Consideration of Safety Measures in a Roundabout with Mixed High Motorcycle Traffic –A Case Study of the Roundabout at Prince of Songkhla University-

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Abstract: Thailand's high motorcycle usage demands urgent safety measures at roundabouts, yet research is limited. This study examines two countermeasures at a roundabout in Prince of Songkla University, where motorcycles are prevalent. Using a collision energy model based on the social force model, hazardous vehicle trajectories and key risk areas were identified via a heat map. Two measures were tested: a motorcycle (MC) priority lane and a single-lane restriction. The MC priority lane had minimal impact due to low usage, while the single-lane restriction effectively reduced parallel driving and altered motorcycle behavior. Results suggest that restricting driving space is a more effective safety measure in roundabouts with high motorcycle usage. This study provides key insights into designing interventions that enhance motorcycle safety in such environments.

Keywords: Roundabout, Traffic Safety Measure, Motorcycle, Driving Behavior

1. INTRODUCTION

In Thailand, the predominance of motorcycles in the traffic system necessitates the urgent development of safety measures that account for their high presence. However, research on the specific considerations required for implementing safety measures at roundabouts remains limited. This study focuses on roundabouts with a high proportion of motorcycles and evaluates multiple safety interventions tailored to their presence. In previous studies, evaluations of roundabouts have often been conducted using vehicle-to-vehicle such as PET (Post Encroachment Time) (Bulla-Cruz, et al., 2021; Shawky, et al., 2023). However, in situations where many motorcycles are present, it is possible that not only vehicle-to-vehicle pairings but also multiple surrounding vehicles may significantly affect the behavior of the vehicle being evaluated (Debaditya, et al., 2019). Therefore, in this study, a safety evaluation method based on the potential collision risk in roundabouts that takes into account multiple surrounding vehicles was used..

Furthermore, the study assesses the effectiveness of these measures through real-world implementation in Thailand, analyzing their impact on motorcycle riding behavior and collision risk. By examining the results, the study aims to clarify the efficacy of each intervention and identify the most effective safety measures for roundabouts with a high motorcycle penetration rate.

This study contributes to the growing body of research on improving motorcycle running safety and preventing motorcycle-related traffic accidents in roundabouts and provides empirical evidence for the effectiveness of various road safety measures. The results provide practical insights for policymakers and traffic engineers seeking to enhance roundabout safety in areas where motorcycles make up a significant proportion of road users.

2. LITERATURE REVIEW

In developed countries, roundabouts are established by formulating and applying design standards specific to each country. These standards include safety performance assessment methods designed to enhance the safety of roundabouts (Yoshioka et al., 2018). In the United States, roundabout design standards evaluate safety by estimating travel speeds at the entry, circulatory, and exit sections based on vehicle trajectories derived from specific constraints. The assessment compares the differences in calculated speeds with defined thresholds, known as the fastest path method (Federal Highway Administration, 2016). In Germany, the design standards define the concept of deflection as the ratio between the width of the entry lane and the lateral displacement of vehicles avoiding the central island. This indicator is used to evaluate the safety of roundabouts (Statens vegvesen, 2008). These safety performance assessment methods focus on verifying whether vehicle speeds are appropriately controlled based on estimated trajectories derived from roundabout geometric elements. However, since the sharing of motorcycles in developed countries is not high, those roundabout design standards and safety assessments do not account for motorcycle behavior.

Similarly, Thailand has introduced roundabout design standards that adopt the fastest path method and sight distance as key safety performance evaluation metrics (Department of Rural Roads (DRR), 2015). The sight distance assessment calculates the visible range of vehicles at the entry and circulatory sections and evaluates whether adequate sight distance is secured for vehicles to avoid collisions at different speed levels. However, Thailand's design standards are primarily based on those of the United States and do not consider the presence of motorcycles when designing roundabouts.

Many studies have been conducted on roundabout safety evaluation methods focusing on vehicle collisions. Mohamed et al. (2022) utilized trajectory data from video footage captured by UAVs in New Cairo, Egypt, to calculate the Post Encroachment Time (PET) at each conflict point and proposed a method for identifying hazardous conflict points at roundabouts. Katja et al. (2003) compared the usefulness of headway distance and Time-To-Collision (TTC) as safety indicators at four-leg intersections. Their results demonstrated that calculating TTC enables evaluating drivers' behavior and road design within a specific time frame. Yoshioka et al. (2019) proposed a risk indicator, represented as the product of the probability of oversight and collision intensity, as a safety evaluation metric for assessing roundabout safety from a geometric perspective. Additionally, they examined a predictive model for the risk indicator based on simulation results calculated for various geometric configurations.

Previous studies have examined geometric design aspects and driver behavior regarding motorcycle safety measures on roadways. From a structural perspective, considerable research has focused on motorcycle lane (MC lane) as a primary safety measure. Studies have demonstrated that introducing an MC lane effectively separates motorcycles from the general traffic flow, reducing traffic accidents and vehicle speeds on road segments (Le & Nurhidayati, 2016; Adnan et al., 2010; Mulyadi, 2018). Additionally, Law and Radin Sohadi (2005) conducted a logistic regression analysis on MC lanes implemented in Malaysia to evaluate motorcycle comfort during overtaking and concluded that an optimal MC lane width of 3.81 meters enhances overtaking comfort (Saini et al., 2022). Furthermore, Poi Alvin et al. (2018) employed a negative binomial regression model to analyze accident rates based on the presence and regional characteristics of non-exclusive MC lanes. Their findings suggest that while non-exclusive MC lane contribute to accident reduction, their effectiveness diminishes as the proportion of motorcycles increases.

Despite these extensive studies on motorcycle safety, the research focused on motorcycle behavior within roundabouts remains insufficient. Additionally, there has been a lack of comprehensive investigations into structural safety measures for motorcycles in roundabouts. Addressing these gaps is crucial for improving safety in roundabouts with high motorcycle penetration.

3. METHODOLOGY

3.1 Research Concept

In this study, we evaluated the potential collision risks with multiple surrounding vehicles in roundabouts with a high presence of motorcycles and evaluated the impact of implementing safety measures from the viewpoint of safety by utilizing these potential collision risks. Specifically, we estimated the potential collision risks by calculating parameters that minimize collision energy by incorporating factors such as speed, and position and generated a heat map of hazardous areas based on the trajectories of vehicles identified as dangerous. By comparing these heat maps before and after the implementation of safety measures, we analyzed changes in high-risk areas with potential collision hazards.
Finally, several safety measures for roundabouts with high motorcycle usage were proposed, and the impacts on safety in the roundabouts were evaluated using the potential collision risk. As a result, insights into traffic management strategies that enhance overall safety in such environments were provided.

3.2 Overview of the Safety Evaluation Method

To account for the complex traffic conditions involving motorcycles, this study employed an identification of potential collision risk method that considers vehicle trajectories of multiple surrounding vehicles (Debaditya et al., 2019). Concretely, this study utilized the potential collision to evaluate in terms of collision energy based on Equations (1) to (3) by the individual driving speed, position, and positional relationships with other vehicles for each vehicle.

First, individual vehicles of trajectories were extracted from video data using the CVAT annotation tool. Moreover, based on the extracted trajectories, the potential collision based on collision energy of each vehicle was calculated while considering the movement of surrounding vehicles. The collision energy is defined by the following equations:

$$E_c(v;s_i;s_{j\neq i}|\sigma_d,\sigma_w,\beta)=\sum_{j\neq i} w(si,sj)\,exp\left(\frac{d^2(v,s_i,s_j)}{2\sigma_d{}^2}\right) \quad (1)$$

$$w(s_i,s_j)=exp\left(-\frac{|\Delta p_{ij}|}{2\sigma_w}\right)\cdot\left(\frac{1}{2}\left(1-\frac{\Delta p_{ij}}{|\Delta p_{ij}|}\frac{v_i}{|v_i|}\right)\right) \quad (2)$$

$$d^2(v,s_i,s_j)=\left|\Delta p_{ij}-\frac{\Delta p_{ij}|v-v_i|}{|v-v_j|^2}(v-v_j)\right| \quad (3)$$

Where,

Ec	: Collision energy
σ_d	: Target vehicles prefer to maintain with surrounding vehicles to avoid crossing,
σ_w	: Reaction distance when a vehicle avoids crossing with other vehicles when overtaking or merging,
β	: peak degree of the weighting function of the turning distance,
p_i	: Position of vehicle i,
v_i	: Travel speed of target vehicle i,
s_i	: running condition of vehicle i and
$\triangle p_{ij}$	: Distance between the vehicle i and j.

From these equations, the collision energy for each vehicle is calculated. Assuming that vehicles aim to avoid potential collisions, the optimal state is when the collision energy calculated from each trajectory approaches zero. Therefore, in the evaluation method, we calculated σ_d, σ_w, and β for each trajectory, which minimized the collision energy, as shown in equation (4).

$$\{\sigma_d(i),\sigma_w(i),\beta(i)\} = \underset{\{\sigma_d(i),\sigma_w(i),\beta(i)\}}{argmin}\left(E_c\left(v_i;s_i,s_{-i}|\sigma_d(i),\sigma_w(i),\beta(i)\right)\right) \quad (4)$$

In order to estimate these parameters, we formulated the above minimization equation as a genetic algorithm, following the approach used by Robicquet et al. (2016). Using the obtained values, we applied the k-means method to the values of σd and σw, classifying each trajectory into two clusters. The k-means method is a technique that classifies data into K clusters based on the principle that data points close to each other belong to the same group.

In this study, instances where the value of σw was small, and the distance to the reaction point was short was labeled as "unsafe," while all other cases were labeled as "safe". Furthermore, to identify high-risk locations within the roundabout, vehicle trajectories classified as unsafe were extracted and plotted on the roundabout. Based on the number of plotted points at each location, a kernel density estimation (KDE) method was applied to generate a heatmap, which was used to identify areas within the roundabout where high-risk traffic conditions were likely to occur.

To outline the advantages of the method proposed in this study, Figure 1 presents a comparison between PET and the proposed safety assessment method based on potential collision. PET assesses safety by focusing on two vehicles that may collide at a conflict point. However, it cannot evaluate situations where potential collision exists without a clearly defined conflict point. Additionally, PET does not comprehensively account for the behavior of surrounding vehicles, which is essential for a holistic safety assessment.

Due to these limitations, PET is inadequate for analyzing traffic conditions in roundabouts, where multiple vehicles interact nearby. It does not sufficiently consider critical factors such as vehicle position, speed, and distance, making it challenging to capture the complexity of potential collision. As a result, PET-based assessments may fail to identify specific hazardous interactions. In contrast, the proposed method evaluates collision risk by considering the interactions between multiple surrounding vehicles. By incorporating these relationships, potential collisions can be assessed that PET and similar methods cannot detect. This approach enables a more comprehensive safety evaluation, particularly in complex environments such as roundabouts, where vehicle interactions are dynamic and require a more sophisticated assessment framework.

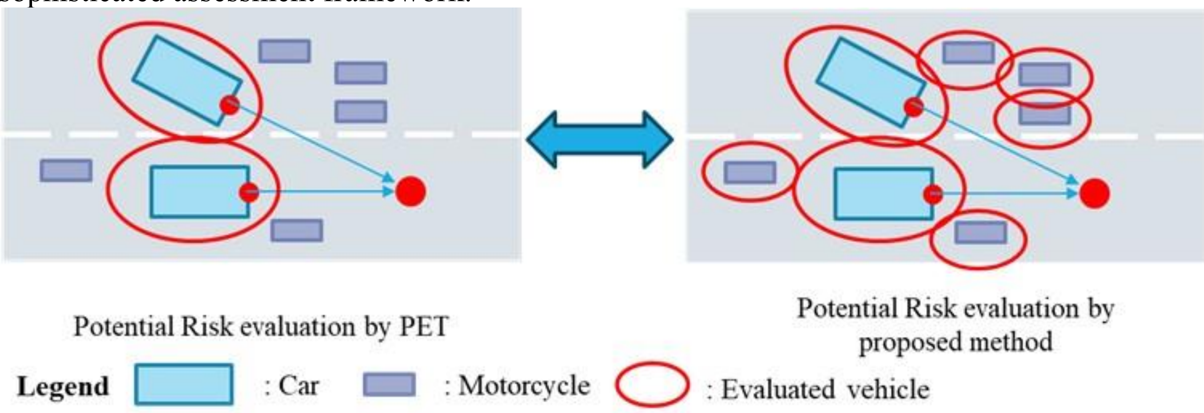

Figure 1. Comparison of PET and the Proposed Potential Collision Risk Assessment Method

3.3 Overview of the Study Site and Video Data Collection

In this study, the study site is a roundabout located within Prince of Songkhla University in Songkhla Province, Thailand. The geometric layout of the roundabout is illustrated in Figure 2. The feature of this roundabout is that it has four legs and two circular lanes. Additionally, designated MC priority lanes are installed at each entry approach and the outside lane of the circular roadway. Details of the video data collection are summarized in Table 1. The video data were captured using an unmanned aerial vehicle (UAV) and recorded for 10 minutes in each situation.

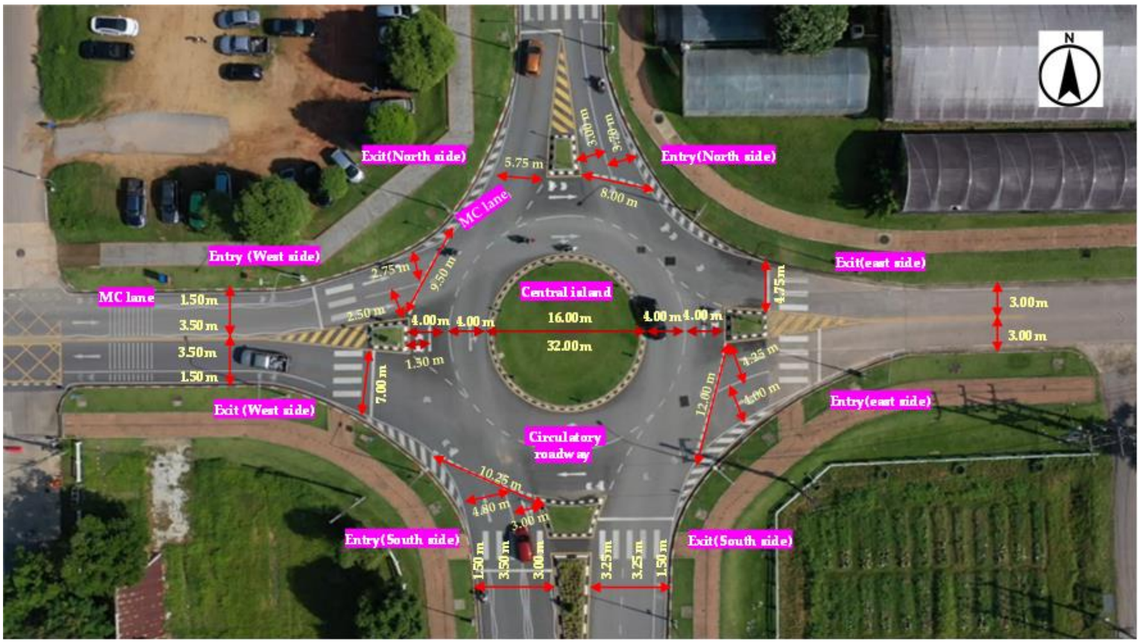

Figure 2. Geometric structure of target roundabout

Table 1. Overview of video data

Situation	Date	Time	Period
Without countermeasure	May 12, 2023	9:00	10 min.
With MC Priority Lane	Oct. 11, 2023	8:00	10 min.
After restriction 1 lane within circulatory roadway	Nov. 24, 2024	16:30	10 min.

Moreover, Table 2 presents the traffic volume for each approach road by transportation mode across different situations based on video data. The survey site is situated at an intersection adjacent to the Prince of Songkla University campus to the north and a national highway to the south. Due to these locational characteristics, the roundabout experiences significant traffic volumes from commuters and students. It is important to acknowledge that user characteristics may vary depending on the time of day.

In this study, practical constraints prevented video data collection at identical times across all observation periods. Despite this limitation, This table indicates that traffic volume is consistently higher on the southern approach in all situations.
Additionally, the proportion of motorcycles remains high across all situations and traffic flow directions. This highlights the critical need for targeted safety measures addressing motorcycle traffic at the roundabout. The consistently high presence of motorcycles in varying traffic conditions suggests that the importance of countermeasures for motorcycles.

Table 2. Traffic Volume by Inflow Direction from Video Data

Situation	Type	North	East	South	West	Sum
Without countermeasure	MC	15	11	89	34	149
	PC	20	19	64	25	128
	Other(B,T)	1	5	0	0	6
	Sum	36	35	153	59	283
With MC Priority Lane	MC	34	52	449	79	614
	PC	30	60	125	28	243
	Other(B,T)	2	1	3	4	10
	Sum	66	113	577	111	867
After restriction 1 lane within Circular Roadway	MC	161	21	64	29	275
	PC	38	15	51	38	142
	Other(B,T)	1	2	1	3	7
	Sum	200	38	116	70	424

Note: The unit is vehicles per 10 min.

3.4 Overview of Traffic Safety Interventions

This study considers two safety countermeasures to reduce conflicts between motorcycles and other vehicles in mixed-traffic conditions with a high motorcycle presence.

3.4.1 Motorcycle (MC) Priority Lane

The MC priority lane is a designated lane for motorcycle travel, marked with chevron patterns to indicate the intended path for motorcycles. Figure 3 illustrates the layout of the MC priority lane. This study implemented the MC priority lane in the outer lane of a two-lane circulatory roadway within the roundabout. Introducing this lane is expected to reduce high-speed motorcycle movement within the circulatory roadway and minimize conflicts with other vehicles by segregating motorcycle traffic from the general traffic flow. Furthermore, by the MC using the MC priority lane, the risk of collision is expected to be reduced when the MC and a vehicle move side by side or overtake each other because a distance will be maintained.

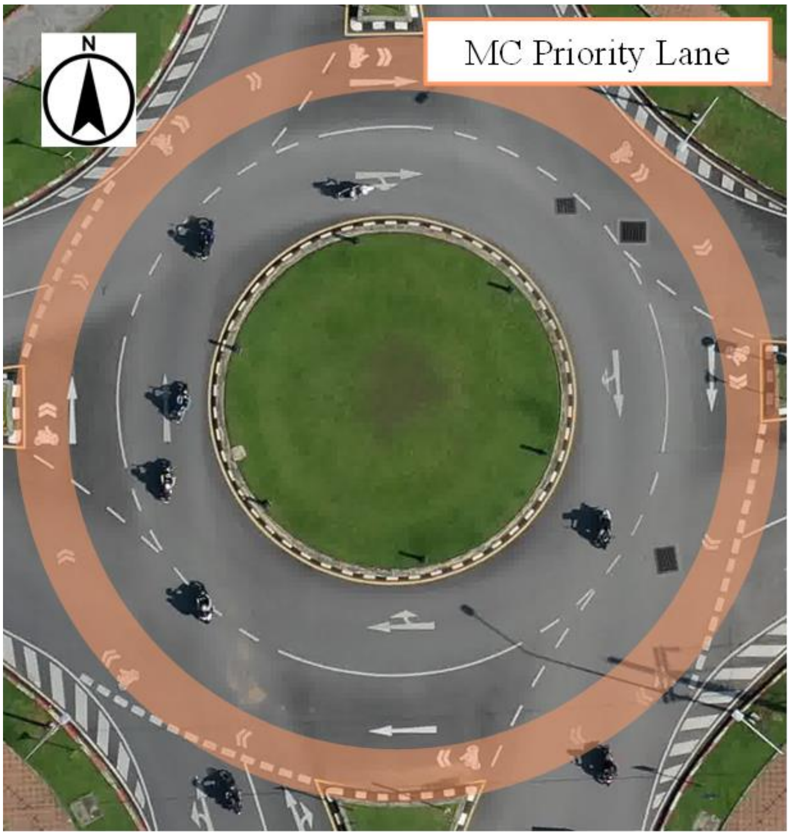

Figure 3. Geometric structure of MC priority lane

3.4.2 Restriction of Single-Lane Circulatory Roadway

One of the key characteristics of vehicle movement at roundabouts in Thailand is the lack of adherence to lane discipline. As a result, motorcycles traveling through the roundabout tend to ride parallel to each other over short distances, which, while not necessarily leading to immediate conflicts, creates a hazardous situation. To address this issue, this study examines the potential impact of restricting access to the inner lane of the two-lane circulatory roadway, effectively converting the roundabout into a single-lane configuration, as shown in Figure 4.

The expected outcomes of this measure include a reduction in parallel riding and overtaking behavior among motorcyclists due to the decrease in available riding space from two lanes to one. This modification is anticipated to lower the frequency of conflicts and mitigate potential collisions. Additionally, by reducing the number of circulatory lanes, the measure aims to minimize conflicts during merging maneuvers, thereby enhancing overall safety. This study provides empirical insights into the effectiveness of space restrictions as a traffic safety measure for roundabouts with high motorcycle penetration. The findings contribute to developing targeted interventions that improve traffic flow and reduce accident risks in environments where motorcycles constitute a significant portion of road users.

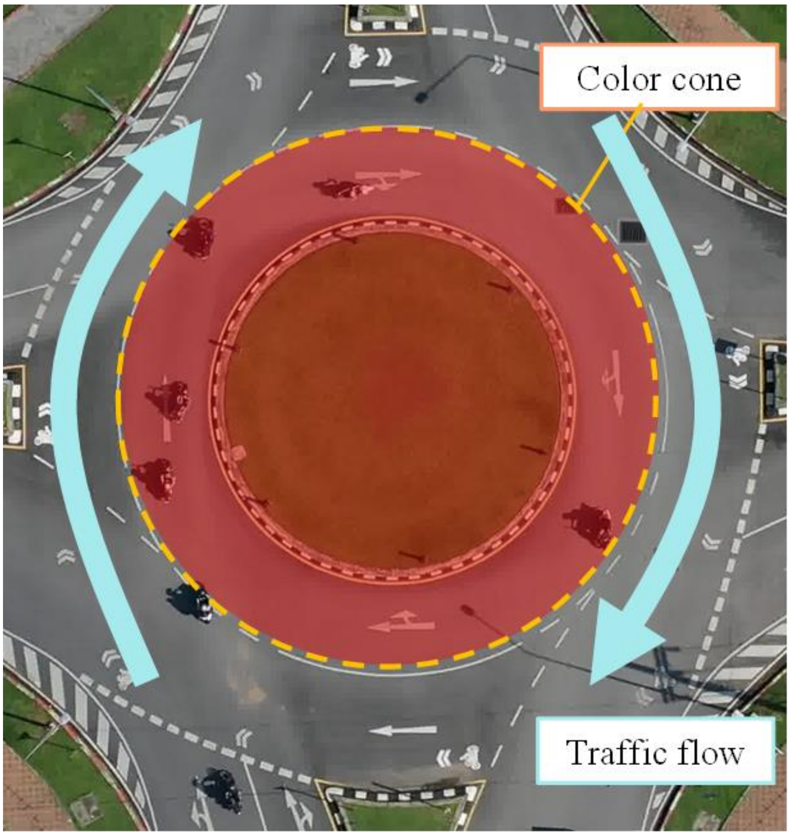

Figure 4. Geometric structure of single circulatory lane restriction

4. RESULTS

4.1 Change of Potential Conflicts from MC Priority Lane

4.1.1 Change of Driver Behavior?

The utilization rate of the MC priority lane by motorcyclists is presented in Figure 5. Additionally, Figure 6 illustrates the vehicle trajectories of each motorcycle within the roundabout before and after implementing the MC priority lane.

Before introducing the countermeasure, observations indicated that, except for left-turning movements, many motorcycles traveled through the inner lane of the circulatory roadway when passing through the roundabout. After implementing the MC priority lane, most motorcycles utilized the inner lane rather than shifting to the outer lane, where the designated lane was marked.

These findings suggest that introducing the MC priority lane did not significantly alter motorcycle positioning within the roundabout. Furthermore, an analysis of the lane utilization rate, as shown in Figure 5, reveals that only 4% of motorcycles used the designated lane. This confirms that most motorcyclists passing the roundabout did not adhere to the MC priority lane.

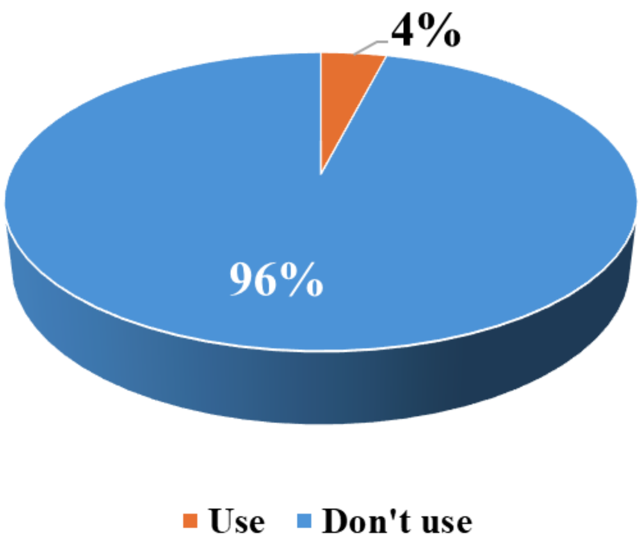

Figure 4. Percentage of usage of MC priority lane

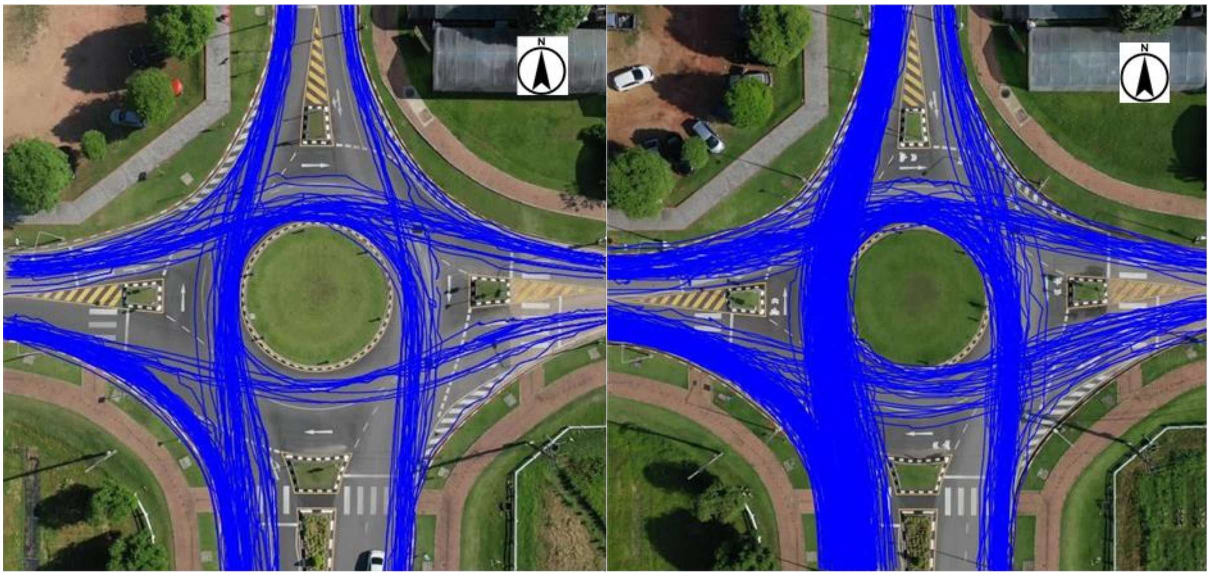

Figure 5. Vehicle trajectory of the motorcycles before (Left) and after (Right) installation of MC priority lane

4.1.2 Comparison of distribution of risk spots

Figure 7 presents heat maps illustrating the frequency of high potential collision risk (classified as unsafe) of motorcycle trajectories at the roundabout before and after implementing the MC priority lane. In these heat maps, areas shaded in blue indicate locations with fewer hazardous trajectories, representing safer zones, whereas areas shaded in red denote a higher frequency of hazardous trajectories, indicating high-risk areas.

As shown in Figure 7 (Left), before implementing the MC priority lane, hazardous locations were primarily identified at the eastern entry, southern entry, western circulatory roadway, and western entry of the roundabout. Similarly, as depicted in Figure 7 (Right), following the implementation of the MC priority Lane, hazardous locations remained concentrated at the southern entry, western circulatory roadway, and western entry. These

findings suggest that the spatial distribution of hazardous locations within the roundabout remained unchanged after introducing the MC priority lane.
The results indicate that implementing the MC priority lane did not substantially reduce hazardous motorcycle trajectories, suggesting that its effectiveness in enhancing roundabout safety may be limited. Further investigations into rider compliance, lane visibility, and driver awareness are warranted to optimize the safety benefits of this intervention.

A comparative analysis of motorcycle riding behavior before and after introducing the MC priority lane revealed a low utilization rate among motorcyclists and no significant changes in motorcycle positioning within the roundabout. Additionally, an analysis of the spatial distribution of hazardous locations indicated that introducing the MC Priority lane did not alter the distribution of high-risk areas. These findings suggest that implementing the MC priority lane had no measurable impact on improving the safety of the target roundabout.

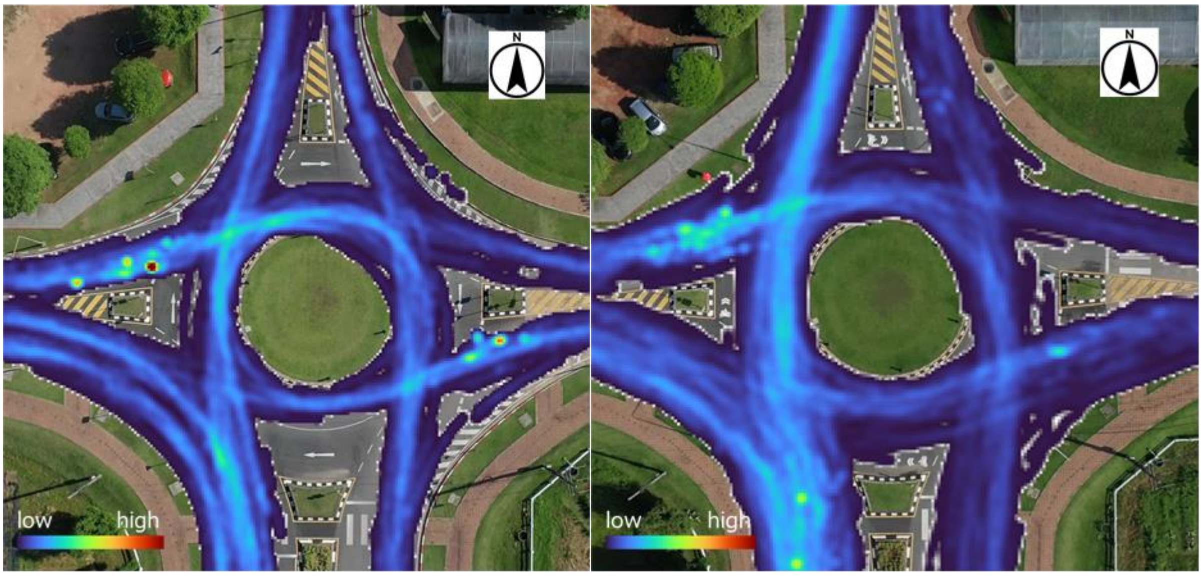

Figure 7. Distribution of risk locations before and after implementation of MC priority lane

4.2 Effects of Single-Lane Circulatory Roadway Restriction

4.2.1 Results of Vehicle Driving Behavior

Figure 8 illustrates motorcycle travel trajectories within the roundabout following the implementation of the single-lane circulatory regulation. Compared to the pre-implementation phase, the curve radius of motorcycle travel trajectories within the circulatory roadway increased, and a reduction in parallel riding behavior was observed.

As shown in the Figure, under the single-lane circulatory regulation, most motorcycles drive in the outer lane of the circulatory roadway. Additionally, restricting the vehicle travel area reduced the complexity of traffic flow within the circulatory roadway. An analysis of motorcycle parallel riding behavior revealed that, before implementing the countermeasure, 11% of all motorcycles exhibited parallel riding behavior. However, after the countermeasure was implemented, this proportion decreased to 2%.

The primary factor contributing to this reduction in parallel riding behavior is likely the restriction of available driving space. Limiting the travel area reduced the lateral distance between motorcycles and other vehicles, increasing the sense of spatial pressure during parallel riding and thereby discouraging this behavior. These findings suggest that implementing the single-lane circulatory regulation is an effective safety measure for roundabouts with a high proportion of motorcycles, as it reduces parallel riding behavior and enhances traffic flow organization within the circulatory roadway.

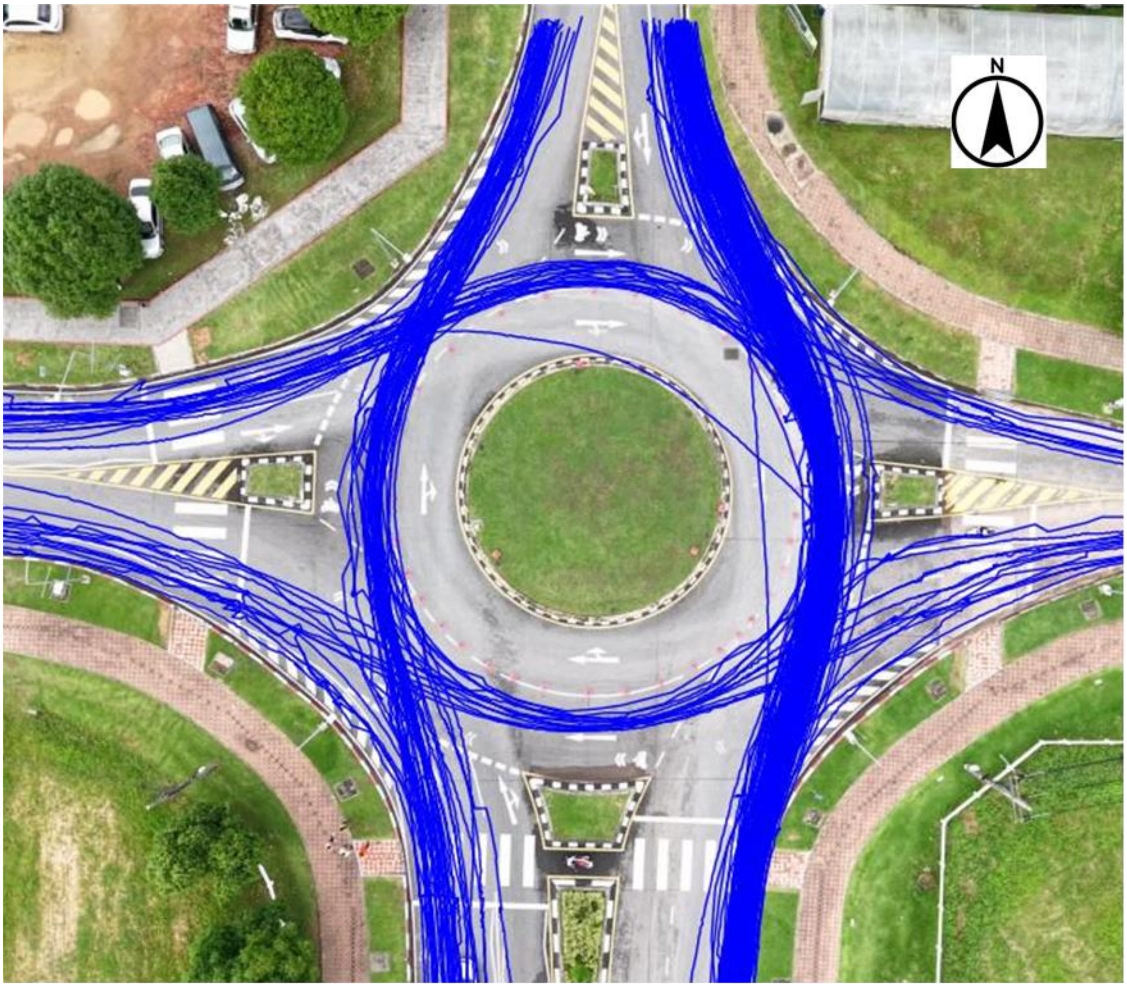

Figure 8. Motorcycle trajectories in the roundabout after the implementation of the Single-lane circulatory restriction

4.2.2 Comparison of the Spatial Distribution of Potential Collision Locations

Figure 9 illustrates the spatial distribution of high-risk locations following the implementation of the single-lane circulatory roadway regulation. After restricting access to the inner lane within the circulatory roadway, high-risk locations were identified at the northern entry, the western circulatory section, and the eastern entry.

A comparative analysis of high-risk locations before and after the countermeasure implementation revealed notable differences in their spatial distribution. These variations are likely influenced by changes in the characteristics of incoming traffic volume. Specifically, an examination of traffic volumes at the northern and southern entries indicates that, prior to implementation, a higher proportion of vehicles entered the roundabout from the southern approach. However, following the introduction of the single-lane circulatory regulation, traffic volume from the northern entry increased.

This shift in traffic patterns is considered to have directly influenced the spatial distribution of high potential collision risk locations, highlighting the dynamic relationship between traffic flow characteristics and safety outcomes in roundabout environments.

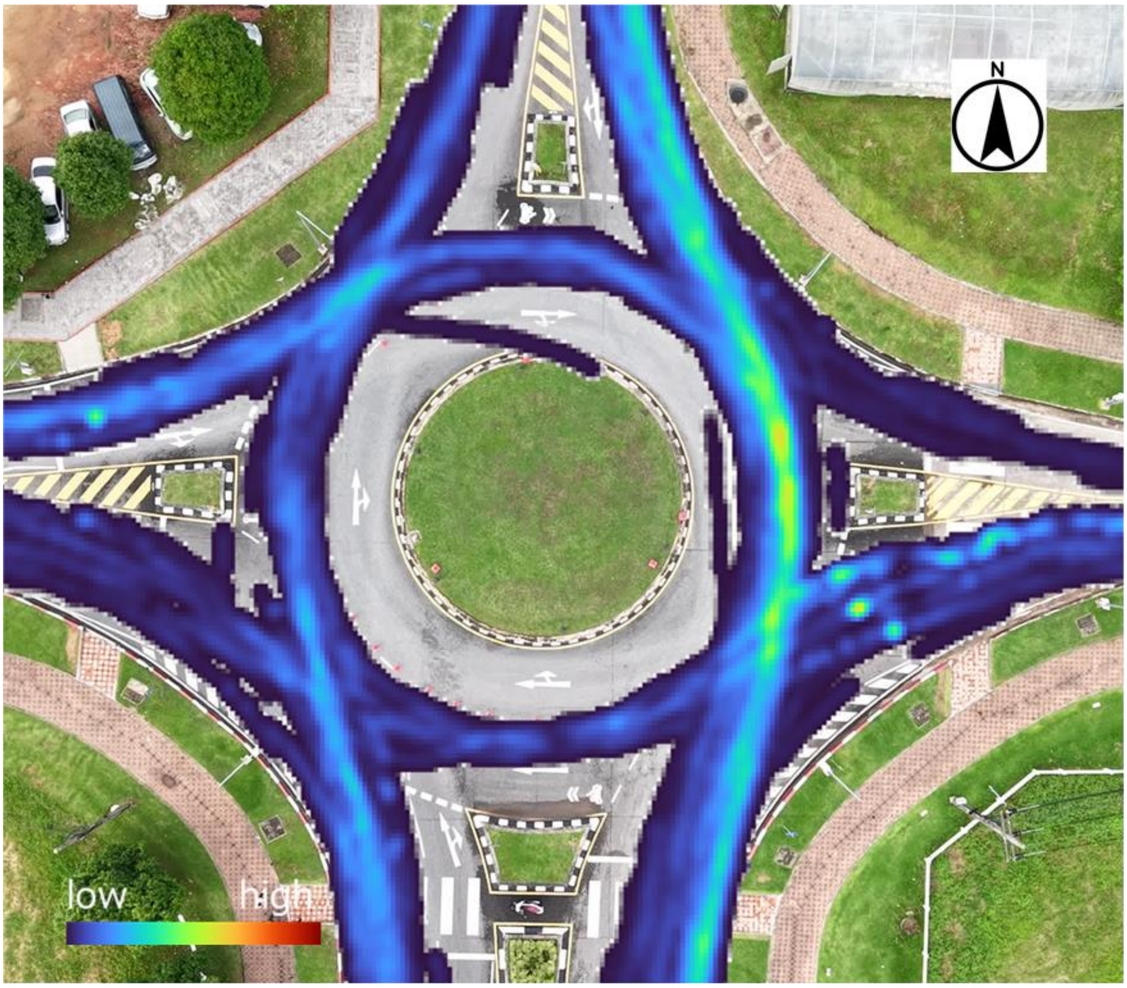

Figure 9. Distribution of risk spots before and after restriction of single-lane within the circular roadway

5. CONCLUSION

This study assessed the safety of roundabouts with a high proportion of motorcycles by identifying potential collisions that consider relationships with multiple surrounding vehicles rather than just the existing one-to-one vehicle relationships that are the subject of many indicators. The implementation of the MC priority lane at the study roundabout did not result in significant changes in motorcyclist riding behavior or overall roundabout safety, indicating that this measure had limited effectiveness from a safety perspective. Similarly, considering inflow traffic volume characteristics, the single-lane circulatory roadway restriction analysis revealed minimal differences in the spatial distribution of high-risk locations before and after implementation.

However, improvements were observed when focusing specifically on motorcycle riding behavior. Notable changes included an increased turning radius in motorcycle travel trajectories and reduced side-by-side riding, both contributing to enhanced motorcycle safety.

Based on these findings, restricting the circulatory roadway to a single lane emerged as a more effective safety measure for roundabouts with a high motorcycle presence.

Conversely, MC priority lane have rarely been implemented nationwide, and their adoption in Thailand remains particularly limited, as roundabouts have only recently been introduced in the country. Consequently, Thai road users may not fully understand how to utilize the MC priority lane, leading to low usage rates. In contrast, MC priority lane have been widely implemented on roadway segments, where they have demonstrated effectiveness in enhancing safety by segregating motorcycles from general traffic. Therefore, with appropriate operational strategies and increased public awareness, the MC priority lane could also improve safety in roundabouts.

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