

Article

Roundabout Geometry and Risky Motorcyclist Behaviour: Identifying Critical Design Thresholds for Safer Road Infrastructure

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Abstract

Motorcyclists are among the most vulnerable road users at roundabouts, particularly in mixed-traffic environments where rider behaviour may be influenced by geometric design. This study investigates the association between roundabout geometry and risky motorcyclist behaviour using the Chi-squared Automatic Interaction Detection (CHAID) method. Video-based observations were conducted at four selected roundabouts in Kuching, Sarawak, Malaysia, generating 15,937 risky-behaviour events from 5400 observed motorcyclists. Six risky-behaviour categories were analysed, covering entry, circulation, and exit manoeuvres. The CHAID results showed that entry radius was the primary geometric factor associated with risky motorcyclist behaviour, while exit radius and exit width acted as secondary variables under specific entry-radius conditions. Four behavioural scenarios were identified. Entry radii of 15–32 m were associated with mixed risky-behaviour patterns, with lane splitting during circulation being the most frequent behaviour. Entry radii of 37–40 m combined with exit radii ≤ 12.43 m were associated with failure to signal before exiting. Entry radii of 43–49 m combined with exit radii ≤ 25.3 m were associated with improper lane positioning when exiting. Larger entry radii of 49–64 m combined with exit widths of 7.38–9.06 m were associated with close stopping or potential blind-zone positioning. The model validation results indicated moderate internal classification performance, supporting the use of CHAID as an interpretable threshold-identification tool rather than a high-precision predictive model. The findings demonstrate that risky motorcyclist behaviour at roundabouts is shaped by non-linear interactions between entry and exit geometric elements. From a sustainability perspective, these results provide preliminary evidence for behaviour-sensitive roundabout design, safety assessment, and policy-oriented geometric improvements that support safer and more inclusive urban transport systems in motorcycle-dominant mixed-traffic contexts.



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1. Introduction

Motorcycles are a major mode of transportation in many Asian countries, especially in Southeast Asian nations, where a significant portion of the vehicle fleet and traffic

movement comprises motorcycles. From a sustainability perspective, motorcycles play an important role in supporting affordable and accessible urban mobility, particularly in developing and emerging regions. However, despite these mobility advantages, motorcyclists remain among the most vulnerable road users and are exposed to various traffic conflicts. As a result, motorcycles contribute substantially to road traffic injuries and fatalities in many motorcycle-dominant countries. Understanding motorcyclist behaviour in complex road environments is therefore critical not only for road safety, but also for the development of safer, more inclusive, and sustainable transport infrastructure.

Roundabouts are commonly adopted as a road intersection management technique for enhancing the efficiency of traffic flow and reducing the occurrence of critical road accidents, especially at intersections controlled by traffic signals and stop signs. Several studies have proven that roundabouts are highly effective in reducing fatal and injury accidents compared to conventional intersections. The majority of existing research work on roundabouts, in relation to road safety and performance, has been conducted and analysed for conventional road vehicles, whereas the behaviour of motorcyclists at roundabouts has not yet been studied in detail, as the behaviour of motorcyclists, especially in relation to roundabouts, may differ significantly due to the nature of their vehicle, which may inadvertently lead to critical road accidents as a result of the geometry of roundabouts.

The geometric characteristics of roundabouts, which include parameters such as the entry width, entry radius, exit width, exit radius, and circulating roadway width, are also significant factors in the determination of the behaviour of both drivers and motorcyclists. These parameters are significant in the sense that they can affect the speed, lane-choice, trajectory, and decision-making process of motorcyclists when they enter, manoeuvre through, and exit the roundabouts. Although there are many research papers that explore the relationship between the geometric characteristics of roundabouts and general traffic safety, there are few research papers that explore the relationship between the geometric characteristics of roundabouts and the risky motorcyclist behaviour. In the case of motorcyclists, the characteristics of their behaviour, which often involve flexible lane usage and filtering, make the relationship between the geometric characteristics of roundabouts and motorcyclist behaviour unique and difficult to understand based on general traffic behaviour research papers. Yousif et al. (2020) [1] reported that behavioural and human factors contribute substantially to motorcycle safety outcomes, often exceeding the influence of vehicle-related factors.

This study therefore explores the relationship between roundabout geometric characteristics and risky motorcyclist behaviour using a tree-based analytical method. Decision tree analysis is appropriate for this study because it can identify hierarchical relationships and interaction effects between geometric variables and behavioural outcomes. Unlike conventional regression-based approaches, tree-based analysis can provide an intuitive interpretation of threshold effects, making it useful for identifying geometric conditions that may be associated with specific risky behaviours. This aligns with the broader aim to support evidence-based assessment, prediction, and improvement of built-environment systems, particularly where infrastructure design has direct implications for safety, accessibility, and long-term urban mobility.

Data were collected from selected roundabouts, and risky motorcyclist behaviour patterns were classified across entry, circulating, and exit manoeuvres. Significant geometric parameters were then analysed to examine their relative influence on different risky behaviour categories. By identifying geometry-related behavioural thresholds, this study contributes to a more behaviour-sensitive understanding of roundabout design in motorcycle-dominant mixed-traffic environments.

The findings of this study are expected to contribute to traffic safety, sustainable transport planning, and infrastructure design by identifying which geometric factors may increase risk-taking behaviour among motorcyclists at roundabouts. The results may also demonstrate the potential of tree-based analytical techniques as practical tools for investigating the relationship between infrastructure design and road-user behaviour in complex traffic environments. In this context, the study supports the wider sustainability agenda by promoting safer, more inclusive, and policy-relevant transport infrastructure for vulnerable road users in rapidly urbanising regions.

2. Literature Review

2.1. Motorcyclist Safety and Behaviour

Motorcyclists are widely recognised as one of the most vulnerable road-user groups due to their limited physical protection and greater exposure to traffic conflicts. Previous studies have shown that motorcyclists face a substantially higher risk of severe injury and fatality, particularly at intersections and roundabouts where traffic interactions are more complex and conflict-prone [2,3]. Rider behaviour has been consistently identified as a major contributor to motorcycle crash occurrence and injury severity. Common risky behaviours reported in the literature include improper lane usage, non-compliance with traffic control devices, unsafe manoeuvring, signalling neglect, and other traffic violations [1,4,5]. Empirical studies have further demonstrated that behavioural dimensions such as violations, control errors, and other aberrant riding practices are closely associated with motorcycle safety outcomes and crash involvement [6–8]. Notably, turn-signal neglect has been identified as one of the prevalent risky behaviours among Malaysian motorcyclists, highlighting the continued relevance of signalling-related behaviours in motorcycle safety research [5]. Beyond individual actions, recent reviews have emphasised that rider behaviour is shaped by a complex interaction of human, vehicle, roadway, and environmental factors [1,9]. These findings suggest that motorcycle safety cannot be explained solely by rider characteristics, but must also consider the influence of surrounding roadway conditions and infrastructure. Consequently, understanding how geometric design features affect rider behaviour is essential for improving motorcycle safety, particularly in complex traffic environments such as roundabouts.

2.2. Influence of Road Geometry on User Behaviour

Road geometry has long been recognised as a fundamental factor influencing the behaviour of both drivers and riders. Geometric features such as lane width and horizontal curvature have been shown to affect speed selection, trajectory control, and decision-making processes among road users [10,11]. Wider lanes and gentler curves are generally associated with higher operating speeds and lower perceptions of risk, which may reduce compliance with safety-related behaviours [12]. Conversely, more constrained geometric conditions can increase cognitive workload and attentional demand, requiring road users to devote greater effort to vehicle control and navigation, thereby influencing behavioural responses.

In the context of motorcyclists, roadway geometric characteristics have been reported to play an important role in shaping riding behaviour and safety outcomes [9]. Roadway design elements may influence rider speed selection, manoeuvring behaviour, and risk perception, thereby affecting both operational performance and crash risk. Similar effects have been observed in roundabout environments, where geometric design has been shown to influence traffic operations, vehicle interactions, and safety performance. For example, roundabout safety performance varies according to geometric characteristics, with larger inscribed circle diameters and a greater number of entry lanes associated with higher crash frequencies [13]. Likewise, the inscribed circle diameter has been identified as a significant

determinant of roundabout safety performance, suggesting that geometric design influences vehicle trajectories and operating conditions within the roundabout [14].

Beyond safety outcomes, geometric characteristics have also been shown to affect traffic operations and manoeuvring behaviour. Substantial variations in entry and circulating capacities have been observed among multi-lane roundabouts, with circulating flow identified as a key factor influencing entry performance [15]. These findings indicate that geometric and operational conditions influence vehicle interactions and movement patterns within the circulatory roadway. Collectively, previous studies suggest that roundabout geometry affects not only operational efficiency and safety performance, but also the behavioural responses of road users. Consequently, variations in geometric design may alter speed choice, manoeuvring decisions, and risk perception, ultimately influencing rider behaviour within roundabout environments.

2.3. Behaviour at Roundabouts

Roundabouts have been extensively used to facilitate smoother traffic flow and reduce the severity of crashes. However, the behavioural aspects of motorcyclists remain a challenge. The continuous movement of vehicles in a circular traffic environment requires appropriate lane positioning, gap selection, and decision-making when entering, circulating, and exiting the roundabout [16,17]. Previous studies have shown that inappropriate lane positioning, lack of signalling, and difficulties in negotiating the geometric complexity of roundabouts are important safety concerns, especially under high traffic volume and multi-lane roundabout conditions [18]. Variations in roundabout safety performance have also been associated with geometric characteristics such as inscribed circle diameter and lane configuration [13]. Similarly, large multi-lane roundabouts have been reported to encourage lane-choice and weaving behaviour, which may alter traffic interactions and influence safety outcomes [19]. Thus, the relationship between roundabout geometric design and motorcyclist behaviour is important in assessing the safety performance of roundabout facilities.

2.4. Cognitive and Behavioural Mechanisms

Driver and rider behavioural patterns can be explained through the concepts of risk perception and cognitive workload. Road users continuously regulate their behaviour by balancing the demands of the driving task against their perceived capabilities [20]. When operating in complex traffic environments, increased cognitive workload may result in greater variability in behavioural responses and a higher likelihood of errors. Conversely, when the traffic environment is perceived as less demanding or safer, road users may exhibit riskier behaviours due to reduced vigilance and increased confidence in their ability to manage the situation. Such behavioural adaptation has also been observed in relation to roadway design, where geometric characteristics influence perceived safety, operating speed, and freedom of manoeuvre [21].

In the context of motorcyclists, behavioural adaptation is shaped by the interaction between roadway conditions and individual risk perception, indicating that rider responses are influenced not only by personal characteristics but also by the surrounding traffic environment [9]. In addition to these environmental influences, psychological factors play an important role in riding behaviour. Rider attitudes, beliefs, and perceived behavioural control have been identified as important determinants of riding behaviour and safety outcomes [22]. Individual personality characteristics have also been shown to influence risky riding behaviour indirectly through factors such as risk perception, perceived benefits of risky actions, attitudes towards unsafe riding, and traffic condition awareness [23]. These findings suggest that behavioural responses are shaped not only by external traffic condi-

tions, but also by cognitive and perceptual processes through which riders interpret and respond to their environment. Similarly, riders' intentions to engage in both safe and unsafe riding behaviours have been found to be significantly influenced by attitudes, subjective norms, and perceived behavioural control [24]. Collectively, these studies suggest that motorcyclist behaviour is shaped by the interaction of cognitive demands, risk perception, psychological characteristics, and environmental conditions. Consequently, variations in roadway geometry may alter riders' perceptions and workload, leading to different behavioural responses under similar traffic conditions.

2.5. Data-Driven Approaches in Behaviour Analysis

Traditionally, statistical techniques such as logistic regression, ordered probit models, and count-data models have been widely applied in transportation safety research to examine the relationships between influencing factors and safety outcomes [25]. These approaches have proven valuable in identifying significant risk factors and quantifying their effects on crash occurrence and behavioural outcomes. For example, a negative binomial regression model has been used to investigate the relationship between motorcycle accidents, traffic offences, and accident locations in Malaysia, identifying dangerous turning manoeuvres as a key factor associated with accident occurrence [26]. While such statistical models provide useful insights into factor–response relationships, they may have limited capability in capturing complex non-linear interactions among multiple variables.

To address these limitations, machine learning techniques such as random forests and neural networks have increasingly been adopted in transportation safety research due to their ability to model complex behavioural patterns and improve predictive performance [27]. However, despite their predictive advantages, these methods are often criticised for their limited interpretability, which can restrict their usefulness in transportation planning, safety management, and policy development [28].

In contrast, decision tree methods provide an interpretable analytical framework capable of revealing hierarchical relationships, interaction effects, and critical threshold values within behavioural data. Among these techniques, the Chi-squared Automatic Interaction Detection (CHAID) algorithm has been widely applied to classify observations into homogeneous groups based on statistically significant associations between predictor and outcome variables [29]. The ability of CHAID to identify non-linear relationships and meaningful segmentation makes it particularly suitable for behavioural studies involving multiple interacting factors.

Previous studies have successfully employed decision tree techniques to investigate driver behaviour, injury severity, and crash risk by identifying critical influencing factors and behavioural patterns within heterogeneous populations [29,30]. In parallel, motorcycle safety research has increasingly focused on the systematic measurement of rider behaviour as an important indicator of safety performance. The Motorcycle Rider Behaviour Questionnaire has been validated to demonstrate that behavioural dimensions such as violations, control errors, and other aberrant riding practices are associated with motorcycle safety outcomes [6]. Extending this work, a systematic review and meta-analysis confirmed that Motorcycle Rider Behaviour Questionnaire dimensions are significant predictors of motorcycle crash involvement [7]. Collectively, these findings highlight the importance of behavioural indicators as meaningful safety measures and support the incorporation of rider behaviour into analytical frameworks aimed at understanding crash risk and identifying contributing factors.

Despite the growing application of data-driven approaches in transportation safety research, limited studies have explored the relationship between roundabout geometric characteristics and motorcyclist behaviour using interpretable decision tree techniques. In

particular, there remains a lack of research examining how roadway geometry interacts with behavioural responses and whether critical geometric thresholds exist that influence risky riding behaviour. Consequently, the CHAID algorithm offers a promising approach for uncovering such relationships while maintaining interpretability for engineering and policy applications.

2.6. Research Gap

Although there has been a growing body of research examining the relationships between roadway geometry, road-user behaviour, and safety outcomes, studies specifically investigating the influence of roundabout geometry on risky motorcyclist behaviour remain limited. Previous research has demonstrated that roundabout geometric characteristics can significantly affect operational performance, weaving behaviour, and safety outcomes [13,19]. Similarly, previous motorcycle safety research has emphasised the need for integrated investigations that consider both rider behaviour and roadway characteristics [1]. Despite these findings, relatively little attention has been given to understanding how specific roundabout geometric features shape motorcyclists' behavioural responses. Existing studies have primarily focused on crash-based safety measures, operational performance, or predefined geometric classifications, providing limited insight into the behavioural mechanisms through which geometric design influences rider behaviour. Furthermore, few studies have attempted to identify critical geometric thresholds that may trigger changes in risky riding behaviour using interpretable data-driven approaches. Therefore, the present study addresses this research gap by applying the Chi-squared Automatic Interaction Detection method to identify the key geometric factors, threshold values, and behavioural patterns associated with risky motorcyclist behaviour at roundabouts.

3. Methodology

3.1. Research Framework

The study applies a behaviour-based analytical framework to investigate the relationship between the geometric characteristics of roundabouts and motorcyclist risky behaviour. As depicted in Figure 1, the framework comprises roundabout geometry characteristics, motorcyclist perception and cognitive processes, and motorcyclist behavioural responses. This framework is predicated upon the assumption that the geometric design characteristics of the roundabout have a bearing on the motorcyclist's perceptual and cognitive processes of the traffic environment, which in turn affects motorcyclist behavioural responses.

The study considers three types of roundabout geometry characteristics: (i) entry geometry, which comprises entry width and entry radius; (ii) circulatory roadway characteristics, which comprise the number of circulatory roadway lanes; and (iii) exit geometry, which comprises exit width and exit radius. These geometric characteristics of the roundabout have a bearing on the motorcyclist's perceptual processes of the traffic environment, which in turn influences motorcyclist behavioural responses.

Motorcyclist behavioural responses were classified into three operational stages: entry, circulation, and exit. Each of these stages comprises a number of behavioural indicators. Outcome variables, which represent the motorcyclist's risky behaviour, were considered. To investigate the relationship between the geometric characteristics of the roundabouts and motorcyclist behavioural responses, the Chi-square Automatic Interaction Detection (CHAID) method is applied. This method enables the identification of significant predictors, the detection of interaction effects among the independent variables, and the classification of behavioural patterns.

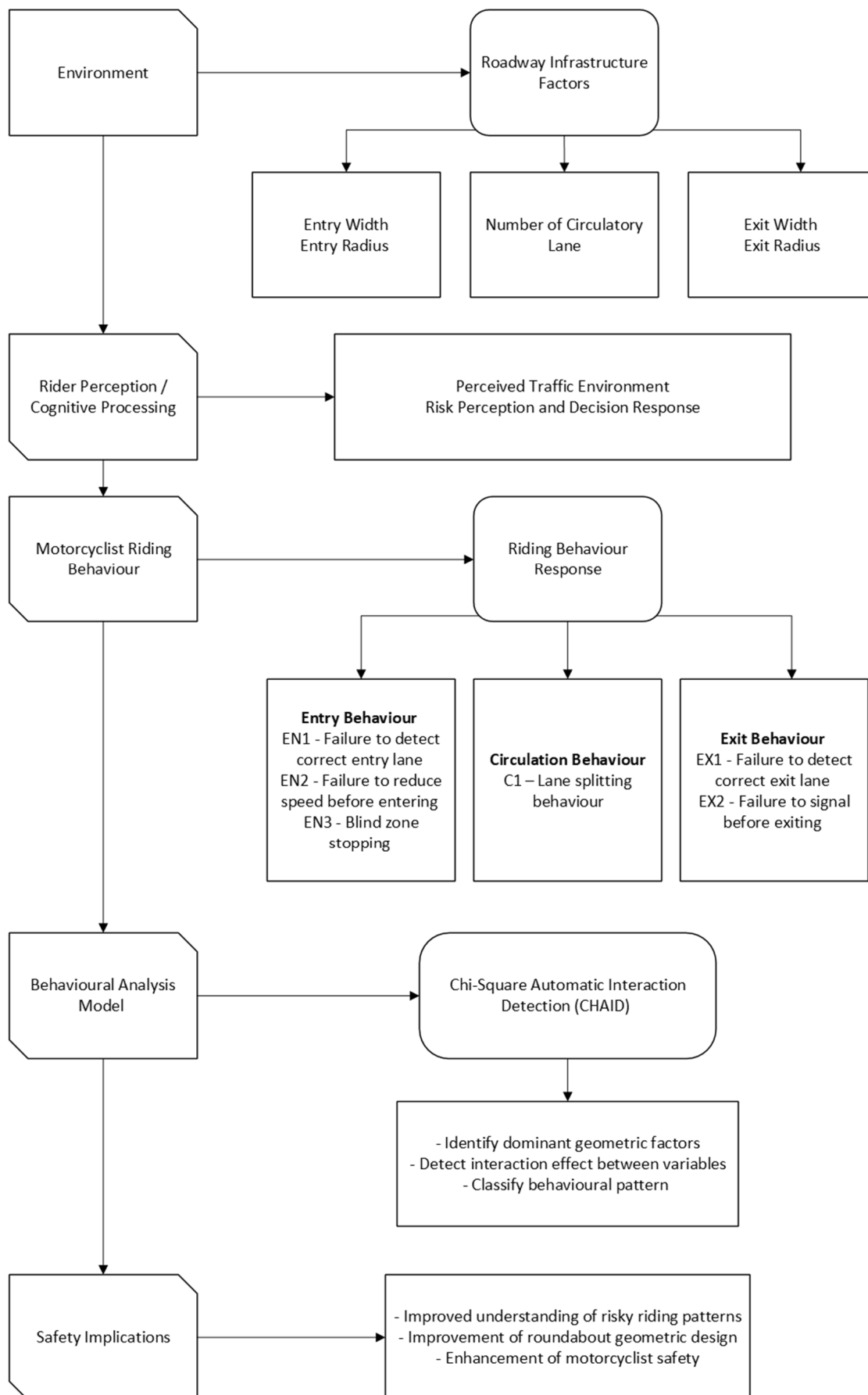


Figure 1. Behaviour-based analytical framework.

3.2. Data Collection and Study Sites

Field observations were conducted at some roundabouts in Kuching, Sarawak, Malaysia. The observation aimed to study the behaviour of motorcyclists based on different geometric design conditions. Four roundabouts were identified for the study and marked as S1, S2, S3, and S4 for clarity and consistency in the study. The geographical locations of the study sites are presented in Table 1.

Table 1. The parameters of the selected study sites.

Site Code	Global Coordinate	Geometry Variation				Circulation Lane
		Entry Width (m)	Entry Radius (m)	Exit Width (m)	Exit Radius (m)	
S1	Latitude: 1.572333 Longitude: 110.304113	10–16	18–40	7.21–9.51	27.79–44.02	3
S2	Latitude: 1.510411 Longitude: 110.32772	4.35–5.14	13–15	3.75–4.69	12.64–17.31	1
S3	Latitude: 1.512344 Longitude: 110.343715	12–13	32–70	6–9.06	120–180	3
S4	Latitude: 1.505161 Longitude: 110.373786	9.42–10.96	43–69	7.38–11.37	25.3–71.72	2

The roundabouts for the study were identified based on their relatively higher accident rates. This provided an opportunity to study the behaviour of motorcyclists concerning their unsafe acts and the existing geometric design elements. Although the study was limited to four selected roundabouts, the geometric parameters covered a broad range of design conditions. The selected sites included roundabouts with narrow and wide entry widths, small and large entry radii, varying exit widths, and substantially different exit radii. For example, the entry width ranged from 4.35 m to 16.00 m, while the entry radius ranged from 13 m to 70 m. Exit width ranged from 3.75 m to 11.37 m, and exit radius ranged from 12.43 m to 180 m. In addition, the number of circulatory lanes varied from one to three lanes. Therefore, the selected sites provided sufficient geometric variability to examine how different roundabout design characteristics are associated with risky motorcyclist behaviour.

Video recording and drone video recording were used to obtain data on the behaviour of motorcyclists as in Figure 2. A video-based data collection method was used to collect the motorcyclist behavioural data at the identified roundabouts. Cameras were placed strategically at elevated viewpoints to ensure comprehensive coverage of the entry, circulating, and exit sections of the identified roundabouts. The placement of the recording equipment was intended to ensure minimal obstruction of the view while allowing the cameras to observe the field of view as much as possible. Cameras were placed in the identified roundabouts to observe specific sections of the motorcyclists' trajectories. The method provided an uninterrupted observation of the movement and behaviour of motorcyclists. The observation was conducted for three different operational phases during the process of traversing the roundabouts. The data on the behaviour of motorcyclists was extracted from the video recording based on the classification criteria. A total number of 5400 motorcyclist observations were obtained for the study based on the four study sites. The data provided a comprehensive illustration of the behaviour of motorcyclists based on different geometric and traffic conditions.

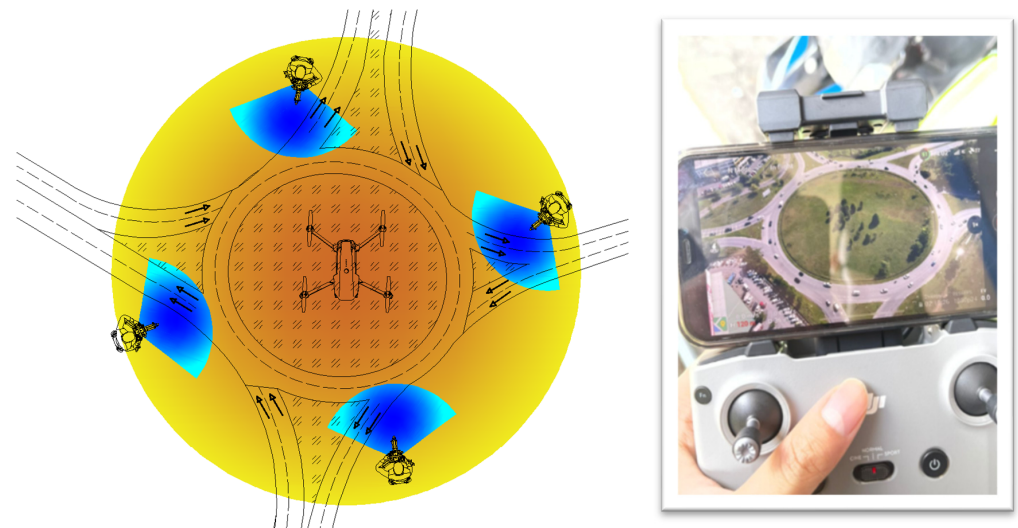


Figure 2. Data collection setup and observation coverage.

Figure 3 presents the structural count method used to develop the event-level behavioural dataset. The arrows indicate traffic movement directions, the blue shaded areas represent the ground-camera fields of view, and the yellow shaded area represents the overall aerial observation coverage. Each motorcyclist was first observed through video recordings and tracked individually from the entry approach, through the circulatory roadway, and towards the exit leg. The rider's behaviour was then assessed at three manoeuvring stages: entry, circulation, and exit. At the entry stage, the observer identified whether the rider exhibited EN1, EN2, or EN3. During circulation, C1 was recorded when lane-splitting behaviour was observed. At the exit stage, EX1 and EX2 were recorded when the rider demonstrated improper lane positioning or failed to signal before exiting.

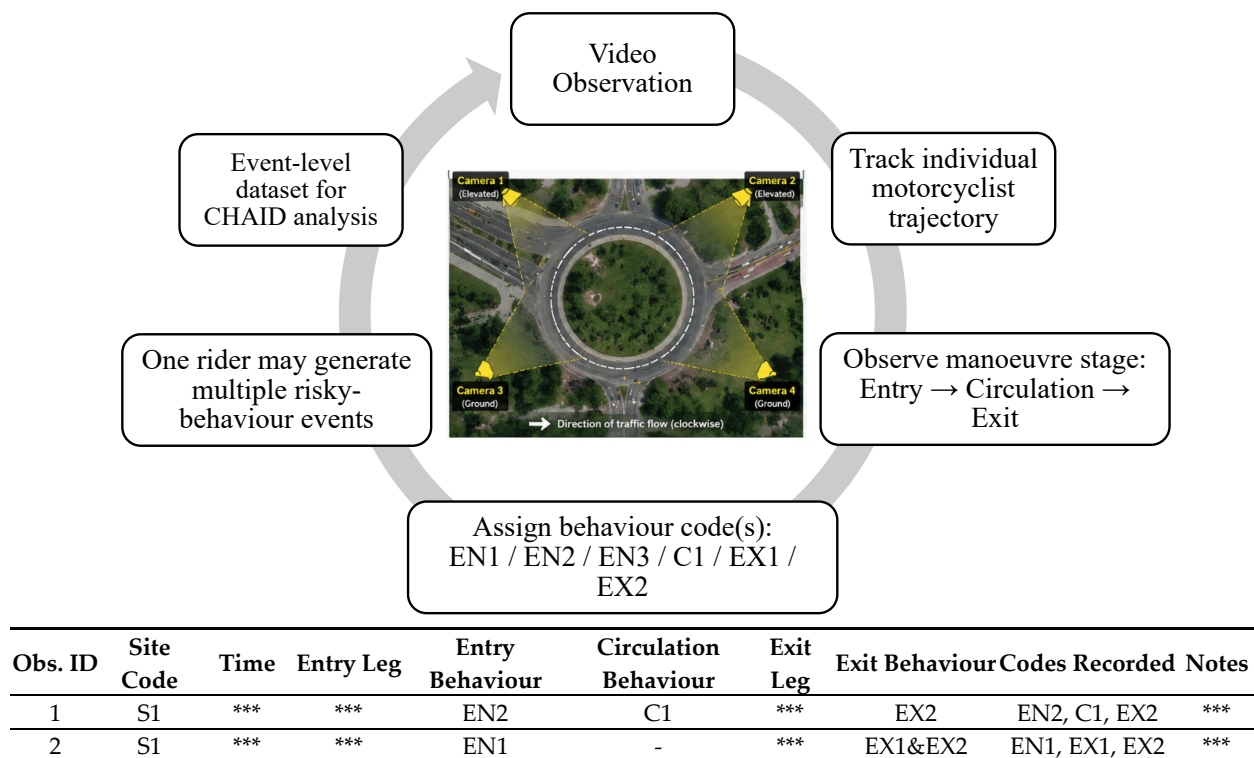


Figure 3. Structural count method. *** indicates information intentionally omitted from the illustrative example.

Since a single rider could exhibit more than one risky behaviour during the same roundabout movement, more than one behaviour code could be assigned to the same rider. For instance, one rider could be coded as EN2, C1, and EX2 if all three behaviours were observed during the same trajectory. Therefore, the structural count method allowed the study to retain the complexity of motorcyclist behaviour rather than reducing each rider to only one behaviour category. The recorded behaviour codes were subsequently transformed into an event-level dataset for CHAID analysis, where each coded risky behaviour represented one analytical event.

3.3. Behaviour Coding Framework

To reduce coding subjectivity, behaviours were coded only when the rider's movement involved an observable deviation from the expected manoeuvring path under moving or partially moving traffic conditions. Behaviours that occurred solely because of complete traffic blockage or forced queuing at roundabout circulation lane were not coded as risky behaviour. The same coding framework was used by both coders during the inter-rater reliability assessment as show in Table 2.

Table 2. Operational codebook.

Code	Risky Behaviour Category	Operational Definition	Coding Criterion/Decision Rule
EN1	Improper lane positioning when entering	Rider enters the roundabout using an inappropriate entry-to-circulation lane path.	Coded when the motorcyclist enters from the right-side entry lane and directly moves into the left-side circulatory lane, or enters from the left-side entry lane and directly moves into the right-side circulatory lane, without following the expected lane continuity. It is also coded when the rider crosses lane markings abruptly or shows unclear entry-lane positioning relative to the intended circulating path.
EN2	Observable failure to slow down before entering	Rider enters the roundabout circulation lane without observable approach-control behaviour.	Coded when the motorcyclist enters the roundabout circulation lane with no visible deceleration, hesitation, yielding adjustment, or gap-adjustment behaviour. This includes cases where the rider enters together with, or closely alongside, another vehicle that is also entering the roundabout, using the vehicle's movement as an opportunity to merge into the circulation lane. This category is based on visible approach behaviour, not quantitatively measured speed.
EN3	Close stopping/potential blind-zone positioning	Rider stops too close to another vehicle or positions within a visually restricted area near another vehicle.	Coded when the motorcyclist stops within close proximity to a preceding or adjacent vehicle, or positions at the rear-quarter side/close-side area of a passenger car, truck, bus, or larger vehicle where the rider may be less visible to the driver. For larger vehicles, this includes likely blind-zone/no-zone areas along the sides and rear of the vehicle. Where video scale permitted, close stopping was identified as approximately one motorcycle length or about 1.0–1.5 m from another vehicle.

Table 2. *Cont.*

Code	Risky Behaviour Category	Operational Definition	Coding Criterion/Decision Rule
C1	Lane splitting during circulation	Rider weaves or travels through narrow gaps between vehicles within the circulatory roadway.	Coded when the motorcyclist moved between vehicles, cars, trucks, or adjacent traffic streams within the circulation lane, especially when the rider was not preparing to exit the roundabout and continued circulating between traffic streams. This includes close-distance weaving or filtering between vehicles under moving or partially moving traffic conditions. This behaviour was not coded when the entire circulatory roadway was fully congested or stationary, where motorcycles had no realistic lane-following option and all vehicles were forced to queue.
EX1	Improper lane positioning when exiting	Rider exits the roundabout directly from an inappropriate inner circulatory lane without first moving progressively toward the outer exit lane.	Coded when the motorcyclist exited directly from the innermost or inner circulatory lane into a roundabout leg without first transitioning gradually from the inner circulatory lane to the outer circulatory lane before exiting. This also includes cases where the rider cut across one or more circulatory lanes abruptly to reach the exit.
EX2	Failure to signal before exiting	Rider exits the roundabout without indicating the intention to leave the circulatory roadway.	Coded when the motorcyclist left the circulation lane and entered an exit leg without activating a visible turn signal before the exit manoeuvre. The signal must be visible before or during the exit approach. If the rider signalled only after already entering the exit leg, it was not counted as proper signalling.

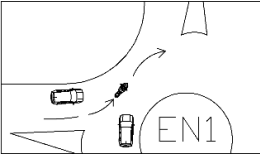
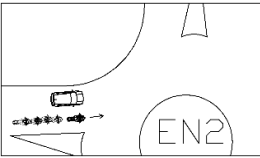
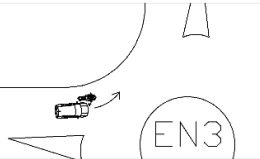
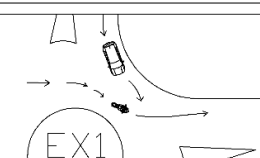
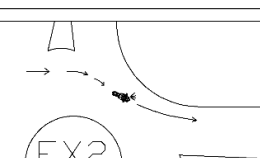
Motorcyclist behaviour observed during the study was systematically grouped into six behaviour categories based on pre-established criteria, as presented in Table 3. The classification system for motorcyclist behaviour at roundabouts differentiates between movement type, including entry, circulation, and exit, as well as related conflict type. This framework allows for a systematic evaluation of risky motorcyclist behaviour at roundabouts.

Entry behaviour includes behaviours like not detecting the correct entry lane, observable failure to slow down before entering, and stopping at a location close to the intersection. The most common behaviour observed was stopping at an unsafe location or a blind zone, which accounted for 24.3% of the total observed behaviour. This type of behaviour is related to aspects of lane discipline, speed management, and communication.

Circulation behaviour includes behaviours like lane splitting, which occurred within the circulatory roadway, accounting for 17.4% of the total observed behaviour, which falls under the category of lane discipline conflict.

Exit behaviour includes not detecting the correct exit lane and not signalling prior to exiting. The latter behaviour was found to be the most dominant behaviour, accounting for 26.1% of the total observed behaviour, which indicates a major concern regarding communication compliance.

Table 3. Operational classification and frequency distribution of risky motorcyclist behaviours at roundabouts. The arrow sign is the direction of the motorcyclist flow.

Movement Type	Risky Behaviour	Cases Recorded	% of Total	Conflict Type
	EN1—Improper lane positioning when entering	870	5.5	Lane discipline
	EN2—Observable failure to slow down before entering	1295	8.1	Speed management
	EN3—Close stopping/potential blind-zone positioning	3875	24.3	Interaction and visibility
	C1—Lane-splitting behaviour within the circulatory roadway	2780	17.4	Lane discipline
	EX1—Improper lane positioning when exiting	2954	18.5	Lane discipline
	EX2—Failure to signal before exiting	4163	26.1	Communication and signalling

Classifying behaviour into different categories, including their related frequencies, allows for a more comprehensive analysis of the data using the CHAID model, which will reveal the relationships between geometric elements and motorcyclist risky behaviour. The independent variables used in the study include the geometric characteristics of the roundabout, which include the entry width, entry radius, exit width, exit radius, and the number of circulatory lanes. Some of the independent variables were used as continuous inputs, whereas the others were classified into groups for the CHAID algorithm.

The CHAID algorithm was used to identify the relationship between the geometric characteristics (predictor variables) and the behavioural responses (target variables), which enabled the identification of the significant predictors, the interaction effects, and the motorcyclist behavioural patterns.

3.4. Behavioural Analysis Using CHAID

To understand the relationship between roundabout geometric characteristics and motorcyclist behaviour, the Chi-square Automatic Interaction Detection (CHAID) method was applied. CHAID is a non-parametric decision tree technique that segments data into mutually exclusive groups based on statistically significant associations between predictor and response variables.

In this study, motorcyclist behaviour categories (EN1, EN2, EN3, C1, EX1, EX2) were treated as the dependent variable, while roundabout geometric characteristics—such as entry width, entry radius, exit width, exit radius, and the number of circulatory lanes—were considered as independent variables. The CHAID algorithm partitions the dataset iteratively by selecting the predictor with the strongest association with the dependent variable at each stage, based on chi-square statistics.

This approach enables the identification of key geometric factors influencing motorcyclist behaviour, the exploration of interaction effects among variables, and the classification of behavioural patterns under different geometric conditions. To facilitate the analysis, continuous variables were categorised into intervals where necessary, improving both model performance and interpretability.

The resulting CHAID tree was interpreted by examining statistically significant splits and terminal nodes, with particular attention given to terminal nodes that represent dominant behavioural patterns. These nodes provide meaningful insights into how roadway geometry relates to risky riding behaviour.

Overall, the analysis focuses on identifying critical geometric thresholds and understanding how these thresholds influence rider perception, decision-making, and behavioural responses when navigating roundabouts.

3.5. Model Validation Procedure

Table 4 shows the inter-rater reliability results for the risky-behaviour classification. Across 15,937 paired observations, the coders achieved an observed agreement of 99.20%. The Cohen's Kappa value of 0.990 indicates almost perfect agreement, demonstrating that the behavioural categories were coded consistently and that the video-based dataset is reliable for subsequent CHAID analysis.

Table 4. Inter-rater reliability result.

Indicator	Value
Number of paired observations	15,937
Observed agreement	99.20%
Cohen's Kappa	0.99

To evaluate the internal stability of the CHAID model, 10-fold cross-validation was conducted. The dataset was divided into ten approximately equal subsets. In each iteration, nine subsets were used to train the model, while the remaining subset was used for validation. This procedure was repeated ten times, and the average validation risk was used to assess model performance. Model performance was evaluated using the apparent risk estimate, also referred to as the resubstitution risk, cross-validation risk, classification accuracy, and misclassification rate. The CHAID model specification and validation settings are summarised in Table 5.

Table 5. CHAID model specification and validation settings.

Item	Setting/Description
Analytical method	CHAID decision tree
Dependent variable	Risky behaviour
Behaviour categories	1 = EN1, 2 = EN2, 3 = EN3, 4 = C1, 5 = EX1, 6 = EX2
Independent variables entered	Entry width, entry radius, exit width, exit radius, circulation lane
Chi-square test	Pearson chi-square
Multiple-comparison adjustment	Bonferroni adjustment
Significance level for splitting	0.05
Significance level for merging	0.05
Maximum tree depth	4
Minimum parent node size	30 cases
Minimum child node size	15 cases
Number of intervals for scale predictors	10
Validation method	10-fold cross-validation
Performance indicators reported	Resubstitution risk, cross-validation risk, classification accuracy, and misclassification rate
Cost matrix	Equal misclassification costs

4. Results and Discussion: CHAID Tree Analysis

The Chi-squared Automatic Interaction Detection (CHAID) analysis was conducted to identify the geometric conditions associated with different risky motorcyclist behaviours at multi-lane roundabouts. The dependent variable consisted of six risky-behaviour categories: EN1, EN2, EN3, C1, EX1, and EX2. The independent variables included entry width, entry radius, exit width, exit radius, and number of circulatory lanes.

As shown in Figure 4, entry radius emerged as the root splitting variable, indicating that it was the most influential geometric factor in differentiating risky motorcyclist behaviour. The first split was statistically significant, with an adjusted p -value of 0.000, a chi-square value of 3839.779, and 40 degrees of freedom. This suggests that variations in entry radius are strongly associated with changes in motorcyclist risky-behaviour patterns.

The first-level split classified the data into four entry-radius ranges: 15–32 m, 37–40 m, 43–49 m, and 49–64 m. Each range was associated with different dominant risky behaviours. For entry radii of 15–32 m, lane splitting during circulation (C1) was dominant. For entry radii of 37–40 m, failure to signal before exiting (EX2) became dominant, particularly when the exit radius was ≤ 12.43 m. For entry radii of 43–49 m, improper lane positioning when exiting (EX1) was dominant when the exit radius was ≤ 25.3 m. For entry radii of 49–64 m, close stopping or potential blind-zone positioning (EN3) became dominant when the exit width was between 7.38 m and 9.06 m.

These results indicate that risky motorcyclist behaviour is not associated with one geometric factor alone. Instead, the CHAID tree shows a hierarchical relationship where entry radius acts as the primary geometric discriminator, while exit radius and exit width function as secondary variables under specific entry-radius conditions. This confirms the presence of non-linear threshold effects in the relationship between roundabout geometry and motorcyclist risky behaviour.

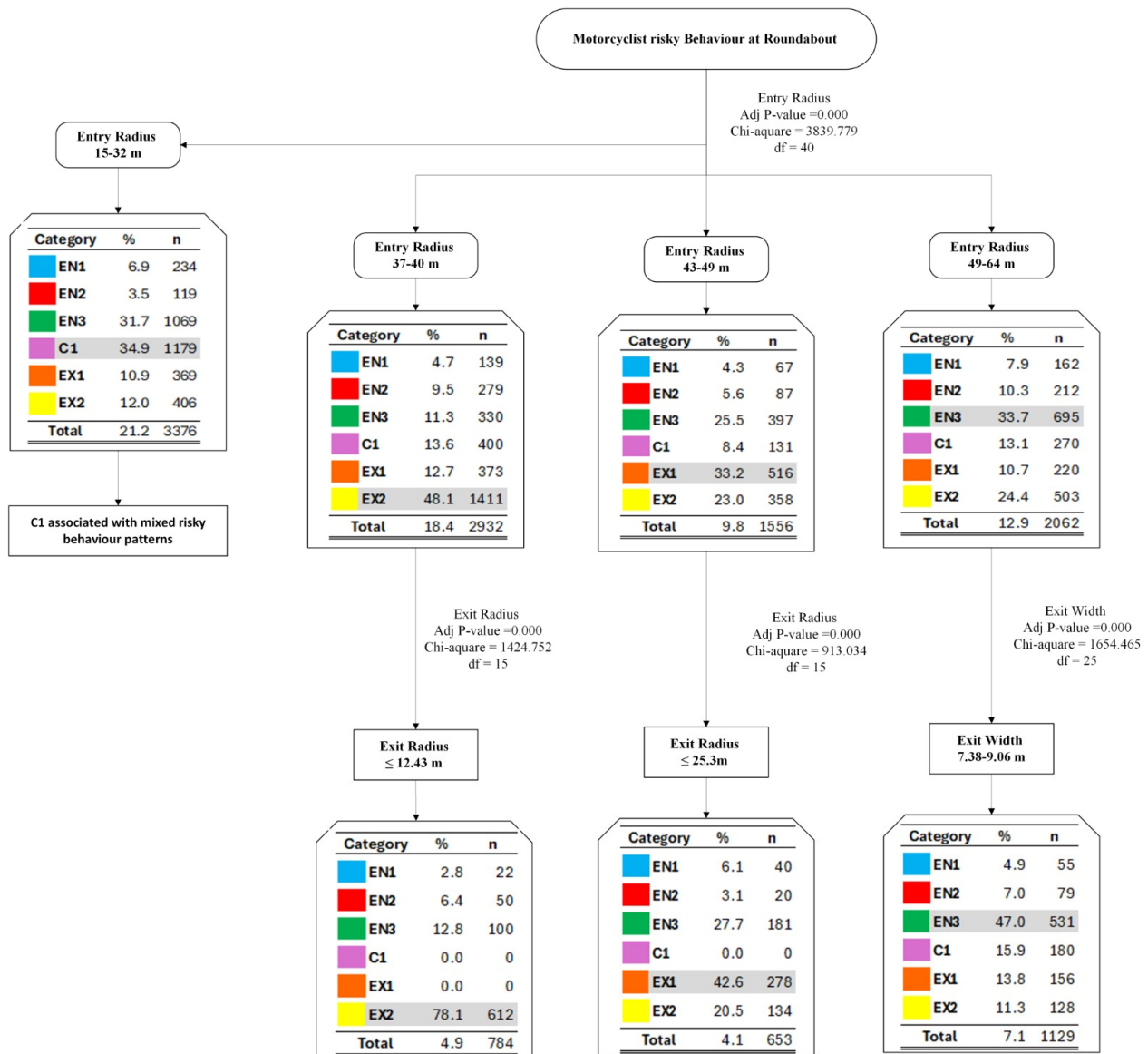


Figure 4. CHAID tree results.

This finding is consistent with previous studies showing that roundabout geometric characteristics influence traffic operations, vehicle trajectories, and safety performance [13–15]. However, unlike earlier studies that mainly examined crash outcomes, capacity, or general vehicle operations, the present study extends this understanding by demonstrating how specific geometric thresholds are associated with observed motorcyclist risky-behaviour patterns.

4.1. CHAID Model Validation Results

Table 6 shows the CHAID model validation performance in this study. The final CHAID model was evaluated using 10-fold cross-validation to assess its internal stability and classification performance. The model produced a resubstitution risk of 0.465 and a 10-fold cross-validation risk of 0.471, corresponding to classification accuracies of 53.5% and 52.9%, respectively. The difference between the resubstitution risk and cross-validation risk was 0.006, suggesting that the model did not exhibit substantial overfitting.

Table 6. CHAID model validation performance.

Model Performance Indicator	Value	Interpretation
Resubstitution risk	0.465	Apparent misclassification rate
Resubstitution accuracy	53.50%	Apparent classification accuracy
10-fold cross-validation risk	0.471	Cross-validated misclassification rate
10-fold cross-validation accuracy	52.90%	Moderate internal validation performance
Difference between risks	0.006	No substantial overfitting indicated

Although the overall classification accuracy was moderate, the result is meaningful because the model attempted to classify six categories of risky motorcyclist behaviour using geometric variables only. Therefore, the CHAID model should not be interpreted as a high-precision predictive model. Instead, it is more appropriately used as an interpretable threshold-identification tool for identifying geometry-related behavioural patterns. This interpretation is consistent with previous applications of classification-tree methods in road safety research, where decision trees are valued for revealing hierarchical relationships, interaction effects, and interpretable decision rules rather than only for predictive accuracy [29,30].

In the CHAID classification table, misclassified cases refer to observations where the predicted risky-behaviour category differed from the observed risky-behaviour category. This does not indicate an error in the video-based behavioural coding. Rather, it reflects the extent to which the geometry-based CHAID model could classify the six risky-behaviour categories. Since rider behaviour may also be influenced by non-geometric factors, including traffic flow, surrounding vehicles, rider judgement, visibility, and operational context, the moderate classification accuracy suggests that roundabout geometry provides meaningful but incomplete explanatory power. Accordingly, the identified thresholds should be interpreted as context-specific behavioural indicators, rather than universal design standards.

4.2. Scenario 1: Lane Splitting Under Small Entry-Radius Conditions

The first behavioural scenario was observed under entry radii of 15–32 m. Within this branch, lane splitting during circulation (C1) recorded the highest proportion, accounting for 34.9% of observations, with 1179 cases out of 3376. Close stopping or potential blind-zone positioning (EN3) was also highly represented, accounting for 31.7% of observations, with 1069 cases out of 3376. This indicates that small entry-radius conditions were not associated with one overwhelmingly dominant risky behaviour, but rather with a mixed risky-behaviour pattern involving both circulation-stage lane splitting and close vehicle interaction.

Unlike the other CHAID scenarios, the subsequent splits under this entry-radius condition did not produce a stable secondary geometric threshold with one clearly dominant risky behaviour. Instead, the following branches showed mixed behavioural outcomes across the six risky-behaviour categories. Therefore, this scenario is interpreted as a mixed-behaviour condition, where C1 emerged as the most frequent behaviour at the primary entry-radius split, but no single risky behaviour consistently dominated across the subsequent branches.

The prominence of C1 suggests that smaller entry radii may create more constrained entry and circulation conditions. Under such conditions, motorcyclists may use their manoeuvring flexibility to travel through narrow gaps between vehicles within the circulatory roadway. This interpretation is consistent with previous motorcycle safety research, which notes that motorcyclists often display flexible lane usage and manoeuvring behaviour in mixed-traffic environments [1,9]. It also aligns with findings on large and complex round-

abouts where lane-choice and weaving behaviour can influence vehicle interactions and safety outcomes [19]. In mixed-traffic environments, this behaviour may occur when motorcycles attempt to maintain movement despite limited space or partial traffic obstruction.

However, C1 was not coded when the entire circulatory roadway was fully congested or stationary. It was only coded when the motorcyclist actively weaved or travelled between vehicles under moving or partially moving traffic conditions. This distinction is important because the study did not classify forced queuing behaviour as risky behaviour. Instead, C1 represents active lane-splitting behaviour where the rider moved through narrow gaps between circulating vehicles or traffic streams.

This behaviour is considered risky because it reduces lateral clearance between motorcycles and surrounding vehicles. It may also increase the likelihood of side-swipe or merging conflicts, particularly when vehicles change lanes, continue circulating, or prepare to exit the roundabout. Therefore, Scenario 1 suggests that small entry-radius conditions are associated with mixed risky-behaviour patterns, with lane splitting during circulation being the most frequent behaviour at the primary split.

4.3. Scenario 2: Failure to Signal Under Moderate Entry Radius and Very Small Exit Radius

The second behavioural scenario was identified under the combination of entry radius of 37–40 m and exit radius ≤ 12.43 m. Within this terminal node, failure to signal before exiting (EX2) was the dominant risky behaviour, accounting for 78.1% of observations, with 612 cases out of 784. This result suggests that very small exit radii may increase manoeuvring demand during the exit process. When the exit path is geometrically constrained, motorcyclists may need to focus more attention on steering control, balancing, and negotiating the exit trajectory. Under such conditions, signalling may receive lower priority, leading to a higher occurrence of EX2 behaviour.

From a behavioural perspective, EX2 is important because signalling communicates the rider's intention to leave the roundabout. When a motorcyclist exits without signalling, surrounding road users may have difficulty anticipating the rider's movement. This finding is supported by previous Malaysian motorcycle behaviour research, which identified signalling neglect as a common risky riding behaviour among motorcyclists [5]. The present result adds a geometric interpretation by showing that signalling-related behaviour may become more prominent under constrained exit-radius conditions. This can increase uncertainty and potential conflict at the exit area, particularly in multi-lane roundabouts where several vehicles may be circulating, exiting, or changing lanes simultaneously.

Therefore, Scenario 2 indicates that a moderate entry radius combined with a very small exit radius is associated with signalling neglect among motorcyclists. This suggests that exit geometry should not only be evaluated in terms of vehicle turning path and capacity, but also in relation to rider workload and communication behaviour.

4.4. Scenario 3: Improper Lane Positioning Under Moderate-to-Large Entry Radius and Small Exit Radius

The third behavioural scenario occurred under entry radii of 43–49 m and exit radii ≤ 25.3 m. In this terminal node, improper lane positioning when exiting (EX1) was the dominant risky behaviour, accounting for 42.6% of observations, with 278 cases out of 653. Other behaviours were also present, including EN3 at 27.7% and EX2 at 20.5%, suggesting that this geometric condition was associated with multiple exit-related and interaction-related behaviours.

This result indicates that when motorcyclists enter the roundabout under a relatively larger entry radius, they may experience a smoother and less restrictive entry path. However, when this is followed by a smaller exit radius, riders may need to make a sharper

trajectory adjustment when leaving the roundabout. This mismatch between entry and exit geometry may contribute to improper lane positioning during the exit manoeuvre.

In practical terms, EX1 may occur when a motorcyclist exits directly from the inner circulatory lane without first moving progressively toward the outer exit lane. It may also occur when the rider cuts across one or more circulatory lanes abruptly to reach the exit leg. Such manoeuvres may conflict with vehicles travelling in the outer lane or vehicles continuing within the circulatory roadway. This is consistent with previous roundabout studies indicating that multi-lane roundabouts require appropriate lane positioning, gap selection, and exit decision-making, particularly under complex traffic interactions [16,18]. The present finding extends this by identifying a specific geometric combination in which improper exit-lane positioning becomes more prominent among motorcyclists.

Scenario 3 therefore highlights the importance of geometric consistency between entry and exit design. A smooth or less constrained entry path combined with a relatively constrained exit path may create unexpected manoeuvring demands. For motorcyclists, this may encourage sudden lane changes or improper exit positioning. Therefore, entry and exit geometry should be considered together when assessing motorcycle safety at multi-lane roundabouts.

4.5. Scenario 4: Close Stopping and Potential Blind-Zone Positioning Under Larger Entry Radius and Moderate Exit Width

The fourth behavioural scenario was observed under entry radii of 49–64 m and exit widths of 7.38–9.06 m. In this terminal node, close stopping or potential blind-zone positioning (EN3) was the dominant risky behaviour, accounting for 47.0% of observations, with 531 cases out of 1129. Other behaviours were recorded at lower proportions, including C1 at 15.9%, EX1 at 13.8%, EX2 at 11.3%, EN2 at 7.0%, and EN1 at 4.9%.

This result suggests that larger entry radii may be associated with smoother vehicle trajectories and a greater sense of manoeuvring freedom. Under these conditions, motorcyclists may be more likely to position themselves closer to surrounding vehicles, especially when approaching, waiting, or interacting with vehicles near the entry area. When combined with moderate exit widths, the available road space may further encourage flexible positioning and closer interaction with other vehicles.

EN3 was defined as close stopping or potential blind-zone positioning. This includes situations where a motorcyclist stops too close to another vehicle or positions near the rear-quarter or close-side area of a passenger car, truck, bus, or larger vehicle, where the rider may be less visible to the driver. This interpretation is supported by blind-spot studies showing that areas outside a driver's field of view may create visibility-related risks for surrounding road users [31,32]. Therefore, EN3 should be understood as a potential visibility-related surrogate behaviour rather than direct evidence of actual driver non-detection. The dominance of EN3 under this scenario suggests that wider or less restrictive geometric layouts may not always lead to safer behavioural outcomes. Instead, they may allow motorcyclists greater freedom to manoeuvre closer to other vehicles.

However, this interpretation should be made cautiously. The study did not directly measure driver visibility or motorcyclist speed. Therefore, EN3 should be interpreted as an observed surrogate behaviour indicating potential visibility-related conflict, rather than direct evidence that the rider was invisible to the driver. Nevertheless, the finding remains important because it highlights the need to consider spacing behaviour and visibility-related interaction when evaluating roundabout geometry.

4.6. Summary and Comparison of CHAID Scenarios

The CHAID analysis identified four key behavioural scenarios associated with different geometric conditions as in Table 7. These scenarios demonstrate that risky motorcyclist

behaviour varies across entry-radius ranges and is further shaped by secondary geometric variables such as exit radius and exit width.

Table 7. Summary of key CHAID behavioural scenarios.

Scenario	Geometric Condition	Secondary Variable	Dominant Risky Behaviour	Percentage	Interpretation
Scenario 1	Entry radius 15–32 m	Subsequent branches showed mixed risky-behaviour patterns, with no stable dominant behaviour	C1: Lane splitting during circulation	34.90%	Small entry-radius conditions may be associated with constrained circulation and lane-splitting behaviour.
Scenario 2	Entry radius 37–40 m	Exit radius ≤ 12.43 m	EX2: Failure to signal before exiting	78.10%	Very small exit radius may increase manoeuvring demand and reduce signalling compliance.
Scenario 3	Entry radius 43–49 m	Exit radius ≤ 25.3 m	EX1: Improper lane positioning when exiting	42.60%	Inconsistent entry and exit geometry may encourage abrupt or improper exit-lane positioning.
Scenario 4	Entry radius 49–64 m	Exit width 7.38–9.06 m	EN3: Close stopping/potential blind-zone positioning	47.00%	Larger entry radius and moderate exit width may encourage close spacing and potential blind-zone positioning.

Table 7 summarises the four behavioural scenarios derived from the CHAID tree. The table shows that entry radius was the common primary geometric condition across all scenarios, while exit radius and exit width acted as secondary variables for Scenarios 2, 3, and 4. Scenario 1 differs from the other scenarios because subsequent branches under the 15–32 m entry-radius condition showed mixed risky-behaviour patterns, without a stable secondary geometric threshold. Therefore, C1 was interpreted as the most frequent behaviour at the primary split rather than as a strongly dominant terminal-node behaviour. In contrast, Scenarios 2, 3, and 4 represent clearer terminal-node conditions where specific combinations of entry and exit geometry were associated with distinct risky behaviours, namely EX2, EX1, and EN3, respectively. This comparison indicates that risky motorcyclist behaviour is not explained by entry geometry alone, but by the interaction between entry geometry and downstream exit conditions.

The CHAID results support previous evidence that roundabout geometry influences road-user behaviour, vehicle interactions, and safety performance [13–15]. However, the present study extends earlier work by focusing specifically on motorcyclist risky behaviour rather than crash frequency or general vehicle operation. The identification of the entry radius as the primary splitting variable suggests that entry geometry plays an important role in shaping rider perception and manoeuvring decisions. This is consistent with studies showing that roadway geometry influences speed choice, trajectory control, and behavioural adaptation [10–12,21].

The observed dominance of C1 under small entry-radius conditions also supports previous motorcycle safety research, which highlights the flexible lane usage and manoeuvring characteristics of motorcyclists in mixed-traffic environments [1,9]. Similarly, the dominance of EX2 under very small exit-radius conditions is consistent with Malaysian evidence

that signalling neglect is a common risky riding behaviour [5]. However, the present study adds a new contribution by showing that this behaviour may be associated with specific exit-geometry thresholds. The dominance of EX1 under moderate-to-large entry radius and small exit radius further suggests that geometric inconsistency between entry and exit design may influence exit-lane positioning, supporting previous findings that multi-lane roundabouts require complex lane-positioning and gap-selection decisions [16,18]. Finally, the dominance of EN3 under larger entry radius and moderate exit width highlights the need to consider close-spacing and visibility-related interactions, particularly where motorcyclists position themselves near larger vehicles or potential blind-zone areas.

From a sustainability perspective, these findings are relevant because safe and inclusive transport infrastructure is an important component of sustainable urban mobility, particularly in rapidly urbanising and motorcycle-dominant cities. Roundabout design that does not adequately consider vulnerable road-user behaviour may reduce the safety and accessibility benefits expected from intersection improvements. Therefore, identifying geometry-related behavioural thresholds can support more evidence-based, behaviour-sensitive, and policy-relevant road safety assessment.

Overall, the findings demonstrate that risky motorcyclist behaviour is shaped by the interaction between geometric design and rider behavioural adaptation. The results reinforce the value of CHAID as an interpretable analytical tool for identifying critical geometric thresholds associated with behavioural changes. These insights provide a basis for improving roundabout safety assessment and supporting more sustainable transport infrastructure planning in motorcycle-dominant mixed-traffic environments.

5. Conclusions

This study investigated the association between roundabout geometric characteristics and risky motorcyclist behaviour at multi-lane roundabouts in Kuching, Sarawak, Malaysia. Using video-based observation and CHAID analysis, 15,937 risky-behaviour events generated from 5400 observed motorcyclists were analysed across four selected roundabouts. The study focused on six risky-behaviour categories: improper lane positioning when entering, observable failure to slow down before entering, close stopping or potential blind-zone positioning, lane splitting during circulation, improper lane positioning when exiting, and failure to signal before exiting.

The CHAID results showed that entry radius was the primary geometric factor associated with changes in risky motorcyclist behaviour. Exit radius and exit width acted as important secondary variables under specific entry-radius conditions. Four behavioural scenarios were identified. Small entry radii of 15–32 m were associated with mixed risky-behaviour patterns, with lane splitting during circulation being the most frequent behaviour. Entry radii of 37–40 m combined with exit radii ≤ 12.43 m were associated with failure to signal before exiting. Entry radii of 43–49 m combined with exit radii ≤ 25.3 m were associated with improper lane positioning when exiting. Larger entry radii of 49–64 m combined with exit widths of 7.38–9.06 m were associated with close stopping or potential blind-zone positioning.

These findings demonstrate that risky motorcyclist behaviour at roundabouts is not shaped by a single geometric element in isolation. Instead, behavioural patterns are associated with the interaction between entry and exit geometry, indicating a non-linear and threshold-based relationship. The results therefore highlight the value of CHAID as an interpretable method for identifying geometry-related behavioural patterns in complex mixed-traffic environments.

The study also strengthened the reliability and transparency of the behavioural analysis by applying a structured coding framework, inter-rater reliability assessment, and

model validation procedure. The Cohen's Kappa result indicated strong consistency in video-based behavioural coding, while the 10-fold cross-validation result showed moderate internal validation performance. Therefore, the CHAID model should be interpreted primarily as a threshold-identification and explanatory tool, rather than as a high-precision predictive model.

From a practical and sustainability-oriented perspective, the findings highlight the importance of incorporating vulnerable road-user behaviour into roundabout design and evaluation. Geometric characteristics that improve traffic flow efficiency may also influence rider perception, manoeuvring decisions, and risk-taking behaviour. Therefore, transportation agencies, road designers, and urban planners should consider the behavioural implications of entry and exit geometry when developing roundabout design guidelines and safety improvement measures.

By providing empirical evidence on the interaction between infrastructure design and motorcyclist behaviour, this study contributes to the broader sustainability agenda of promoting safer, more inclusive, and evidence-based urban transport systems. In motorcycle-dominant mixed-traffic environments, behaviour-sensitive roundabout assessment can support sustainable mobility by reducing safety risks for vulnerable road users while maintaining the operational benefits of roundabout design.

Limitations and Contextual Factors

While this study provides useful evidence on the relationship between roundabout geometry and risky motorcyclist behaviour, the findings should be interpreted within the scope of the selected study sites. The four roundabouts were located in Kuching, Sarawak, and were selected because they represented different geometric configurations and relevant motorcycle safety concerns. Although the selected sites covered a wide range of entry widths, entry radii, exit widths, exit radii, and circulatory lane arrangements, the identified CHAID thresholds are best understood as context-specific behavioural indicators for similar Malaysian mixed-traffic roundabout environments. Future studies may extend this work by including a larger and more diverse set of roundabouts, additional operational variables such as traffic flow and approach speed, and complementary safety measures such as near-miss or crash data. In particular, future research could apply video-based trajectory tracking or high-resolution speed extraction methods to directly quantify motorcycle approach speed, deceleration behaviour, and gap-selection decisions under different entry-radius and exit-geometry conditions. This would allow the speed-related behavioural mechanism proposed in this study to be tested empirically rather than treated as a tentative interpretation. Such extensions would help strengthen the transferability of the proposed behaviour-sensitive roundabout assessment framework.

Overall, the study contributes preliminary empirical evidence that roundabout geometric characteristics are associated with distinct risky motorcyclist behaviour patterns. By linking geometric design, rider behaviour, and safety assessment, the findings support the development of more sustainable, inclusive, and policy-relevant transport infrastructure for motorcycle-dominant urban environments.

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Institutional Review Board Statement: This study is waived for ethical review as the data collection was conducted through video-based traffic observations and did not involve any interaction with participants and no personal information was collected, and the dataset does not contain any identifiable information relating to participants, patients, or individuals. Furthermore, no images were used to identify specific persons, and the analysis was based solely on aggregated traffic and behavioural observations.

Informed Consent Statement: Informed consent for participation is not required as the study consisted of non-interventional observations conducted in public spaces and did not involve the collection of personal or sensitive information.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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Abbreviations

The following abbreviations are used in this manuscript:

EN1	Failure to detect proper lanes when entering roundabout
EN2	Motorcyclist not slowing down before entry roundabout
EN3	Motorcyclist stopping at a close distance or within blind zones
EX1	Motorcyclist failure to detect proper lanes when exiting roundabout
EX2	Motorcyclist failure to signal before exiting
CHAID	Chi-squared Automatic Interaction Detection

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