This allows to determine the extent to which the results can be applied in practice and how the' contribute to improving the safety, convenience, and efficiency of road traffic.

In general, the critical interval reflects an important interaction between various factors that influence the decision-making process when entering a junction. In this regard, the research aims to determine the value of the critical interval for a particular roundabout and to compare and evaluate the effectiveness of different statistical methods for determining the critical interval. This will provide a more accurate understanding of the dependence of the critical interval on various factors and circumstances and provide a basis for further improvements in road safety and traffic efficiency.

MATERIALS AND METHODS

A four-lane roundabout located in the urban area of Sulaymaniyah, Kurdistan Region, Iraq, was selected for the study. This roundabout is an unsignaled intersection located at the intersection of Shekh Salam Road, Meer Road and Yilmaz Gonai Road. The diameter of the intersection is 67 metres, and it has two inbound lanes. The inventory survey and video recording were conducted on Monday, Tuesday, and Wednesday of the week at three-day intervals, covering the peak hours. Each interval lasted three hours (from 7:00 to 10:00, 12:00 to 15:00, and 16:30 to 19:30). Video recording was carried out in favourable weather conditions. The recorded video was played back using video playback software, PotPlayer media player, to obtain data on traffic intensity and analyse data on the allowed intervals. Using a classified vehicle count, the values of the incoming and circulating flows were determined for each section of the selected roundabout.

The video was processed manually by collecting timestamps at specific events using AVS Video Editor 9.6 Online Media Technologies Ltd. This software creates lines on each video corresponding to the locations where the timestamps were obtained. The critical interval cannot be measured directly at roundabouts because drivers will accept all intervals that exceed their critical interval. Intervals can only be divided into those that are accepted and those that are rejected by drivers. Therefore, five different methods of determining the critical interval were applied to best validate the theoretical values. The most well-known methods have been used and reviewed, namely, the Raff, Trautbeck, Root Mean Square (RMS), Wu, and Ashworth methods.

Raffa's method. To apply it, two cumulative frequency distributions were created, one for the rejected intervals and the other for the allowed intervals. They define the critical interval tc as the value of t at which the functions $1 - F_r(t)$ and $F_a(t)$ intersect:

$$F_a(t) = 1 - F_r(t), \tag{1}$$

That is, the value of t is estimated as a critical interval, where t – main traffic speed; $F_a(t)$ – is the cumulative distribution function (CDF) of the accepted interval, and $F_r(t)$ is the CDF of the rejected interval. The probabilities of accepted and rejected intervals were determined. On-site measurements can also be used to empirically determine $F_a(t)$ and $F_r(t)$. The probability that an interval of length t will not be rejected (($1 - F_r(t)$) and that it will be rejected (($F_r(t)$) is thus observed. It estimates the average critical interval by constructing the CDF of accepted intervals $F_a(t)$ and the inverse CDF of rejected intervals $F_r(t)$.

Maximum likelihood method (Trautbeck). This method calculates the average critical interval for all drivers, as the driver's critical interval is between two observed values: the largest rejected interval and the accepted driver's interval. A lognormal distribution was used to determine the critical interval. The probability of a critical interval between r_i and a_i for an individual driver is $F(r_i)$, $F(a_i)$. Summing up for all drivers, the probability that a sample of n drivers accepted and rejected the intervals (a_i, r_i) is shown in formulas (2, 3). The maximum likelihood method calculates the probability that the critical interval tc is between r_i and a_i. The probability that the driver's critical interval is between r_i and a_i is defined as $F(a_i) - F(r_i)$. By maximising this probability function, the parameters μ and σ^2 are obtained. The mean and variance of the logarithms of the critical interval (m and s^2) were calculated using formulas (2-4):

$$L = \sum_{i=1}^{n} ln((F(a_i) - F(r_i)), \quad (2)$$

$$\sigma^2 = ln\, ln \left(\frac{s^2}{m^2} + 1\right), \quad (3)$$

$$\mu = ln\, ln\, (m) - 0.5 * \sigma^2, \quad (4)$$

where: a_i – the logarithm of the accepted interval for ith driver; r_i – the logarithm of the largest rejected interval for the ith driver (r_i is 0 if no interval was rejected); $F(a_i)$ – the CDF of the accepted intervals; $F(r_i)$ – the CDF of the largest rejected interval; L – the probability of a critical interval; m – the mean value; s – the standard deviation; a – a sample of n observed drivers.

Wu's method. This method determines the critical interval based on an equilibrium calculated macroscopically from the cumulative distributions of accepted and rejected intervals. Using the data, this method calculates the probability of occurrence of any interval. Then the accumulated frequencies of these probabilities are calculated. Based on these accumulated frequencies, probability distribution functions are calculated for the critical, acceptable, and rejected intervals. The average value gives the value of the critical interval. This method is easily implemented in a table and is defined by the following expression:

$$F_{tc} = \frac{F_a(t)}{F_a(t)+1-F_r(t)} = \frac{1-F_r(t)}{F_a(t)+1-F_r(t)}, \quad (5)$$

Ashworth method. This method assumes that the circulation flow intervals are exponentially distributed with probability independence between consecutive intervals and a normal distribution for ta and tc. The solution may become more complicated if ta is not normally distributed. This method does not use data on rejected intervals, but only data on acceptable intervals. The mean critical clearance tc can be determined by estimating the mean of the acceptable clearances ta; in seconds (mka), the standard deviation of the acceptable clearances (σ_a), and "p" is the circulating traffic flow (v/s) using the following equation:

$$t_c = \mu_a - p * {\sigma_a}^2, \quad (6)$$

RMS method. The RMS, or mean square, is a statistical measure. In statistics, it is calculated as the square root of the sample mean. The RMS of a set of values is the square root of the arithmetic mean of the function that defines the continuous variable. The critical interval was estimated by minimising the objective function in equation (7) (the sum of the RMS values of the function for each data set) by adjusting the value of the critical interval provided at random. Since this is an iterative process, the Excel "Solve" function was used:

$$RMS = \sum_{i=1}^{n} \sqrt{\frac{(t_{ai}-t_c)^2+(t_c-t_{ri})^2}{2}}, \tag{7}$$

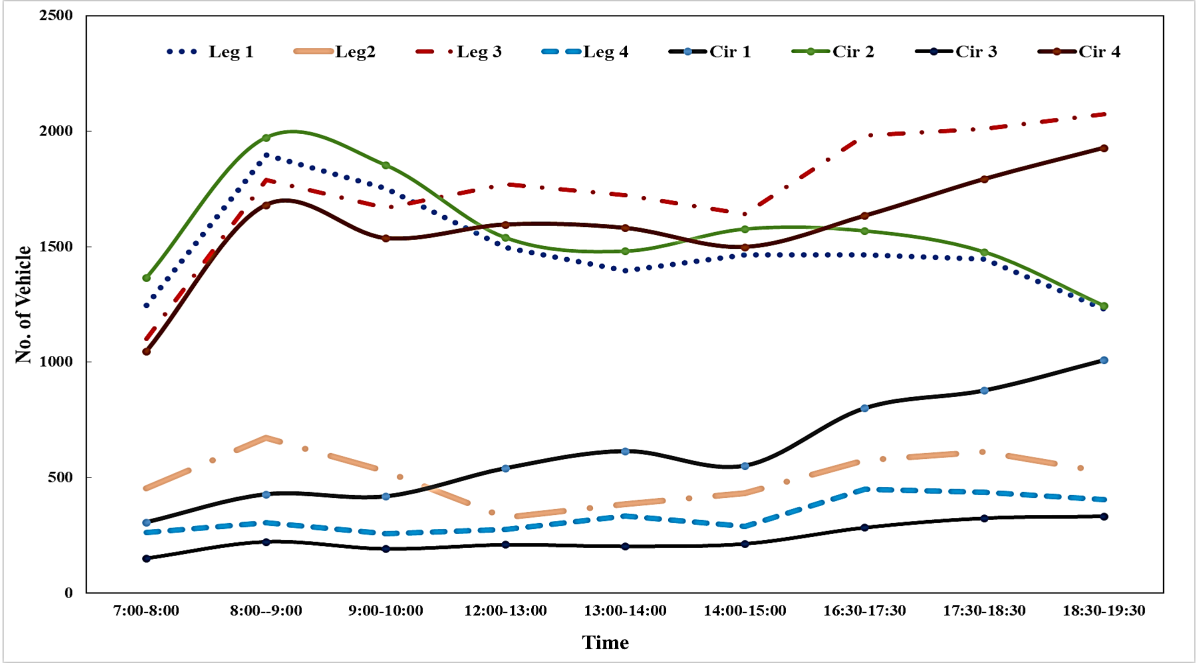
where: t_{ai} – the accepted interval for individual vehicle i; t_{ri} – the rejected interval for individual vehicle i; t_c – the critical interval value.

Thus, these methods were selected based on an extensive analysis of the literature and previous comparative studies of critical gap analysis techniques. The goal was to choose a diverse set covering the spectrum of simple probability-based approaches like Raff's, to more computationally intensive methods like Troutbeck's maximum likelihood. Additionally, these methods were preferred due to substantial evidence of their capability to produce valid results for critical gap assessment and their widespread usage in past roundabout capacity research. Other newer or more complex methods were excluded at this stage due to limited verification of their effectiveness on real-world mixed traffic data. However, evaluating different emerging approaches could form a useful extension of the research in future.

RESULTS

According to the vehicle counts, the traffic flow in the selected section was characterised by volumes ranging from 232 to 2259 vehicles per hour. The traffic entering the roundabout from all four directions was 4809 vph and 4507 vph during the morning and evening peak periods, respectively. The maximum number of vehicles circulating the roundabout was 4459 vph and 4587 vph in the AM and PM peak periods, respectively (Figure 1).

Figure 1. Traffic volume at a roundabout



Source: compiled by the authors.

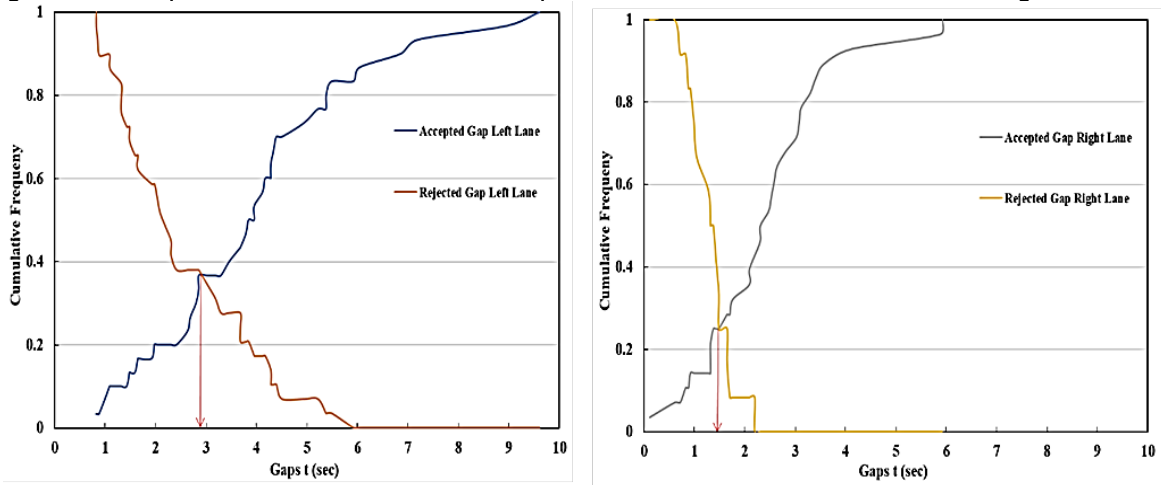
Figure 2 shows the location of timing marks at a roundabout. The lines marked for the roundabout (red line), left-turn and right-turn (green line) are perpendicular to the traffic flow.

Figure 2. An example of time stamps

Source: compiled by the authors.

In the process, the intervals were collected from the roundabout data and the critical interval was calculated using the Raffa method. After that, the cumulative probabilities were calculated and a graph illustrating the cumulative probability of accepted and rejected intervals was constructed. The value of the critical interval was determined by intersecting the two cumulative distributions of accepted and rejected intervals. Figure 3 shows the cumulative probabilities of obtaining the critical interval for the left and right lanes. The critical interval is the value of t at which the functions $1 - F_r(t)$ and $F_a(t)$ intersect. The Raff method gives a critical interval value of 2.89 seconds for the left lane, while for the right lane, it is only 1.5 seconds.

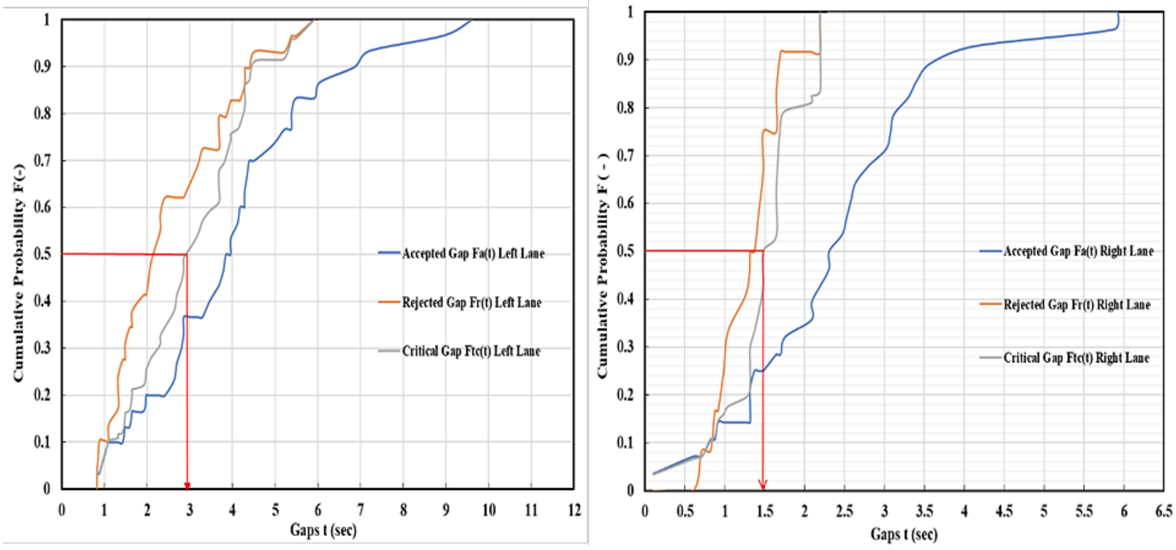
Figure 3. Analysis of the critical interval by the Raff method for the left and right lanes



Source: compiled by the authors.

The Wu method uses the extracted data to determine the probability of occurrence of any interval. Figure 4 shows the graphs obtained using this method for the left and right lanes. The critical interval for the left lane is 2.997 seconds, and for the right lane, it is 1.49 seconds.

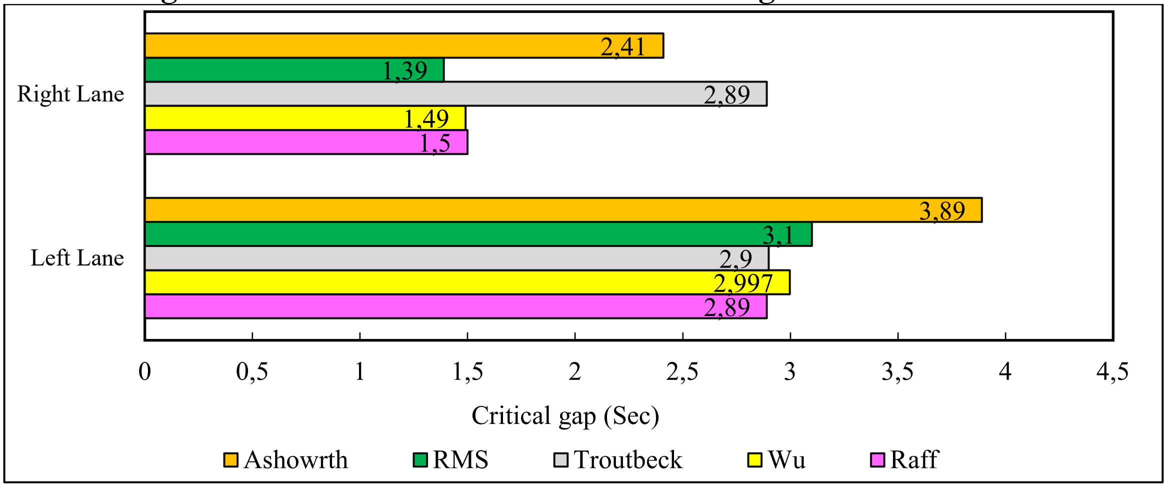
Figure 4. Construction of the critical interval for the left and right lanes by the Wu method



Source: compiled by the authors.

The Trautbeck method used the SOLVER procedure to maximise the likelihood, and the mean and standard deviation for the left lane converged to 2.9 sec and 0.046 sec, respectively. However, it should be noted that the mean and standard deviation for the right lane were 2.89 sec and 0.0644 sec, respectively. The Ashworth method, in turn, used only the mean and standard deviation of the adopted interval and circulating flow. The result of the Ashworth method for the critical interval is 3.89 and 2.41 seconds for the left and right lanes, respectively. The RMS value of a data set is equal to the square of the function describing a continuous variable or the arithmetic mean of the values. The result of the standard deviation method for the critical interval is 3.1 and 1.39 seconds for the left and right bands, respectively (Figure 5).

Figure 5. Results for each method of estimating the critical interval



Source: compiled by the authors.

It should be noted that the difference between the results of the five methods is minimal. As shown in Figure 5, the critical values for the left lane range from 2.89 to 3.89 seconds, and the right lane – from 1.39 to 2.89 seconds. The value of the critical interval for the left lane determined by the maximum likelihood (Trautbeck) method is much closer to the value of the critical interval determined by the Raff method, while the value obtained for the right lane by the Raff method is lower than the value for the right lane by the Trautbeck method. The value of the critical interval determined by the Wu method is much closer to the value determined by the RMS method. For the left band, the Ashworth method predicts a larger value of the critical interval, while the Raff method predicts a smaller value. The estimates of the critical interval by the Wu, Trautbeck, and Raffa methods are much closer to each other. On the other hand, the Raff method estimates a smaller critical spacing for the right lane, while the Trautbeck method estimates a larger critical spacing for the same lane. Table 1 shows a comparison of the five methods, with the Wu method as the baseline. The difference between the Wu method and the other methods is small, except that the Ashworth method has a 23% difference for the left lane and a 38.2% difference for the right lane. Theoretically, any of these methods can be used to calculate the critical spacing at roundabouts. Because of its ease of use, the Wu method was recommended in this study.

Table 1. Comparison of results obtained using different methods

Lanes	Critical gap (sec)				
	Wu method	**Raff's method**	**Troutbeck (MLM) method**	**Ashworth's method**	**RMS method**
Left lane	2.997	2.89	2.9	3.89	3.1
Difference %		-3.7	-3.34	23	3.32
Right lane	1.49	1.5	2.89	2.41	1.39
Difference %		0.66	48.44	38.2	-7.19
Standard deviation		0.003	0.667	0.463	0.051

Source: compiled by the authors.

The difference between the different methods of determining the critical interval is due to the specifics of the approach used in each method, as well as the variety of approaches to data processing and analysis. Each method has its particular advantages, limitations and assumptions that may affect the final results. The maximum likelihood method (Trautbeck) aims to find the model parameters that maximise the probability of observing the data. This can lead to more accurate parameter estimates, but it also requires certain statistical assumptions that may not be sufficiently accurate for certain situations. The maximum likelihood method can provide more accurate estimates of the model parameters, as the process finds the parameters for which the data are most likely. However, this also means that certain statistical assumptions about the distribution of the data must be made. If these assumptions are incorrect or insufficiently accurate, the parameter estimates may be inaccurate or unreliable (12).

The Raffa method uses the idea of estimating model parameters by minimising or optimising a certain deviation function between observed data and predicted values from the model. One of its main features is that it can be less sensitive to outliers or random variations in the data compared to the maximum likelihood method. If some of the observations are anomalous, i.e., they deviate strongly from the general trend of the data, the Raffa method may give less weight to these anomalies when fitting the model parameters. This can lead to less vulnerability to large variations in the data and help avoid overestimation of parameters. The Raff method can also be more robust to random variations in measurements. This means that it can provide a narrower range of estimates of the model parameters with slightly variable data. Related to this is its ability to provide more conservative estimates, i.e., less “stretching” or “shrinking” of parameter estimates due to random variations in the data. Given these features, the Raff method can be useful when analysing data with possible anomalies or small variations. However, it is also important to remember that the choice of method should consider all the features of the study and the characteristics of the data (13).

The Wu method used to determine the critical interval is based on the idea of reducing the influence of random variables and considering the peculiarities of the data distribution. This method is aimed at improving the accuracy and reliability of model parameter estimates by minimising the influence of random variations. One of the key aspects of the Wu method is the use of weights for observations. These weights can be set in such a way as to reduce the influence of random variation or to consider the specifics of the data distribution. For example, if some observations are weighted more heavily due to their accuracy or significance, they may be given a higher weighting, thereby providing a greater impact on the estimation of the model parameters (14). This method can be particularly useful in situations where some measurements are less precise or are more affected by random factors. By placing less weight on these measurements, the Wu method can help to produce more realistic estimates of the model parameters, as they will be less affected by random noise or anomalies. This approach can also provide more robust estimates, as the weights can equalise the effects of random variation and provide less sensitivity to small changes in the data. Hence, the Wu method can be useful for reducing the influence of random variables, improving accuracy, and obtaining more realistic estimates of model parameters (15).

The Ashworth method is another approach for determining the critical interval, but it has some specific features. As it is based solely on acceptable intervals, the lack of use of rejected interval data makes it unique for analysis. The main feature of this method is to focus on the spacing that has been deemed safe and acceptable by drivers to enter the corner and use this data to determine the critical spacing. One possible reason for the higher estimates of critical left turn lane spacing using the Ashworth method may also be that it considers additional aspects of driver behaviour that go beyond traditional analytical methods. For example, drivers may be more cautious when turning left due to the absence of a straight intersection, additional obstacles, or other factors. It is important to note that the Ashworth method, using only acceptable intervals, may raise questions about the representativeness of the sample and the ability to account for all possible scenarios. However, if applied with appropriate limitations and careful analysis, this method can help to highlight the specifics of drivers' decision-making on the road and their impact on the critical interval (16).

The standard deviation method is also important in the process of determining the critical interval. This method is based on measurements of intervals whose influence is reflected through the standard deviation of these measurements. The basic idea is that the method calculates the average value and the degree of divergence of the intervals. The measurement of the degree of divergence, or dispersion, indicates how far the measurement values are located relative to the mean (17). In this context, the standard deviation method can use data on the intervals that are considered acceptable for road entry and analyse the differences between these intervals. This can establish how large the variations are between intervals and therefore how reliably the critical interval can be determined.

If the standard deviation method reveals a large variance between intervals, this may indicate a significant discrepancy in the data and may affect the uncertainty of the critical interval. On the other hand, a smaller standard deviation value may indicate a lower level of data dispersion and greater consistency in interval measurements (18). This approach can be useful in the context of analysing the reliability and content of interval data, as it allows for an assessment of the degree of data diversity. However, it is important to be aware of the factors that can affect measurement and variance and to consider this when interpreting the results of the method (19).

The capabilities of modern intelligent transport systems (ITS) should also be considered regarding their ability to optimize roundabout traffic flow and safety. Solutions like adaptive traffic signal control, real-time congestion mapping, and vehicle-to-infrastructure communication could significantly improve capacity and reduce crashes (20,21). For example, installing vehicle detection sensors on roundabout approaches paired with adaptive signals could smooth upstream flow rates, reducing entry queues. Likewise, tracking volumes on each arm and visually conveying congestion status through digital signs allows drivers to approach with more awareness and appropriate speeds (22, 23). Vehicle-to-infrastructure connectivity even shows promise for hazard notifications when a conflict arises with a pedestrian or other vehicle. As the market penetration of vehicle tech advances, the possibilities grow tremendously. Roundabout navigation alerts, lane guidance, and collision warnings could all become reality through ITS innovation. To the extent these systems

can complement driver perception and decisions, both capacity and safety at roundabouts stand to benefit dramatically from technological progress. Realizing these gains does assume proper infrastructure investment and equipment upgrades, but the potential is immense (24, 25).
In summarising the methods for determining the critical interval, it is worth noting the diversity of approaches and their specific features. The difference in values revealed indicates that each method is aimed at solving specific aspects of the problem. A combination of these approaches can provide more complete information about the critical interval at a roundabout, helping to better understand the impact of various factors and make informed decisions about road safety and traffic efficiency.

DISCUSSION

In today's environment, efficient intersection management is of great importance for transport engineering. Roundabouts have already proved their effectiveness in many countries due to their operating principle, but the capacity and safety of these junctions are determined by several factors, including terrain, road geometry, and driver behaviour. Among the key parameters that determine the operation of roundabouts, a special place belongs to the critical interval (26,27). It is important to note that this interval can vary significantly in different areas and countries due to different driving styles, road culture, road geometry, and the location of the roundabout concerning populated areas or important infrastructure. For example, in urban areas, drivers may be more conservative, resulting in a higher critical spacing. On the other hand, on motorways or in high-speed areas, drivers may be more confident in their actions, which may result in a shorter critical interval (28,29). A thorough understanding and analysis of the specifics of determining the critical interval in different conditions is a key step in developing accurate and adaptable traffic models. This is an important step towards improving the efficiency, safety, and smoothness of traffic at roundabouts.
Gap acceptance traits have been shown to differ across roundabout environments as well. Research in Greece found rural single-lane roundabouts exhibited longer critical headways (5.63 sec) versus urban two-lane designs (4.18 sec). Drivers were more cautious entering rural roundabouts potentially due to higher approach speeds. At multilane roundabouts, critical gaps decreased for inner lanes, indicating comfort following closer vehicles. However, the presence of pedestrians increased gaps. Similarly, Australian studies determined critical gaps rose from around 3 seconds on single lane roundabouts up to 5.5 seconds for large 3-lane configurations, influenced by the multiplicity of conflicts. As Lane Count and complexity increases, drivers wait for larger margins of safety before gauging adequate entry space. Thus, any capacity analysis would need to calibrate to local driver risk tolerance and vehicle speeds, which can vary by roundabout type (30).
R. Guo (31) conducted a study in which different methods were used to determine the size of the critical interval, such as the Raff method, the Ashworth method, and the maximum likelihood method. Usually, when different methods were used for the same interval data, the results were different. The critical interval values for the Raffa, Ashworth and maximum likelihood methods were 2.91, 3.2 and 2.65 seconds, respectively. The Ashworth result was higher than the others because it used only acceptable intervals. Raff's method was also simple and intuitive, and it can produce reliable results when large samples are used. Differences in the results obtained by different methods may indicate different methodological approaches used in these methods. For example, the study noted that the Trautbeck, Raffa and Wu methods showed similar results to each other, indicating a certain similarity in their approaches. At the same time, in the study by the researcher, Raff's method was noted as simple and intuitive, which may indicate its simplified nature compared to other methods. The difference in results may also reflect the specifics of the data on which the study was conducted. Different methods may be more or less appropriate depending on the nature of the data, such as its distribution, volume, and characteristics. The research context, objectives and limitations may also influence the choice of method and its results.
A.L.P. Vasconcelos et al. (32) described a study that directly evaluated critical intervals at single and two-lane roundabouts. Several estimation methods were used (Zygloch method, maximum likelihood method, Raffa method, Logit method, and Wu method). These methods have some

specific characteristics that should be noted, such as the fact that the Raff method is simpler and does not involve any iterative calculations; the Wu method procedure was similar to the Raff method. Trautbeck's method, based on maximum likelihood, used the accepted interval and the largest rejected interval of drivers who rejected at least one interval. The Logit method allowed for the explicit use of independent variables other than intervals. The Raff, Wu, and Troutbeck methods were more reliable due to the limited sample size. The results of both studies show that the Raff, Wu and Troutbeck methods produce more reliable results, especially in limited sample conditions. These methods can be an excellent choice for estimating critical intervals when data are limited. In general, the difference in results indicates important aspects in the process of determining critical intervals at intersections. Different methods may have their advantages and limitations, and the choice of a particular method may depend on the nature of the study and other factors.

A. Gazzarri et al. (33) used maximum likelihood, median, and Raffa methods to determine the critical interval. Data were collected at seven selected roundabouts. The value of the critical interval was significantly lower than the values recommended by some international sources. The procedure for applying the median method was simpler and faster than the maximum likelihood method. The smallest critical interval was calculated for the single-band Raffa method, while the critical interval values for the maximum likelihood and median methods were 3.86 seconds and 3.57 seconds, respectively. It should be noted that both studies use the maximum likelihood method and the Raff method to determine the critical interval. In the study by the researchers, they focused more on comparing the median method with the maximum likelihood and Raffa methods. This indicates a practical approach to the choice of methods, where the median method is considered simpler and faster, which may make it more convenient to use. It is particularly important that the Raff method in this study gave the smallest value for the critical interval, which may have important implications for road safety.

A. Ahmad et al. (34) proposed a new method for determining the critical interval based on minimising the sum of the absolute difference between the interval value and the rejected or accepted interval. They also compared the proposed method with the methods of Ashworth, Harders, Wu and the modified Raff method. It was determined that the proposed method is the most appropriate estimation method. It was concluded that the new method is more suitable than any other method because it can be applied to situations where the priority rule is not followed. As the size of the vehicle increased, the value of the critical interval also increased. This approach indicates that the authors tried to find the optimal point of determining the critical interval, which would best consider the difference between the actual value of the interval and its permissible value. A special aspect of this method is its ability to work in cases where the priority rule is not followed. This can be an important advantage, as real traffic can often deviate from theoretical rules and regulations (35, 36). Also, the study noted that as the size of the vehicle increased, the value of the critical interval also increased. This indicates that this method can consider different parameters and characteristics of vehicles, which can be important in practical conditions (37,38).

S.F. Azhari et al. (39) evaluated the critical interval at a roundabout using different statistical methods, namely the Ruff method, the Wu method and the simple Logit method. The Ruff method and the Logit analysis produced similar results of 3.45 seconds, while the Wu method resulted in a critical interval of 3.6 seconds. The Raff method procedure was extremely simple and did not require complex calculations. The critical interval values for the three methods were lower than the values recommended by the 2010 Road Capacity Manual, 4.11 seconds for the right and 4.29 seconds for the left lane. This study highlights the crucial point that road capacity assessment methods cannot be unconditionally transferred from one country to another without some modification and calibration. For example, approaches that have been successful in one country may not take into account the unique properties of traffic in another country. This can lead to underestimation or overestimation of road capacity, which in turn can affect road safety and efficiency.

D. Radovic et al. (40), in turn, estimated the critical interval for single-lane roundabouts using five methods: Logit, Harders, Ruff, maximum likelihood and Wu's method. To determine which of these methods provides the most realistic estimate of the critical interval, the field values of the capacity were compared with theoretical capacity values. Based on the comparative analysis, it was determined that the Harders method provides the most accurate estimate of the critical interval. This approach, which included a comparison of field (experimental) capacity values with theoretical (calculated) values, allowed to determine which method best correlates with real traffic conditions and the realities of the traffic situation. The results of the study indicate that the Harders method most accurately reproduces the real conditions and dynamics of traffic at single-lane roundabouts, which indicates its adequacy and reliability in practical applications. Such analysis helps to improve assessment methods and ensure more accurate design and management of road infrastructure.

Research in the field of traffic engineering has shown the complexity and importance of choosing the right method for estimating traffic flow capacity (41). Different methods, such as Logit, Harders, Raffa, maximum likelihood and Wu, have their advantages and limitations, but they help to consider the various factors that affect traffic flow. Studies have highlighted that considering driver behaviour, specific traffic conditions and cultural characteristics of each country are important aspects when choosing a capacity estimation method. Given the diversity of road traffic, it is important to develop and adapt methods to ensure that the appropriate level of safety, comfort and efficiency is maintained on each country's roads.

This study has several limitations. One limitation of this study is that it focused on a single traffic circle site with certain characteristics. Further analysis at multiple sites with a greater variety of geometries, vehicle types, and driver populations would have increased the generalizability of the results. In addition, only the total traffic flow speed was considered, not its variation at different times of the day. Investigating methods for determining capacity under fluctuating hourly or seasonal load conditions could have opened up new opportunities. This study was also limited to traditional traffic circle intersection designs. As innovative intersection shapes continue to emerge, the application and adaptation of capacity determination methods will be an important challenge. In the future, it will be possible to analyze the effectiveness of methods similar to Wu's approach on turbo, flower, and other non-traditional traffic circles. Finally, the impact of connected and autonomous vehicles (CAVs) was not considered here, but capacity models should be revisited as these technologies evolve. Additional research is needed to expand the sample and number of study sites, evaluate intersections beyond standard traffic circles, and consider transformative mobility solutions such as CAVs. Using these directions in future work will allow for more robust, broadly applicable methods that anticipate revolutionary changes in transportation. Maintaining realistic and reliable capacity prediction methods in future research will prove vital as both the infrastructure and the vehicles themselves evolve.

CONCLUSIONS

This study provides important insights into the effectiveness of different methods for estimating capacity at roundabouts. The finding that the difference between the methods is minimal indicates that the estimates obtained have a reasonable level of reliability and stability. This demonstrates that, despite varying approaches, traffic engineering methods can produce consistent capacity predictions within a certain acceptable range. An important practical implication is that the Wu method proved to be the most accurate and convenient to use for capacity calculations in this context. By recommending this method based on the analysis, more dependable estimates of roundabout capacity can be achieved. This enables traffic engineers and planners to more realistically design and manage road infrastructure involving roundabouts.

While the capacity prediction methods showed similar estimates, it is critical to consider that they rely on certain assumptions and ideal conditions. Their ability to accurately reflect real-world traffic dynamics may vary depending on driver behaviour, vehicle mix, geography and other local factors. Further research across diverse traffic situations and roundabout types would provide a more comprehensive perspective. As automated vehicles emerge and road infrastructure evolves, continually evaluating and adapting capacity analysis methods will be vital. Examining the impacts of new technologies and layout features can help enhance safety and efficiency. This study delivers an important building block, but capacity prediction requires ongoing refinement attuned to shifting transportation realities. Applying advanced methods while calibrating for local conditions will allow for superior roundabout design and traffic management.

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