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An Optimized Design of Roundabout for Safety Enhancement on Road Users: A Case Study of Suranaree University of Technology

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List of Abbreviations and Acronyms

ATRANS	Asian Transportation Research Society
SUT	Suranaree University of Technology
UAV	Unmanned aerial vehicle
MC	Motorcycle
PC	Passenger car

CHAPTER 1 INTRODUCTION

1.1 Statement of problems

Nakhon Ratchasima is the biggest third province, in terms of population, in Thailand. The province is a main corridor connecting Bangkok, the capital of Thailand, and the Northeast provinces. In addition, there are several major trip attractions, for example, universities, schools, hospitals, and department stores, located in the urban area. As a result, Nakhon Ratchasima has encountered both high traffic movement and traffic congestion problems. These problems tend to increase the potential risk of road traffic crashes. Thus, suitable traffic operations and controls are one of the major keys that can be able to improve road safety and traffic congestion problems. Moreover, safety knowledge and awareness of road users are basic to properly running traffic networks safely and securely.

Implementation of a roundabout is the concept to move traffic more efficiently through unsignalized intersections which have evolved from a conventional traffic circle to a modern roundabout. Give way when entering or driving in a roundabout to any vehicle in the roundabout is the international rule and the most important rule. Moreover, the other configurations should also be emphasized, which include optimization design, traffic signs, pavement markings, regulation, and education of road users.

However, many roundabouts implemented in Nakhon Ratchasima are doubted by either standard design or well-educated road users. Especially, the roundabout has been installed to reduce the conflicts in front of the Suranaree University of Technology (SUT) main gate, as shown in Figure 1. Most of the road users are students who are at beginner or intermediate level in motorcycle riding or car driving. Also, some riders may not be conscious during using the roundabout. Some may not understand how to use the roundabout. Moreover, unappropriated design may lead to misunderstandings between the riders and drivers.

There is a situation in which the driver did not give way for priority rule compliance which cause a serious conflict, especially between mixed traffic of cars and motorcycles. Also, as shown in Figure 2, a car drives on the truck apron area which mean traffic lane changing is ignored while rotary in a roundabout cause higher speed driving. As a result, road crashes at this roundabout have been happening since the roundabout was implemented. Most of the students are not conscious of the rules for using the roundabout, this may cause by the reason of both inappropriate design and a lack of educational behavior. The traffic crash (Figure 3) was recorded by the security office of SUT. There is the evidence that crash number at the Gate 1 roundabout was dominant at the 2nd highest after the crack of road pavement at the Gate 4 intersection.

Figure 1 Overview of the existing roundabout at SUT gate

Figure 2 Vehicle entering the truck apron area of the existing roundabout

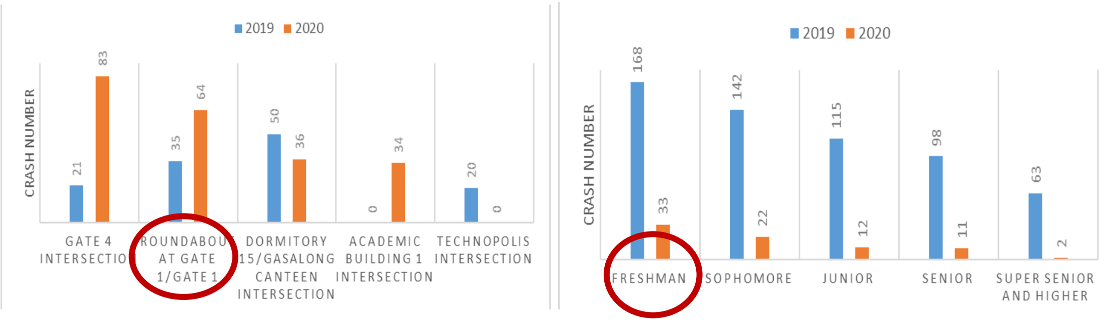


Figure 3 The number of crashes and road users involved

1.2 Research objectives

Based on the concept of the safe road system in Figure 4, this study aims to fulfilling the gaps between safe roads and the roadside by improving the physical design of roundabouts, and safe road users by educating them on a basic knowledge of rider safety in roundabouts. The roundabout at SUT main gate is selected as a case study. Two specific objectives of this research are as follows:

1) To investigate potential risks and risky driving behaviors at the SUT roundabout.
2) To propose guidelines for designing the roundabout under motorcycle-dominated environments considering both safety and traffic performances.
3) To educate students and staff on basic knowledge of driving and riding safely at roundabouts.

Figure 4 The safe road system
Source: towardszero.nsw.gov.au

1.3 Expected outputs

The expected outcomes are the optimal design of the case study roundabout by integrating both international guidelines and local road users' behavior. Also, this research work provided the essential international idea of using roundabouts or the concept of using roundabouts which will be educated to freshman students. The research results can be useful to not only the SUT area but also other upcoming roundabouts in other areas.

1) The algorithms for vehicle detection and tracking developed in this research could be used as an effective tool for tracking the traffic trajectory of vehicles and analyzing related parameters in other roundabouts.
2) Safer design guidelines for improving the mixed traffic study roundabout were proposed to the concerned authority for further action.
3) The trainees could comply with traffic rules, avoid risks, and drive safely at roundabouts.
4) The content and materials from the roundabout training could be applied to other areas.

1.4 Scope of the study

The traffic characteristic of the roundabout at SUT is the case to examine. The proposed area had mixed traffic between passenger buses, cars, and motorcycles with a variety of driver ages and experience. The roundabout had presented as the four legs intersection traveling between educational activity, residential zone, shopping area, and intercity connection. There were two scopes of this study the first one was to see the traffic circumstance (traffic parameters) and the other was to provide international rules to young drivers (freshman students). The collected data on traffic was focused on the evening peak hour covering all directions. The target group of students was the beginner experience driving who need to participate in education training that is set for three hours. The basic knowledge of using roundabouts and preference design was asked during the training.

CHAPTER 2 LITERATURE REVIEW

2.1 Roundabout design standards and guidelines

Implementation of roundabouts is the concept to move traffic more efficiently through unsignalized intersections which have evolved from conventional traffic circles. Giving way when entering or driving in a roundabout to any vehicle in the roundabout is the international rule and most important. Also taking the correct lane during driving in a roundabout must pay attention to eliminate conflict for safety issues. Designing the geometry of a roundabout involves choosing between trade-offs of safety and capacity. Roundabouts operate most safely when their geometry forces traffic to enter and circulate at slow speeds. Many of the design techniques and parameters are different, depending on the speed environment and desired capacity at individual sites. Additionally, many of the design techniques are substantially different from single-lane roundabouts and roundabouts with multiple entry lanes. Moreover, the other configurations that should concern are optimization design, traffic information signs, pavement marking, regulation policy, and educated people. Some existing implemented roundabouts are doubtful about the design and whether or not to cover all international standards. Moreover, there is no performance and safety assessment during its operation according to the information guide procedure Figure 5.

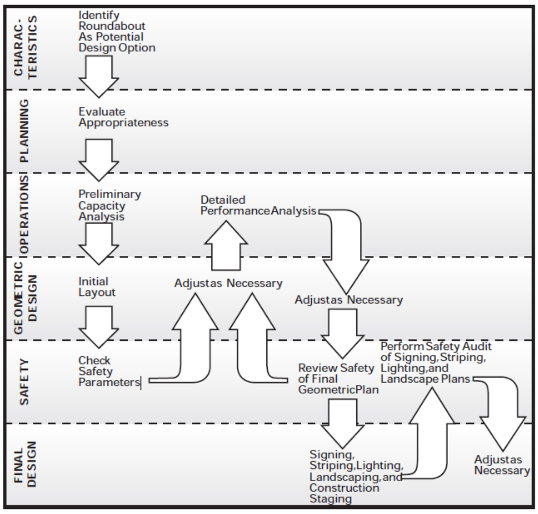


Figure 5 A roundabout information guild procedure [1]

Roundabouts rely on two basic and important operating principles which are speed reduction and yield-at-entry rule. Thus, sight distance is a fundamental consideration for roundabout design. Two types of sight distance apply to roundabouts: 1) stopping sight distance must be provided for users approaching the roundabout and for users traveling through the roundabout, and 2) intersection sight distance sometimes called "sight triangles" must be provided for drivers entering the roundabout as shown in Figure 6.

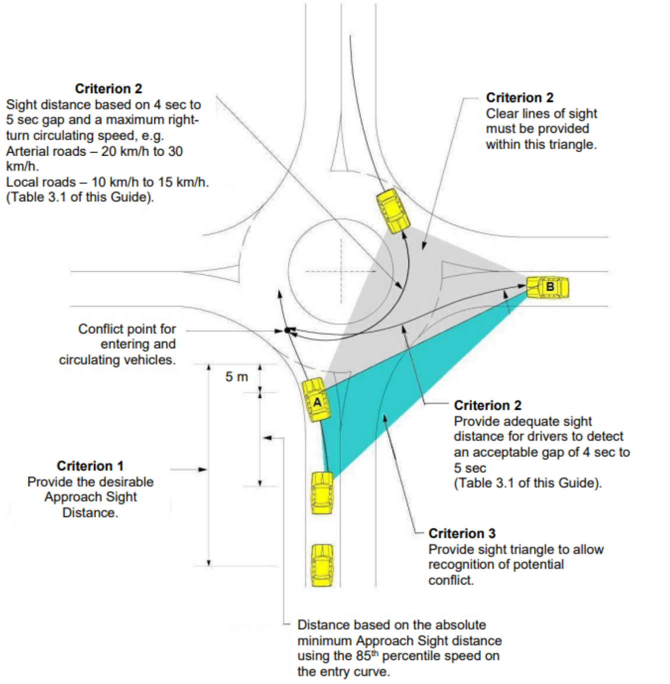


Figure 6 Sight distance criteria for roundabouts [2]

Moreover, the lane configuration and line marking of the multi-lane roundabout is important as shown in Figure 7. Some countries in Europe have proposed the priority lane for bike users as a separate bike lane adjacent to the traffic lane, providing some exclusive paths separate for bike lanes and providing a full exclusive bike lane shown in Figure 8.

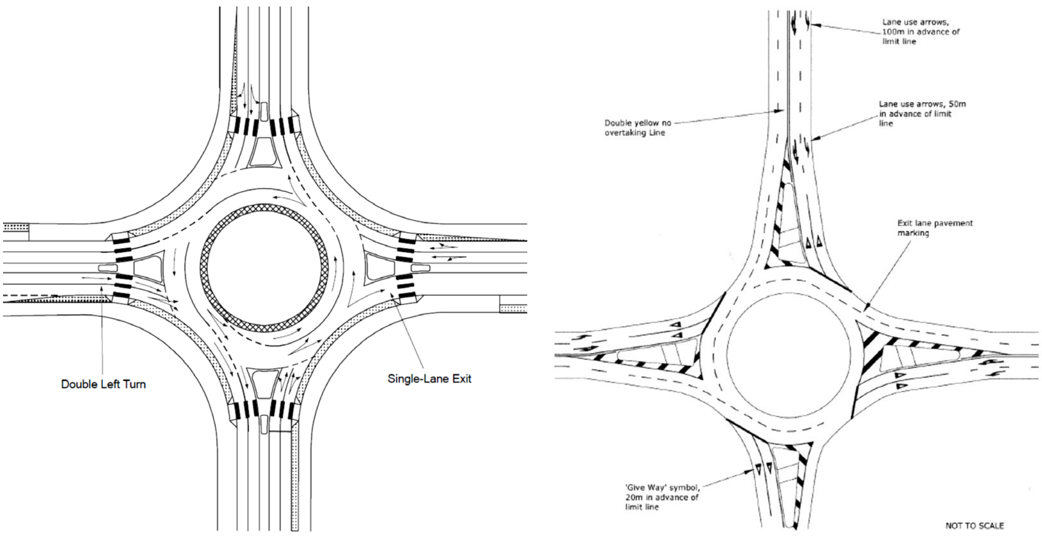


Figure 7 Roundabout lane configuration example standard and line marking of a multi-lane roundabout [2,3]

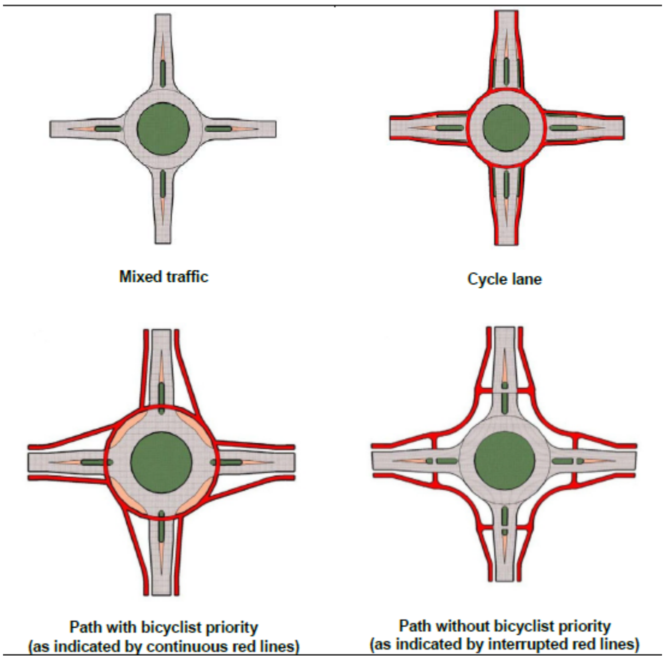


Figure 8 Roundabouts with bike lanes

2.2 Good practices of the roundabout from international and national perspectives

In the national press, it was dubbed a £2.3m cyclist killing zone, while one columnist argued it would only intensify the war between cyclists and drivers. As shown in Figure 9, the Fendon Road roundabout is the UK's first and so-far-only so-called "Dutch-style" roundabout situated near Addenbrooke's and Papworth hospitals. This roundabout was built by the county council and opened in July 2020 in an attempt to improve the safety of its predecessor, which had seen 12 collisions between cars and cyclists between 2012 and 2017. Cyclists have an outer ring on the Cambridge roundabout, with cycle crossings over each of the four approach roads in a contrasting red surface. There are also zebra crossings over each approach road for pedestrians. Motorists must give way to pedestrians and cyclists when joining and leaving the roundabout. Reduced lane widths on the roundabout and at the exit and entry points are designed to encourage drivers to slow down.

Figure 9 Good example of roundabouts with a bike lane
Source: BBC news

2.3 New technologies for traffic data collection and analysis

Recently, unmanned aerial vehicles (UAV) have been increasingly involved to collect traffic data. This technology can benefit seeing from the top view together with image processing analysis, the traffic flow trajectory can be tracked.

Figure 10 An unmanned aerial vehicle UAV technology
Source: https://www.youtube.com/watch?v=sswTaiNzKlo

2.4 Previous research studies

Chauhan [4] proposed the traffic flow simulation at Malhar circle, India by using VISSIM to recognize the zone of influence through acceleration and deceleration activities of a vehicle to generate the pollution amount. UAV-based Traffic Analysis [5] was applied at a roundabout to observe the trajectory. The results determined traffic volume via OD metrics for each leg and analyze driver behaviors via gap acceptance. Paul [6] introduced the methodology being developed for the detailed analysis of driving behavior, trajectory interpretation, and conflict measures in modern North American roundabouts. The analysis explored the methods used to prepare microscopic speed maps, compiled speed profiles, lane-change counts, and gap time measures. The collected data was based on video data extracted using computer vision. Dinh [7] proposed an automated traffic data collection system dedicated to a roundabout, resulting in the vehicle trajectory of each vehicle giving the position, size, shape, and speed of the vehicle at each time moment. Therefore, this study would like to fill the gap to consider more deeply the direction trajectory angle analysis of lane changing in the roundabout by a recent popular drone application. Then, using this to further improve the physical element design of the roundabout for the road user.

Now drone is popular in transportation fields because of their low cost, flexible design, small size, high mobility, and adaptability [8]. The image from the drones are equipped with a camera to collect the visual information of the environment, and then, computer vision techniques have been used to extract the information of the environment as post-image analysis. This information can be used to analyze the information traffic. Many researchers proposed various methods to analyze the information of the traffic by using computer vision technology with the image from the drone. Analysis of the images from a drone in the transportation fields has been studied in road safety [9], traffic monitoring and surveying [10], highway infrastructure management [9], etc. [11,12].

The detection algorithm is the main part of the algorithm for drone traffic monitoring and surveying systems. The well-known detection algorithms are CNN [13], Fast R-CNN [14], YOLO [15, 16], etc. [17-19]. If the surveying area is not too large, only one drone can be used for traffic monitoring. Barmpounakis [20] used one drone to measure the accuracy of the microscopic traffic parameter. In addition, the basic analysis parameter from the drone could be used to analyze the prediction of the traffic. Yu [21] used the traffic data from the drone to predict the trajectory data of freeway high-risk events. In some cases, only one drone cannot be used for traffic monitoring because the drone must be surveyed in a very large area. So, the survey drone trajectory management must be developed. Shi [22] proposed a hierarchical DRL approach for multiple drone surveying trajectory management systems. Conte [23] used a machine-learning-based prediction for drone planning paths. Nguyen [24] proposed an autonomous drone flight trajectory system for traffic management in a smart city. The traffic data from multiple drones is also very useful for traffic monitoring and management. Barmpounakis [25] used 10 drones to record the 1.3 km^2 area with more than 100 km in total road length and around 100 busy intersections of the road network. Kumar [26] developed the software for on-road traffic monitoring and management using traffic data from multiple drones.

CHAPTER 3 METHODOLOGY

3.1 Research framework

The research framework consists of 9 tasks as shown in Figure 11, which include:

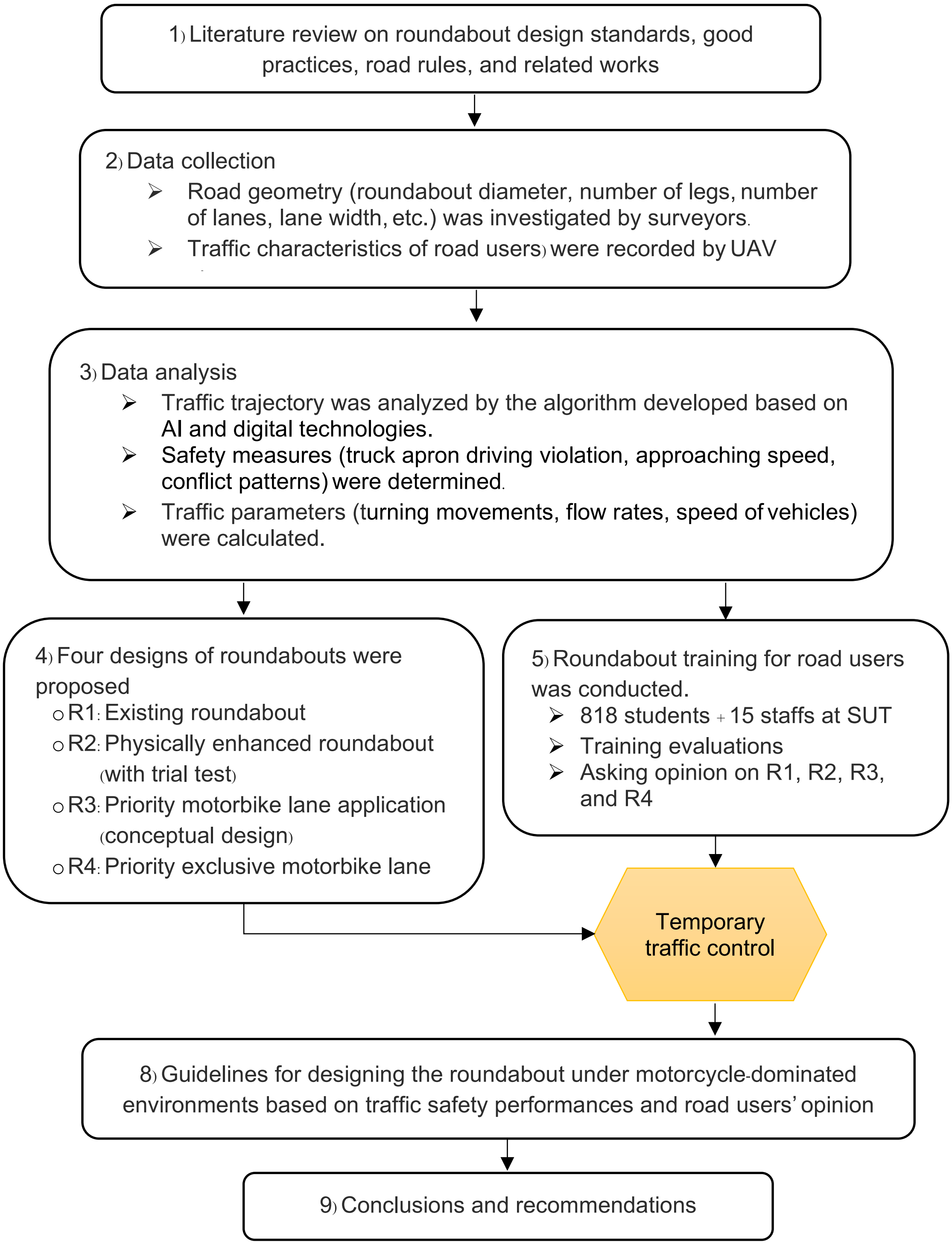


Figure 11 Research framework

3.2 Data collection

All related traffic parameters and physical road data such as roundabout diameter, number of legs, number of lanes, and lane width right of way, were collected. The existing traffic circumstances were also investigated by surveying the traffic parameters and the traffic measurements which are the frequency of traffic trajectory violence on lane marking and driving speed. A method for deriving traffic information in the roundabout using a camera installed on the unmanned aircraft vehicle (UAV or shortly called drone) was used. The method applied a machine-learning-based approach for image processing by vehicle detection, vehicle type classification, and trajectory tracking.

Aerial video surveillance using a wide field-of-view sensor was applied to provide new opportunities in traffic monitoring over such extensive areas. A UAV equipped with automatic position stabilization units and high-resolution cameras could be the most effective choice for data acquisition of sufficient quality. UAVs, unlike satellites or airplanes, can collect visual data from low altitudes, and therefore provide images with the adequate spatial resolution for further traffic inspection, i.e., vehicle detection and tracking.

Traffic data was recorded at the evening peak hour on Friday every 15 minutes. Figure 12 shows the driving behavior of whether drivers are concerned to drive in the appropriate lane for safety or not. Some cars and motorcycles are driving on the truck apron area which is not their driving lane. This leads to the unappropriated directional angle that can be controlled for approaching speed. The approaching speed was investigated as one of the factors in designing a safer roundabout.

Figure 12 Driving behavior approaching the roundabout

3.3 Data analysis

Traffic trajectories, which are primarily concerned with tracking multiple vehicles, were investigated to obtain detailed and accurate information about the vehicles' trajectories during their passage through the roundabout. The visual data for the analysis was captured by a camera mounted on a UAV. The operating time of a UAV was about 15 minutes due to its limitation of battery capacity. The data were recorded on a memory card and subsequently post-processed on a high-performance computer.

Object detection algorithms were developed with pre-trained models and then fine-tuned as per our requirements. Generally, the object detection task was carried out in two steps:

1) Generates the small segments in the input.

2) Feature extraction is carried out for each segmented rectangular area to predict whether the rectangle contains a valid object.

Analyzing the safety level based on the traffic trajectory that varies from the lane marking guideline and the safety distance between adjacent cars was concerned. The conceptual idea was to use the angle collision avoidance and lane-changing base for safety. The Safety Performance Evaluation Standard for Highway Fences (2013) have stated this angle should be less than 20 degrees, which is following the study of Yang [27] indicated that the angle during lane-changing is less than 23 degree and safety distance between adjacent cars 2 meters. Simultaneously, an education content design based on the current problems and international guidelines (the details will be explained in step 5).

Moreover, the others traffic parameters were investigated for further performance analysis. Therefore, the data analysis was categorized into two parts the traffic situation and performance parameters and safety indicators which are listed below:

1) Traffic situation and performance parameters
    a. Traffic trajectory
    b. Turning movement
    c. Headway
    d. Flow rate
2) Safety indicators
    a. Physical site road safety audit
    b. Sight distance and Approach deflection
    c. Truck apron driving violation
    d. Approaching speed and outgoing speed
    e. Rotary speed in the roundabout
    f. Conflicts between mixed traffic
    g. Priority rule of give way to un-compliance.

3.4 Development of an algorithm for traffic data analysis

The machine learning algorithm can track vehicles on multilevel roads. This algorithm can track all the vehicles even when visual occlusion appears. Also, it can follow the whole trajectory of the car for the tracked time and collect reliable data which are average speed, acceleration, gap time, time to follow, heatmaps, or dimensions of vehicles. Track those vehicles can link to our research as this can see the directional driving between adjacent vehicles.

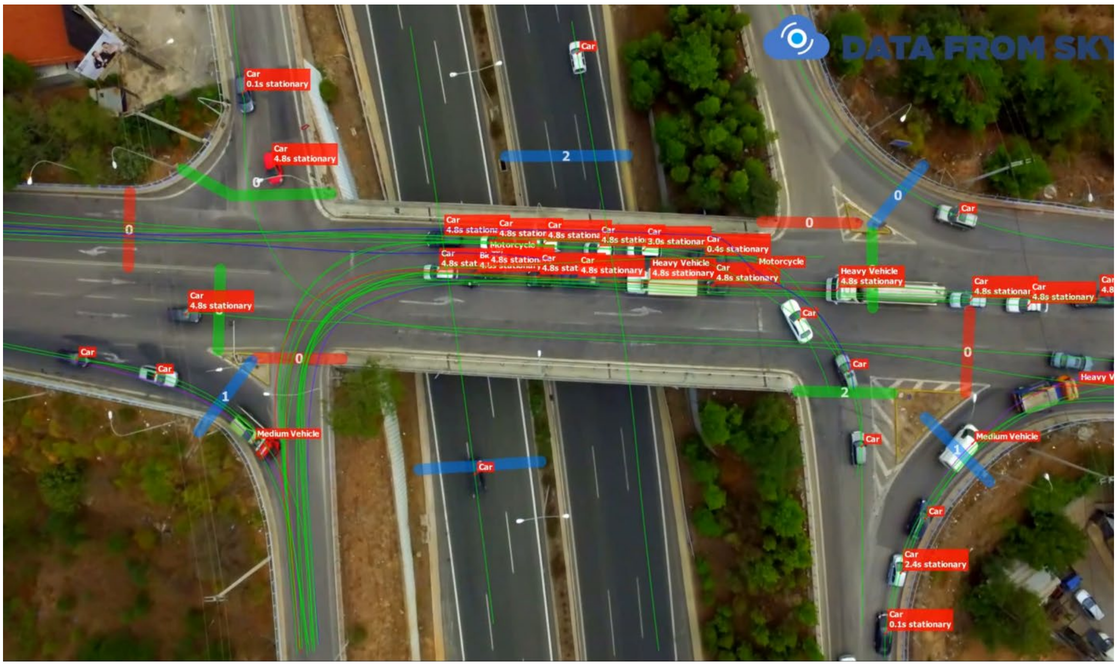
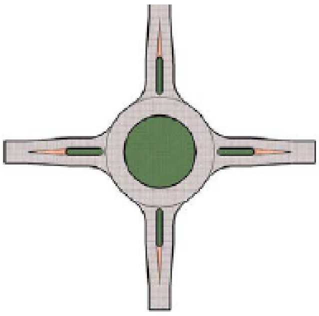


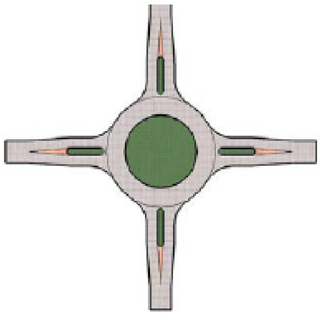
Figure 13 A vehicle tracking algorithm
Source: DataFromSky

3.5 Guidelines for roundabout design under MC dominated condition

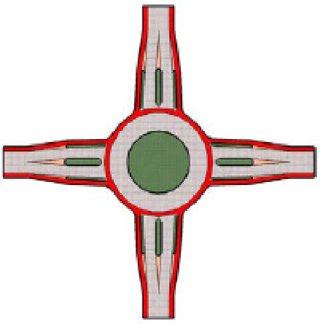
Four potential models were developed covering all vehicles referred from the successful concepts of mixed traffic with bicycling as shown in Figure 14. Firstly, the existing roundabout was investigated as the based model, Model 1. Secondly, the physically enhanced roundabout was studied as Model 2. Lastly, the concept of giving the priority lane to separate the mixed traffic was studied in Model 3 and Model 4. Both the last two models provide the priority lane for motorbikes, however, one provides the same level separately and the other provides the exclusive motorbike lane.



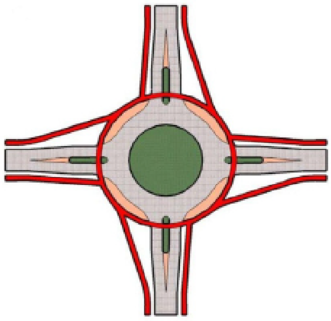
Model 1
Existing roundabout



Model 2
Physically enhanced roundabout



Model 3
Priority motorbike lane application



Model 4
Priority exclusive motorbike lane application

Figure 14 Traffic control of potential models

3.6 Roundabout education training

This task started before the experimental (trial) test was performed. This training aimed to educate the roundabout users to improve their driving in international ways and rising their driving skills. The first step was to promote public relations with SUT students and staff who used the roundabout at SUT. The pre-test was introduced to evaluate their basic knowledge of using roundabouts before the training process started. Roundabout training programs consisted of reviewing the existing situation and how crash risks were possibly occurred. Next, the overview of international rules using roundabouts and the safety parameters were demonstrated to all road users. Then, a discussion on the existing roundabout and possible solutions for a safer roundabout was presented. Post-test to evaluate the knowledge after the training was conducted after finish training. The training and instructions for safe roundabout use were delivered to more than 800 SUT undergraduate students. Students' basic knowledge of using roundabouts before and after the training was evaluated using the paper-based test. Finally, the road users' opinions on different types of roundabouts (R1, R2, R3, R4 as shown in Figure 15) were examined.

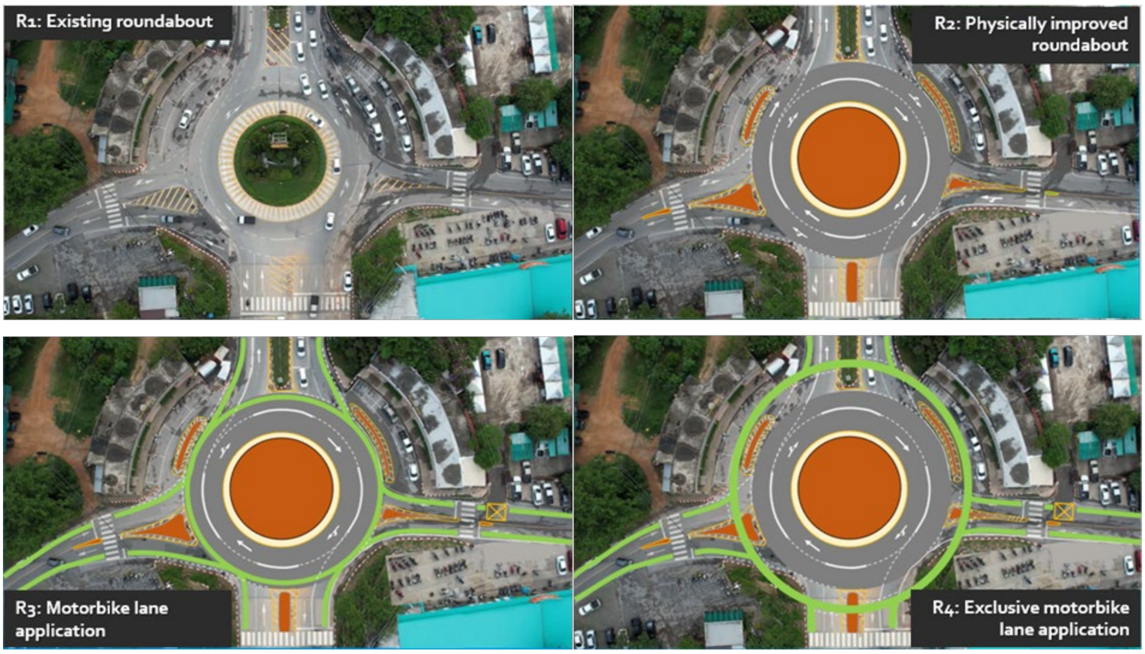


Figure 15 Physical improvement of potential models

3.7 Physically enhanced roundabout experiments

The experiment intends to set instead of the concept of simulation based. Real practice can show more exact driver behavior. However, doing this experiment needs collaboration from road authorities and getting authorized from the university. Once the physically enhanced roundabout was introduced in the education training which focuses on students who have less experience in driving, this prepared the drivers to notice the experiment situation and responded appropriately. Suddenly changing or configuration part changing of a physical roundabout had a high risk to cause the driver to feel unfamiliar which can affect negatively than positive results. Therefore, this study installed only model R2 which is concerned for safe. However, models R3 and R4 keep only asking in the questionnaire for a conceptual idea of how drivers prefer.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Results of the traffic situation and performance

Fundamental traffic parameters were investigated for further analysis of specific safety improvements. Comparison between pre- and post-physically enhanced roundabouts of the traffic trajectory, turning movement, headway, and flow rate are presented as follows.

4.1.1 Traffic trajectory

The traffic trajectory was primarily observed to confirm the statement of the problem about the level of driver awareness rotating in the roundabout. The detections of vehicle objects are presented in Figure 16. The accuracy of the detection algorithm developed is shown in Figure 17. The results show that the detection accuracy is greater than the acceptable threshold, which has the accuracy percentage to detect the passenger car between 75 and 85% and between 40 and 60% for motorcycles. Then, the paths of traffic trajectory were developed as shown in Figure 18. The results found that 99% of drivers have no awareness of correctly driving and rotating following the traffic lane. They freely drive with unconscious familiarity and tend to repeatedly ahead of driver trajectory paths shown as the red line.

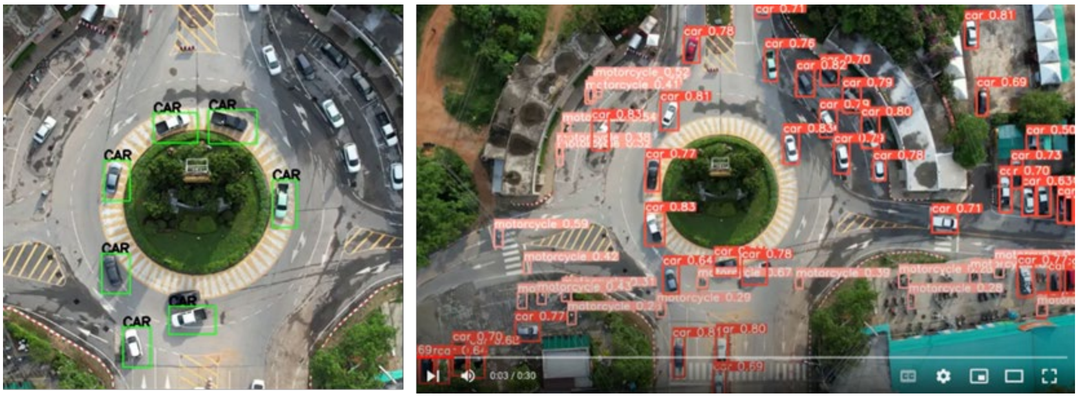


Figure 16 Detection of vehicle objects

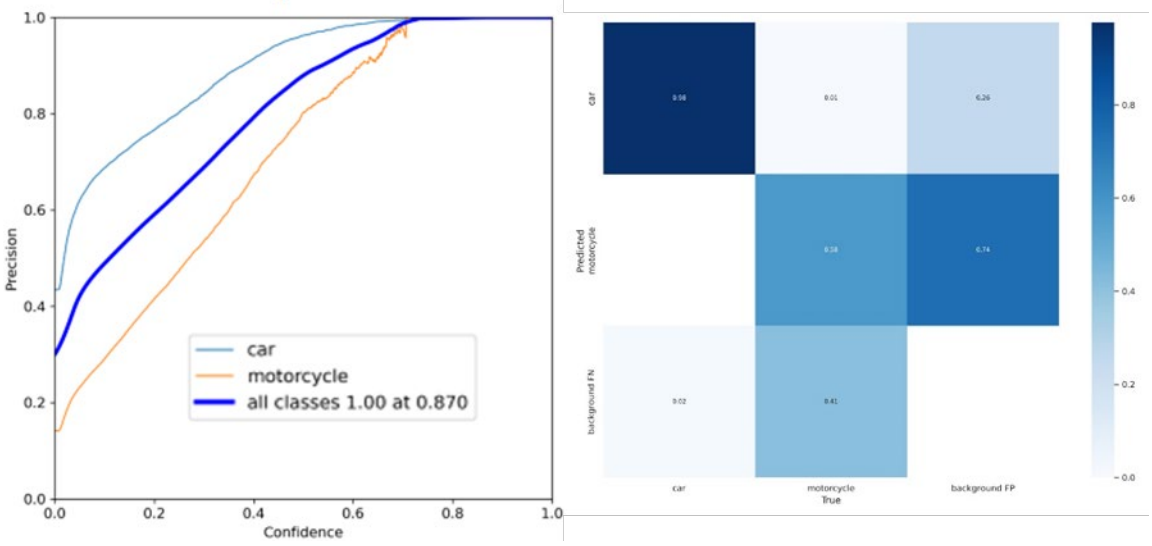


Figure 17 Detection of vehicle object accuracy

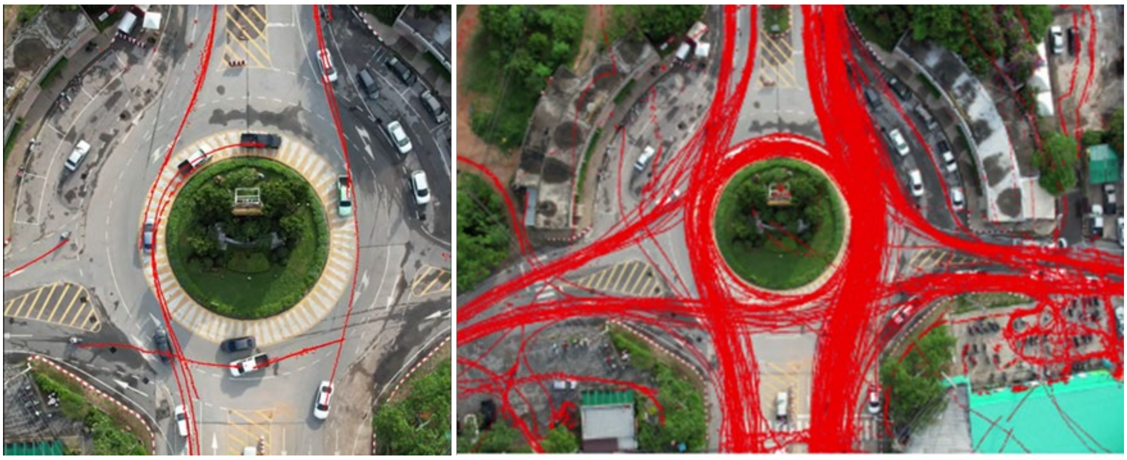


Figure 18 Traffic trajectory path

4.1.2 Turning movement

The turning movement was investigated to determine the proportion of vehicle directions. As shown in Table 1, this proportion did not change according to the physically enhanced roundabout installment, due to this depending on the travel demand. However, the turning movement can lead to improving traffic management where the major traffic direction is focused. The major traffic direction was outbound from the university because the observed time was in the peak evening hour when people traveling back from workplaces. The possibility is that the amount of inbound traffic can be reversed according to the time when the traffic is high in the morning peak.

4.1.3 Headway

The headway was observed to calculate the time interval reaching the roundabout. As shown in Table 2, this is relatively present along with the flow rate to see the number of vehicles driving through the roundabout. The total number of vehicles was quite stable, approximately 500 to 600 vehicles. The average headway was approximately 6.8, 7.9, 9.6, and 11.3 seconds for directions 1 to 4, respectively. The comparison between post-physically enhanced roundabouts was not related to the headway, they rather related to the road traffic demand.

Table 1 Turning movement between the existing roundabout and the physically enhanced roundabout

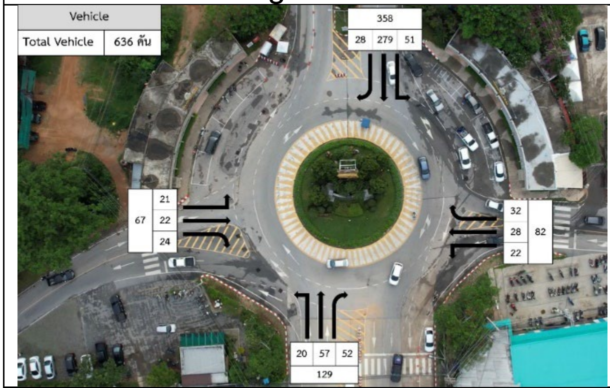
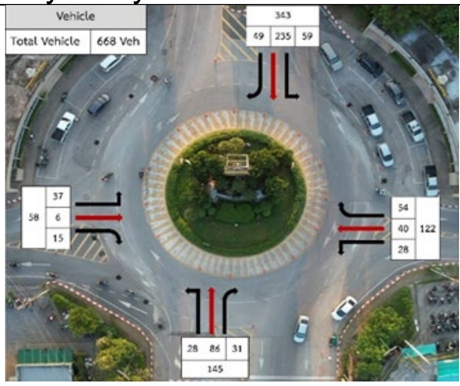
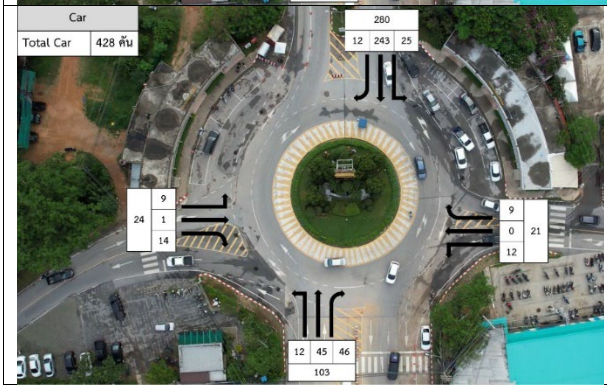
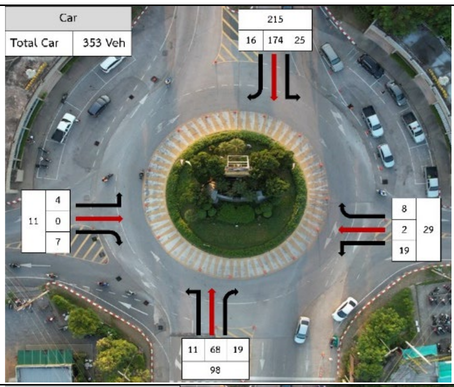
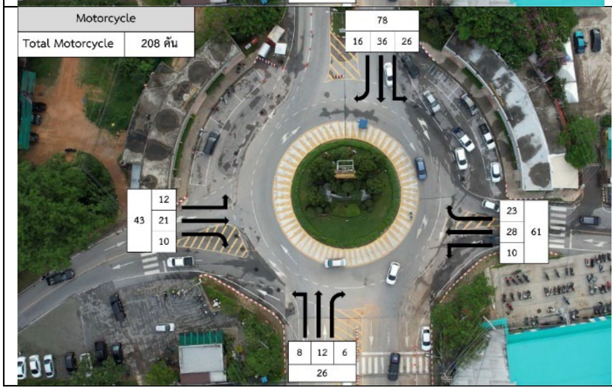
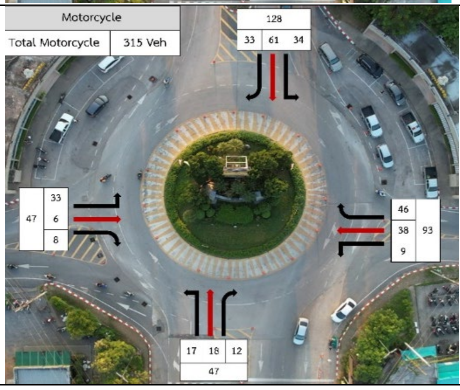
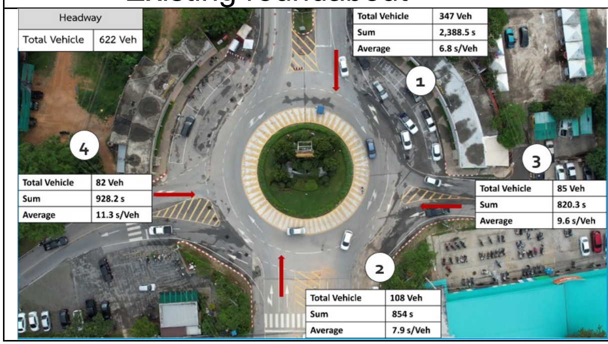
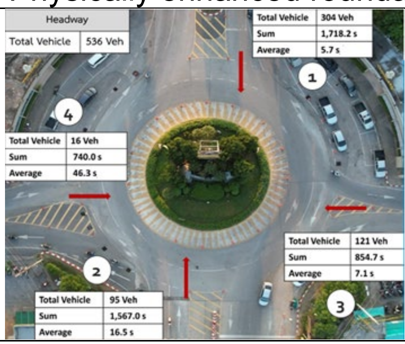
Existing roundabout	Physically enhanced roundabout
	
	
	

Table 2 Headway between the existing roundabout and the physically enhanced roundabout

Existing roundabout	Physically enhanced roundabout
	

4.1.4 Flow rate

The flow rates were counted for both passenger cars and motorcycles as shown in Table 3. The proportion between those vehicle types was shown separately in each direction. The small road access at directions 3 and 4 had a high amount of motorcycles compared to passenger cars. However, the proportions of motorcycles were low in directions 1 and 2. The reason is that there are some road users which are the university staff traveling by long-distance passenger cars. The students normally use motorcycles to travel for their routine activities between the residential area (direction 4) to the shopping area at the market (direction 3) when their outbound peak time from the university is different from university staff.

Table 3 Flow rate between the existing roundabout and the physically enhanced roundabout

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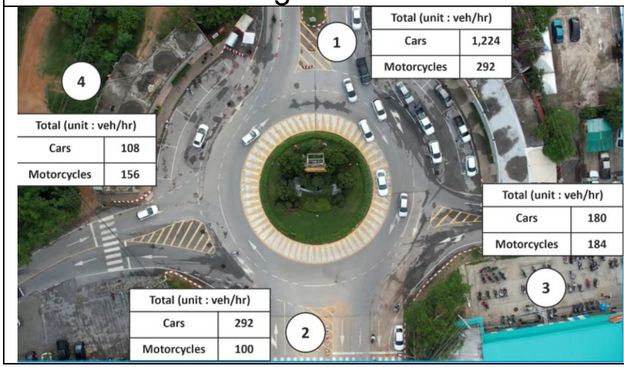
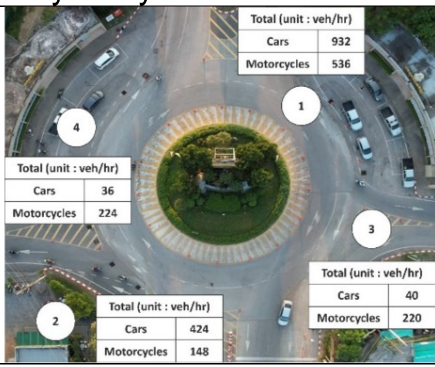
<tr><td>
</td><td>
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</table>

4.2 Results of safety indicators

The preliminary procedure to see the safety situation is to investigate the existing physical roundabout design. Then, the sight distance was examined to confirm a clear vision at the intersection. Further, the truck apron driving violation, approaching speed and outgoing speed, rotary speed in the roundabout, traffic conflict, and priority rule of give way un-compliance were observed to respond to traffic safety situations. These results are important information to provide for further analysis improvement.

4.2.1 Physical site safety audit

The physical roundabout was investigated at the field and collaborated with the aerial photos taken by drone to recheck and report for all configurations. As shown in Figure 19, the critical issue was that this roundabout has various facilities nearby such as security officials, a police station, ATM, a market, coffee shops, and a convenience store. The inappropriate design was that the parking area was adjacent to the roundabout without any physical island or separation, only painted lane markings were provided. This is a reason that drivers freely change their traffic lanes when they rotate in the roundabout. Also, this generates more conflicts when drivers try to park and leave their parking. Traffic controls including the channelizing guidance, truck apron area, and pedestrian crossing are needed. Moreover, there is no physical island to protect the pedestrian crossing while they are waiting in the center of the crossing. According to those problems, the difficulty is to remove all public facilities however, the improvement way can be solved by managing the traffic management principles. The solution of relocating the parking area is most possible due to there is still space behind those facilities. Also, channelizing island guidance to lead drivers in the correct turning way is needed. Moreover, traffic calming measures, e.g., raised pedestrian crossing, can be applied to all four approaches.

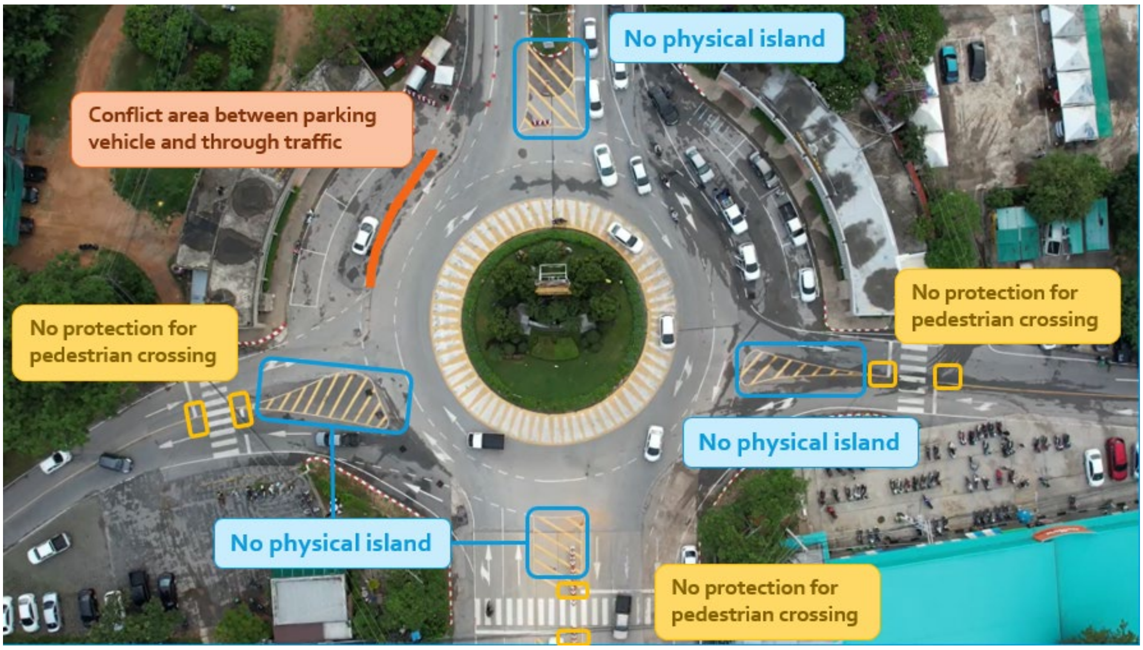


Figure 19 Physical site investigation

4.2.2 Sight distance and approach deflection

The sight distance is examined to see the triangle visions of drivers in all directions of the roundabout. As shown in Figure 20, this roundabout provides a clear sight distance for all directions as presented in the overlapping areas (purple triangular). However, Figure 21 shows that there is a small rotation radius. This could allow drivers to have higher approaching speeds compared to the larger rotation radius which is a more efficient control speed.

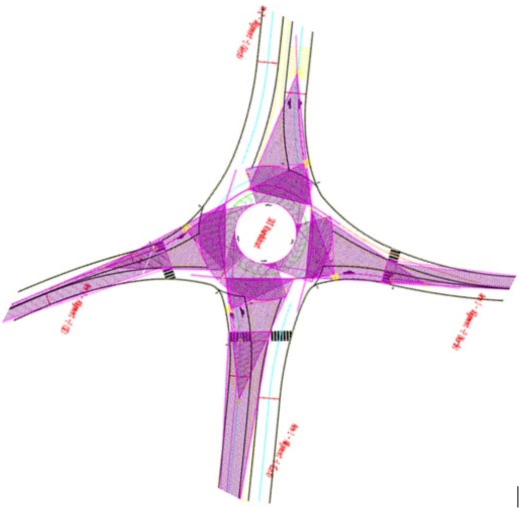


Figure 20 Triangle visions of drivers approaching the roundabout

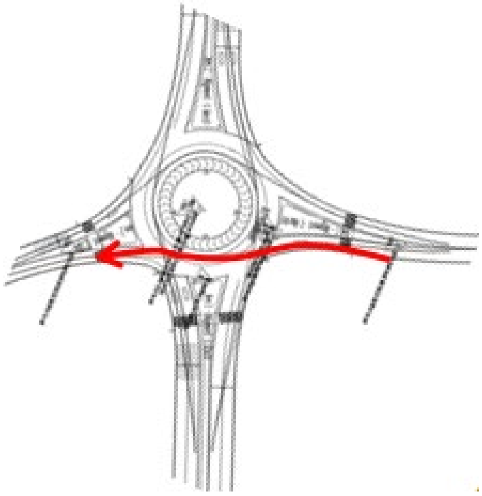
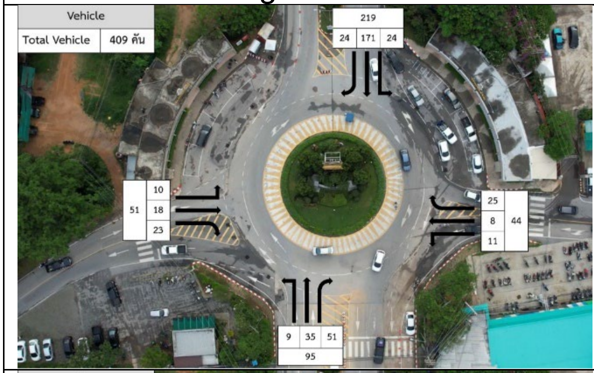
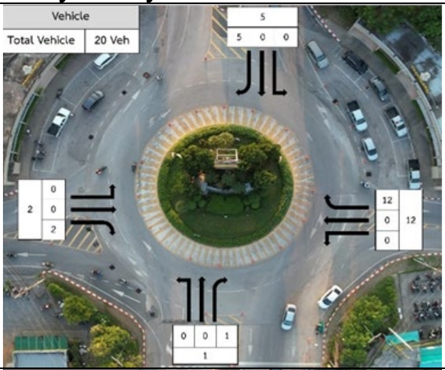
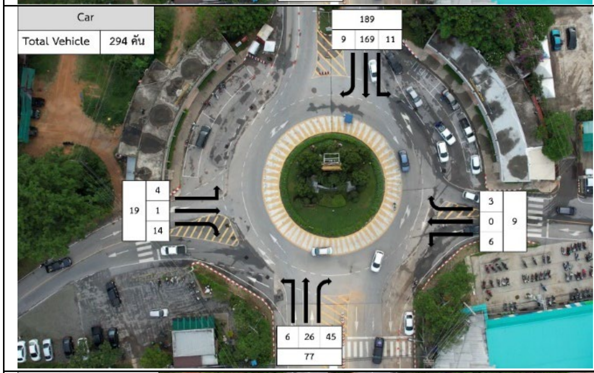
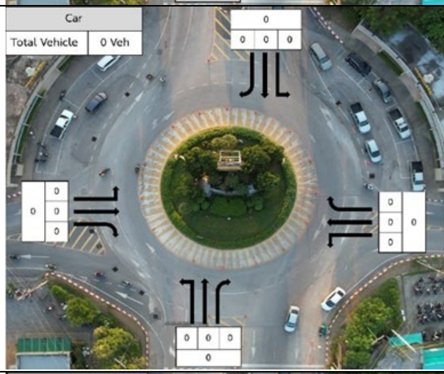
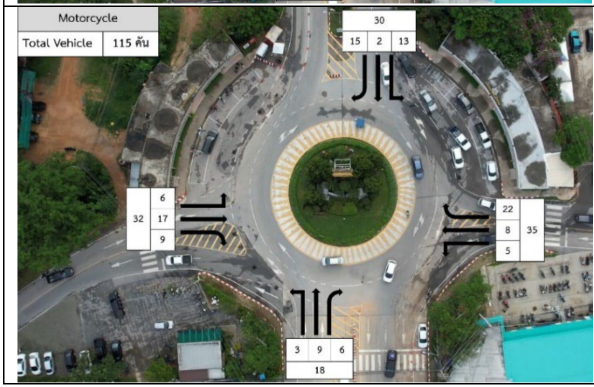
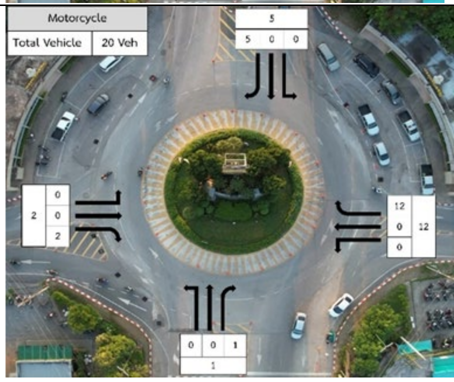


Figure 21 Small turning angle

4.2.3 Truck apron driving violation

The truck apron driving violation was counted from the number of vehicles that drive in the yellow area of the truck apron which provides for the wider turning movement of large vehicles. Generally, this area provides where the roundabout has a small radius. Table 4 shows that 65% of total vehicles drive in the truck apron area leading to less concern about driving along the design lane. Therefore, traffic cones were installed to represent a truck apron-raised island. The expected result is to remind the drivers to not drive in the truck apron area and drive following the design lane. As a result, there is no passenger car causing a violation except a few motorcycles that ignore whatever enhancement. This may be from root behavior, not the physical design. The results can confirm that the truck apron raised island is the suitable solution to apply at this roundabout.

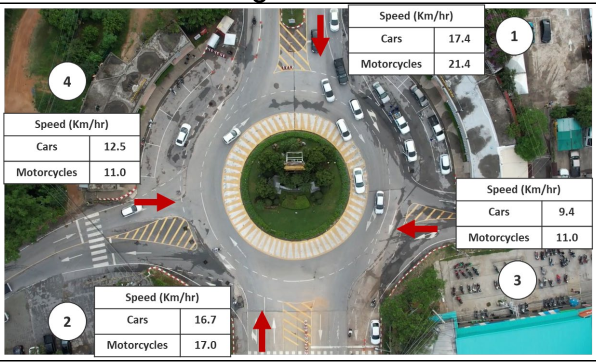
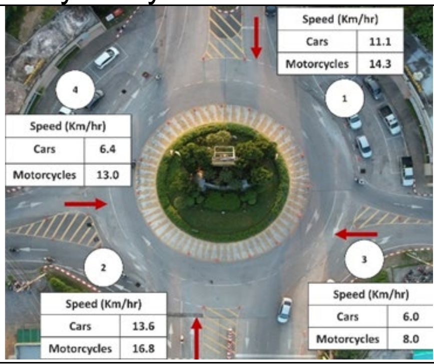
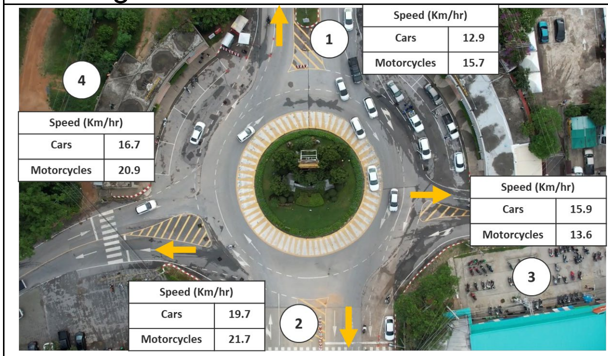
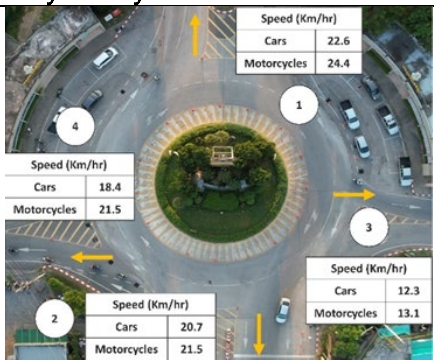
Table 4 Truck apron driving violation between the existing roundabout and the physically enhanced roundabout

Existing roundabout	Physically enhanced roundabout
	
	
	

4.2.4 Approaching speed and outgoing speed

The approaching speed and outgoing speed were investigated to view driving behaviors before entering and after passing the roundabout. The approaching speeds of the existing roundabout were between 10 and 17 kph and the outgoing speeds were between 13 and 22 kph. There was an acceleration rate when the driver left the roundabout, however, the speed was acceptable under the speed limit design. The approaching speed of the passenger car had affected after installing the physically enhanced roundabout however, the motorcycle speed was the same.

Table 5 Approaching speed and outgoing speed between the existing roundabout and the physically enhanced roundabout

<table>
<tr><td colspan="2">Approaching speed</td></tr>
<tr><td>Existing roundabout</td><td>Physically enhanced roundabout</td></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td colspan="2">Outgoing speed</td></tr>
<tr><td>Existing roundabout</td><td>Physically enhanced roundabout</td></tr>
<tr><td>
</td><td>
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4.2.5 Rotary speed in the roundabout

Rotary speed is one of the important rules while driving in a roundabout. Driving slowly maintains the requirement of traffic performance but providing safety is the key to using a roundabout. The design speed is usually limited to 30 kph in roundabout rotation. At the study roundabout, there was a relatively high speed. The average speeds of passenger cars and motorcycles were found at 31 kph and 18 kph, respectively. There was a significant reduction in passenger car driving speed after being physically enhanced from 31 kph to 15 kph which is almost half of the before the case. These results show a safer situation both reducing crash risk and severity level.

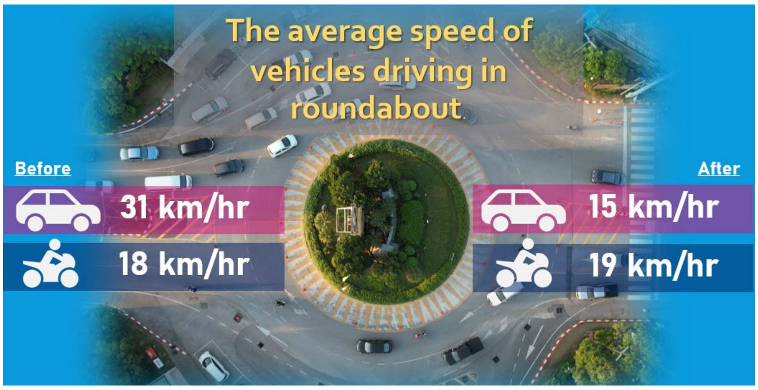

Figure 22 Rotary speed in the roundabout

4.2.6 Conflicts between mixed traffic

The conflicts were primarily observed by human eyes which can be categorized into three major types according to the mixed traffic condition. The first type was the conflicts between a motorcycle and a motorcycle. The second type was the conflict between a passenger car and a motorcycle. The last type was the conflicts between a passenger car and a passenger car. The severity of a potential crash was predicted from the collision angle of each conflict. There were possibly seven cases of conflicts that happen before the physical enhancement. As shown in Figure 23, most of the cases are between a passenger car and a motorcycle which is identified as a vulnerable road user. Also, the potential collision angle was found at a sharp angle. However, the cases after physical enhancement (Figure 24) were not identified as the severity conflict. This can be described that the driver paying more attention at a slower speed.

Figure 23 Conflict cases of the existing roundabout

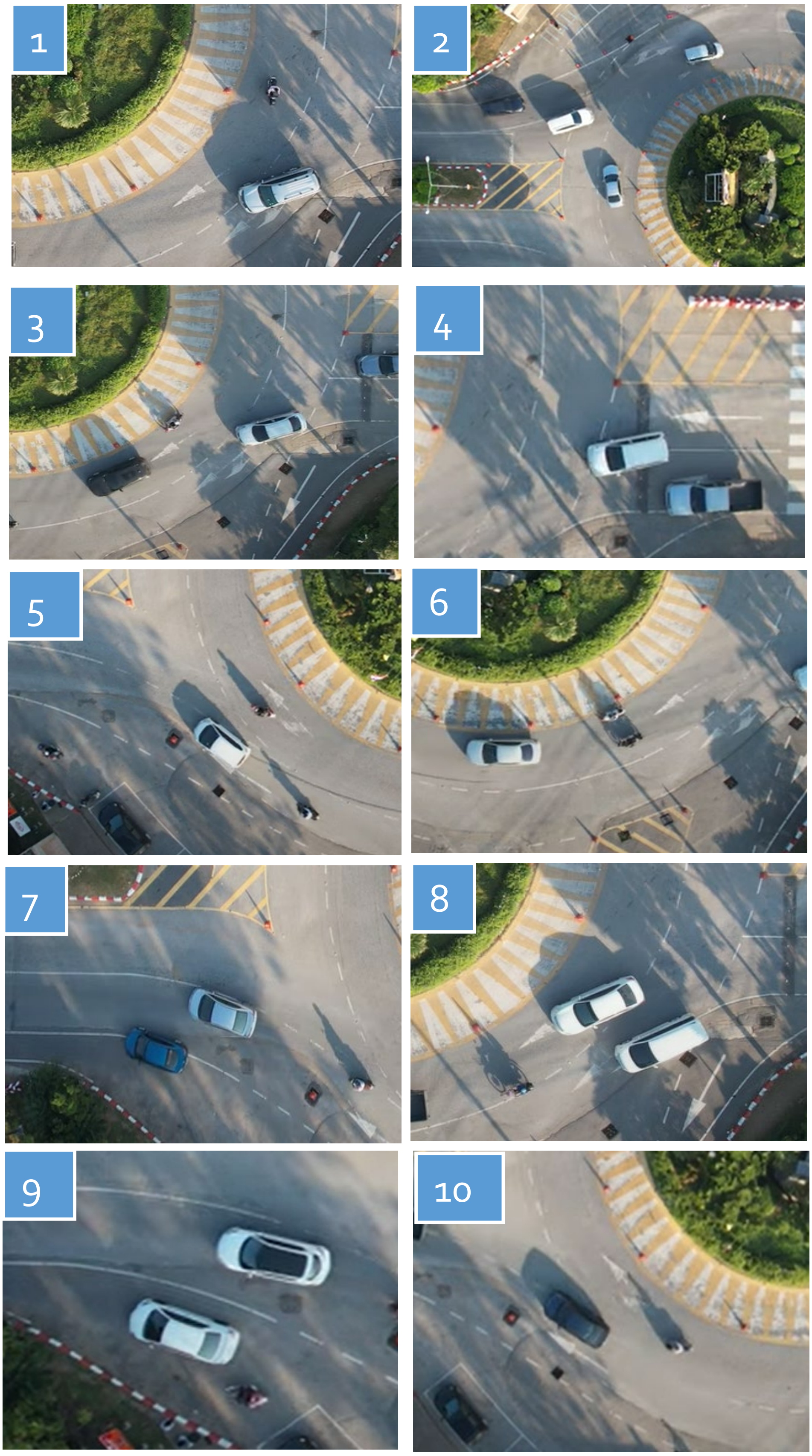

Figure 24 Conflict cases after physical enhancement

4.2.7 Incompliance to give way

One of the international rules for entering a roundabout is to respect the priority rule. The vehicle entering the roundabout must give way to the vehicle rotating in the roundabout. The engineers must design the right of way and provide the roundabout sign in a proper location for a clear see. There are significant values that drivers have more awareness of to give way. From the study, Figure 25 shows that the incompliance passenger cars reduce from 4 to 1.3% and the motorcycles reduce from 3 to 1%.

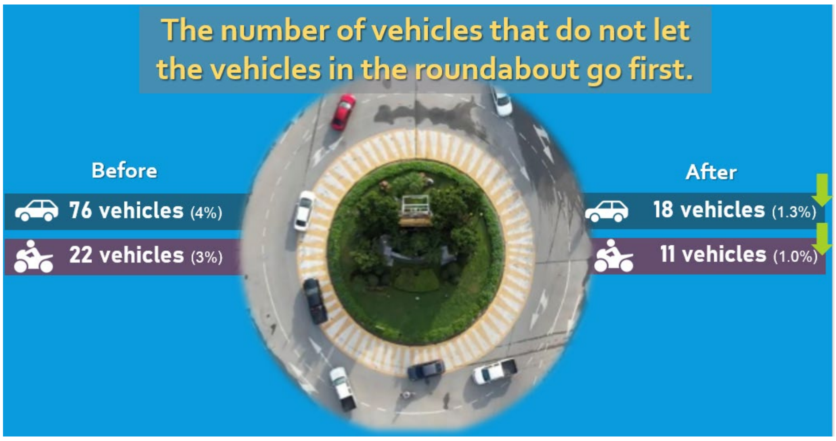

Figure 25 Number of the un-compliance priority rule

4.3 Results of roundabout educational training

The educational training was held in the lecture room which can be served almost 1,500 seats as shown in Figure 26. Public relevance was promoted widely in all university facilities. The focus group was the freshmen that needed the right to understand driving and absorb further driving behavior.

Figure 26 Educational training

The questionnaire was separated into three sections: 1) general information of respondents, 2) driving and traveling behavior and rotary skills, and 3) awareness of safe use at the roundabout. The results of each section are presented as follows.

Questionnaire part 1 General information of respondents

Table 6 Percentage of respondents in terms of gender

Gender	Amount	Percentage
Male	432	52.8
female	386	47.2
Total	**818**	**100**

Table 7 Percentage of respondents in terms of age

Age	Amount	Percentage
10-20 years	781	95.5
21-30 years	37	4.5
31-40 years	-	-
41-50 years	-	-
51-60 years	-	-
More than 60 years	-	-
Total	**818**	**100**

Table 8 Percentage of respondents in terms of educational level

Education level	Amount	Percentage
Bachelor's degree	818	100
Master's degree	-	-
Doctor's degree	-	-
Total	**818**	**100**

Table 9 Percentage of respondents in terms of year of study

Year of study	Amount	Percentage
First-year	806	98.5
Second-year	10	1.2
Third-year	2	0.3
Fourth-year	-	-
Total	**818**	**100**

Table 6 shows the proportion number of respondents by sex. The total was obtained from 818 respondents: 432 male respondents, accounting for 52.8%, and 386 female respondents, accounting for 47.2%. Table 7 shows the age of respondents which are 10-20 years old 781 respondents, accounting for 95.5%, and 21-30 years 37 respondents, accounting for 4.5%. Table 8 shows that 100% of respondents are bachelor's degree students. Table 9 presents the results of the student's year. Most of the respondents are students in the first year, accounting for 98.5%. Then 1.2% are second-year students and 0.3% are third-year students.

Table 10 Percentage of respondents in terms of private motorcycle driving license

Private Motorcycle Driving License	Amount	Percentage
have	483	59
Don't have	335	41
Total	**818**	**100**

Table 11 Percentage of respondents in terms of private car driving license

Private Car Driving Licence	Amount	Percentage
have	179	21.9
Don't have	639	78.1
Total	**818**	**100**

As shown in Table 10, the results obtained from 818 respondents showed that most of them (483 respondents) have private motorcycle driving licenses, accounting for 59%. The other 335 respondents do not have private motorcycle driving licenses, accounting for 41%. Table 11 shows that 639 respondents do not have private car driving licenses, accounting for 78.1%, and 179 respondents have private car driving licenses, accounting for 21.9%.

Table 12 Percentage of respondents in terms of possession of household vehicles

Possession of household vehicles	Amount	Percentage
No vehicle	90	6
Bicycle	348	22
Motorcycle	648	42
Car	210	13
Pickup truck	243	16
Van	16	1

As shown in Table 12, the results obtained by 818 respondents conclude that most of them (648 respondents) owned motorcycles, accounting for 42%. followed by bicycles (348 respondents or 22%), pickup trucks (243 respondents or 16 percent), cars (210 respondents or 13%), no vehicles (6%), and vans (1%), respectively.

Questionnaire Part 2 Driving and traveling behavior

Table 13 Driving and travel behavior of respondents

Behavior	Amount	Percentage
1) Have you ever driven through a roundabout?		
1.1) Yes	776	94.1
1.2) No	42	5.1
2) How often do you drive through roundabouts?		
2.1) every day	226	27.6
2.2) 1 - 2 times a week	279	34.1
2.3) 3 - 4 times a week	155	18.9
2.4) 5 - 7 times a week	158	19.3
3) The most purposes of driving through roundabouts		
3.1) School	449	54.9
3.2) Activities	218	26.7
3.3) Shopping	532	65
3.4) Bussiness	399	48.8
3.5) Other	103	12.6
4) What speed do you drive into the roundabout?		
4.1) less than 60 kph	707	86.4
4.2) 60 - 80 kph	102	12.5
4.3) 80 - 100 kph	5	0.6
4.4) More than 100 kph	4	0.5
5) Have you ever had an accident from driving?		
5.1) Yes	402	49.1
5.2) No	416	50.9
6) Have you ever had an accident while driving in the roundabout?		
6.1) Yes	11	1.3
6.2) No	807	98.7
7) The most common cause of accidents		
7.1) Not enough rest/drowsy	171	24.5
7.2) Can't see the sign	164	23.5
7.3) Drunk/unconscious	187	26.8
7.4) Using a phone while driving	163	23.4
7.5) Damaged road	423	60.6
7.6) Bad weather conditions	316	45.3
7.7) Others	219	31.4
8) Have you ever attended a training course on safe driving through roundabouts?		
8.1) Yes	301	36.8
8.2) No	517	63.2
9) If you have received training, please specify the number of times		
9.1) 1 time	213	59.8
9.2) 2 times	111	31.2
9.3) 3 times	22	6.2
9.4) 4 times	2	0.6
9.5) 5 times	-	-
9.6) more than 5 times	8	2.2

As shown in Table 13, the results from 818 respondents revealed that 94.1% of the respondents had ever used the roundabout and only 5.1% had never used the roundabout. The most frequent of using roundabouts were 1-2 times a week. The purpose of driving through the roundabout was mostly shopping, followed by studying and personal business. The average speed of driving into the roundabout was found that 86.4% lower than 60 kph. The results on crash experiences at the roundabouts showed that only 1.3% had experienced it. Regarding the cause of the crash, the top three causes were 1) damaged roads, 2) bad weather conditions such as heavy rain, and 3) other causes. Experience in safe driving through roundabouts revealed that the majority were untrained (63.2%), while only 36.8% were trained. The average number of training sessions was approximately 1 time per person.

Questionnaire part 3 Rotary skills and safe use of roundabouts

Table 14 Roundabout skills and safe use of roundabouts

Behavior	Amount	Percentage
1) Did you know that there is a roundabout in front of SUT (Gate 1)?		
1.1) know	814	99.5
1.2) Don't know	4	0.5
2) What do you think is the size of the roundabout in front of SUT (Gate 1)?		
2.1) Small	104	12.7
2.2) Large	54	6.6
2.3) Medium	660	80.7
3) You see a traffic sign. or traffic signs before entering the roundabout or not?		
3.1) Not see	152	18.6
3.2) See but not clear	365	44.6
3.2) See clearly	301	36.8
4) How many exits are there at the roundabout in front of SUT (Gate 1)?		
4.1) 1 Exit	48	5.9
4.2) 2 Exit	46	5.6
4.3) 3 Exit	95	11.6
4.4) 4 Exit	606	74.1
4.5) 5 Exit	8	1
4.6) 6 Exit	15	1.8
5) How many driving lanes are there at the roundabout in front of SUT (Gate 1)?		
4.1) 1 Lane	56	6.8
4.2) 2 Lanes	450	55
4.3) 3 Lanes	42	5.1
4.4) 4 Lanes	202	24.7
4.5) 5 Lanes	6	0.7
4.6) 6 Lanes	62	7.6
6) Did you notice the yellow line in the roundabout in front of SUT (Gate 1)?		
6.1) See	762	93.2
6.2) Not see	56	6.8
7) How large of the yellow line in the roundabout in front of SUT (Gate 1)?		
7.1) Small	141	17.2
7.2) Large	139	17
7.3) Medium	538	65.8
8) Do you think the yellow line area in the roundabout is necessary?		
8.1) Necessary	783	95.7
8.2) Optional	35	4.3

Behavior	Amount	Percentage
9) Did you know that the yellow line area by law is called a "safety zone" and driving through the yellow line area is prohibited?		
9.1) Know	632	77.3
9.2) Don't know	186	22.7
10) Have you ever driven into the yellow line area of the roundabout?		
10.1) Yes	517	63.2
102) No	301	36.8
11) Why do you drive into the yellow line area?		
11.1) Didn't notice	248	30.3
11.2) Traffic on the road is unclear.	127	15.5
11.3) Others	443	54.2
12) From the picture, if you want to drive to Exit 3, how do you drive?		
12.1) Driving Method 1	357	43.6
12.2) Driving Method 2	461	56.4
13) Did you know that driving in violation of traffic signs installed at roundabouts is punishable by the law?		
13.1) Know	573	70
13.2) Don't know	245	30
14) From 13), what is the penalty?		
14.1) Punishment according to Section 70 with a fine not exceeding 500 baht.	341	52.6
14.2) Punishment according to Section 73 with a fine not exceeding 1,000 baht.	307	47.4
15) Did you know that not slowing down while entering roundabouts? will be punished by law		
15.1) Know	519	63.4
15.2) Don't know	299	36.6
16) From verse 15, what is the penalty?		
16.1) Punishment according to Section 70 with a fine not exceeding 500 baht.	344	53.7
16.2) Punishment according to Section 73 with a fine not exceeding 1,000 baht.	296	46.3
17) If you drive to a roundabout without traffic signals, which side of the roundabout should give you the right to go first?		
17.1) Left	226	27.6
17.2) right	592	72.4

As shown in Table 14, the results showed that most of the respondents (99.5%) knew that there was a roundabout at Gate 1 in front of SUT. 93.2% saw the traffic around the yellow line area in the roundabout. 36.8% saw the traffic sign or traffic sign before entering the roundabout.

From the skills and knowledge about the roundabout at Gate 1 of SUT, it was found that the respondents had knowledge and understanding of the number of exits at the roundabout with 4 lanes, accounting for 74.1%. 55% knew the number of vehicles in two lanes around the roundabout. 80.7% agreed that the size of the roundabout was appropriate. 65.8% agreed that the size of the yellow lines was appropriate. And 95.7% agreed that there should be a yellow line around the roundabout. In addition, 77.3% had knowledge and understanding of the yellow line area according to the law called the “safety zone” and prohibited driving into the yellow line area. Even though 63.2% still drove into the yellow line area. 70% knew that driving in violation of traffic signs or traffic signs installed at roundabouts is punishable by law. But only 47.4% were aware of the legal penalties for driving in violation of traffic signs installed at roundabouts. 63.4% knew that not slowing down while entering roundabouts would be punished. But only 53.7% were aware of the legal penalties for not slowing down while entering roundabouts. In addition, when asking the respondents to test driving around the roundabout in the 3rd direction in the visual questionnaire, it was found that only 56.4% answered correctly. And it was found that 72.4% answered the right-hand go first.

Questionnaire part 4 Factors affecting safe driving through roundabouts.

The overview of the study on factors influencing driving through roundabouts can be summarized by providing the criteria for analyzing and interpreting the data as follows:

Average rating	4.51-5.00	set to be in the criteria	Strongly agree
Average rating	3.51-4.50	set to be in the criteria	Agree
Average rating	2.51-3.50	set to be in the criteria	Unsure
Average rating	1.51-2.50	set to be in the criteria	Disagree
Average rating	1.00-1.50	set to be in the criteria	Strongly disagree.

Table 15 Average scores of factors affecting driving safely at the roundabout

No.	Considered issues	Opinion level					N	Average	Percentage	S.D.	Assessment Criteria
		5	4	3	2	1					
1	If there is training on using roundabouts safely, that will rise your driving safety in the roundabout.	319	348	133	10	8	818	4.17	83.47	0.81	agree
2	If the roundabout sign is located in a clear position before the roundabout, that will rise your driving safety in the roundabout.	456	309	51	2	0	818	4.49	89.80	0.62	agree
3	If there is a flashing light on the roundabout sign before the roundabout, that will slow down your driving speed.	441	312	60	4	1	818	4.45	89.05	0.66	agree
4	If there is a flashing light on a circular guiding sign inside the roundabout, that will slow down your driving speed in the roundabout.	399	322	85	10	2	818	4.35	87.04	0.73	agree
5	If there is a roundabout symbol on the pavement, that will slow down your driving speed.	353	314	136	11	4	818	4.22	84.47	0.80	agree
6	If there is an increasing frequency of roundabout signs before the roundabout, that will slow down your driving speed.	301	313	173	26	5	818	4.07	81.49	0.87	agree
7	If you allow the vehicles in roundabout priories to go first, that will rise your	428	290	85	6	9	818	4.37	87.43	0.79	agree

No.	Considered issues	Opinion level					N	Average	Percentage	S.D.	Assessment Criteria
		5	4	3	2	1					
	driving safety in the roundabout.										
8	If you drive correctly on the lane in the roundabout, that will rise your driving safety in the roundabout.	488	273	55	1	1	818	4.52	90.46	0.64	strongly agree
9	If the roundabout has an existing characteristic, that will rise your driving safety.  **Figure 1 Current circus condition**	215	294	250	46	13	818	3.80	75.94	0.95	agree
10	If the roundabout has physically improved, that will raise your driving safety.  **Figure 2. Physical development**	334	340	130	9	5	818	4.21	84.18	0.79	agree
11	If the roundabout has a motorbike lane, that will rise your driving safety.  **Figure 3. Motorcycle lane using dividing line**	358	313	133	13	1	818	4.24	84.79	0.79	agree
12	If the roundabout has an exclusive motorbike lane application, that will rise your driving safety.  **Figure 4. There is a special traffic lane for motorcycles.**	338	293	165	18	4	818	4.15	83.06	0.85	agree
13	If the lane marking is clear, that will rise your driving safety in the roundabout.	390	351	73	3	1	818	4.38	87.53	0.67	agree

No.	Considered issues	Opinion level					N	Average	Percentage	S.D.	Assessment Criteria
		5	4	3	2	1					
14	If there is a yield sign, that will rise your driving safety in the roundabout.	357	365	90	3	3	818	4.31	86.16	0.71	agree
15	If there is enough parking area outside the roundabout, that will make you not park obstructing roundabouts	348	318	135	12	5	818	4.21	84.25	0.81	agree
16	If you know safety drive in roundabouts, that will rise your driving safety.	400	337	78	2	1	818	4.39	87.70	0.68	agree
17	If you know the legal penalties for using roundabouts, that will rise your driving safety in the roundabout.	350	340	121	7	0	818	4.26	85.26	0.74	agree
18	If there is strict enforcement at the roundabout, that will rise your driving safety in the roundabout.	341	348	116	11	2	818	4.24	84.82	0.76	agree
19	If you are aware of safe driving at the roundabout, that will rise your driving safety in the roundabout.	412	333	69	2	2	818	4.41	88.14	0.67	agree
20	If you have common morality for good driving, that will rise your driving safety in the roundabout.	440	320	57	1	0	818	4.47	89.32	0.63	agree
21	If the people around you pay attention to the safety of driving at the roundabout, that will rise your driving safety in the roundabout.	417	309	87	1	4	818	4.39	87.73	0.72	agree
Total		7,885	6,742	2,282	198	71		4.29	85.81	0.75	agree

Table 15 shows the results of opinions on the factor affecting safe driving at the roundabout. Most of them (85.81%) agree with the safety issues with an average score of 4.29 and a standard deviation (SD) of 0.75. The details of each issue are as follows:

1) If you drive correctly on the lane in the roundabout, that will raise your driving safety in the roundabout. The average was 4.52, accounting for 90.46%, with an SD of 0.64. The result from the evaluation criteria strongly agrees.

2) If the roundabout sign is in a clear position before the roundabout, that will increase your driving safety in the roundabout. The mean was 4.49, accounting for 89.80%, with an SD of 0.62. The result from the evaluation criteria agrees.

3) If you have common morality for good driving, that will raise your driving safety in the roundabout. The mean was 4.47, accounting for 89.32%, with an SD of 0.63. The result from the evaluation criteria agrees.

4) If there is a flashing light on the roundabout sign before the roundabout, that will slow down your driving speed. The mean was 4.45, accounting for 89.05%,

with an SD of 0.66. The result from the evaluation criteria agrees.

5) If you are aware of safe driving at the roundabout, that will increase your driving safety in the roundabout. The mean was 4.41, accounting for 88.14%, with an SD of 0.67. The result from the evaluation criteria agrees.

6) If the people around you pay attention to the safety of driving at the roundabout, that will increase your driving safety in the roundabout. The mean was 4.39, accounting for 87.73%, with an SD of 0.72. The result from the evaluation criteria agrees.

7) If you know safety driving in roundabouts, that will increase your driving safety. The mean was 4.39, accounting for 87.70%, with an SD of 0.68. The result from the evaluation criteria agrees.

8) If the lane marking is clear, that will increase your driving safety in the roundabout. The mean was 4.38, accounting for 87.53%, with an SD of 0.67. The result from the evaluation criteria agrees.

9) If you allow the vehicles in roundabout priories to go first, that will raise your driving safety in the roundabout. The mean was 4.37, accounting for 87.43%, with an SD of 0.79. The result from the evaluation criteria agrees.

10) If there is a flashing light on a circular guiding sign inside the roundabout, that will slow down your driving speed in the roundabout. The mean was 4.35, accounting for 87.04%, with an SD of 0.73. The result from the evaluation criteria agrees.

11) If there is a yield sign, that will raise your driving safety in the roundabout. The mean was 4.31, accounting for 86.16%, with an SD of 0.71. The result from the evaluation criteria agrees.

12) If you know the legal penalties for using roundabouts, that will raise your driving safety in the roundabout. The mean was 4.26, accounting for 85.26%, with an SD of 0.74. The result from the evaluation criteria agrees.

13) If there is strict enforcement at the roundabout, that will raise your driving safety in the roundabout. The mean was 4.24, accounting for 84.82%, with an SD of 0.76. The result from the evaluation criteria agrees.

14) If the roundabout is renovated with painted traffic lanes for motorcycles will make it possible to drive safely in roundabouts. As shown in Figure 27, the mean was 4.24, accounting for 84.79%, with an SD of 0.79. The result from the evaluation criteria agrees.

Figure 27 Motorbike lane application

15) If there is a roundabout symbol on the road will cause the driver to slow down before entering the roundabout There was a mean of 4.22, accounting for 84.47% with an SD of 0.80. Results from the evaluation criteria were agreed upon.

16) If a parking area is built before the roundabout will not stop the car to obstruct traffic in the roundabout The mean was 4.21, accounting for 84.25%, with an SD of 0.81. The result from the evaluation criteria agrees.

17) If the roundabout is renovated to have a clear street isle will make driving into the roundabout safe. As shown in Figure 28, the mean was 4.21, accounting for 84.18%, with an SD of 0.79. The result from the evaluation criteria agrees.

Figure 28 Physically improved roundabout

18) If there is training in the use of roundabouts safely. will make it safe to use the roundabout. The mean was 4.17, accounting for 83.47%, with an SD of 0.81. The result from the evaluation criteria agrees.

19) If the roundabout is renovated to have a special traffic lane for motorcycles separating the traffic lanes will make it possible to drive safely in roundabouts as shown in Figure 29, the mean was 4.15, accounting for 83.06%, with an SD of 0.85. The result from the evaluation criteria agrees.

Figure 29 Exclusive motorbike lane application

20) If increasing the frequency of installation of traffic signs or traffic signs before the roundabout will cause the driver to slow down. The mean was 4.07, accounting for 81.49%, with an SD of 0.87. The result from the evaluation criteria

agrees.

21) If the condition of the current roundabout as shown in Figure 30, it will make the driver enter the roundabout safely. The lowest mean was 3.80, accounting for 75.94%, with an SD of 0.95. The result from the evaluation criteria agrees.

Figure 30 Existing roundabout

4.4 Preliminary guidelines for mixed traffic roundabout design

International standard guidelines of the roundabout may have some different contexts in social characteristics. In Thailand, mixed traffic conditions between passenger cars and motorcycles have been found in many urban areas. The results from this study revealed that motorcycles were more than half of the total number of all vehicles. In addition, the motorcycle has a high possibility to conflict with a passenger car. This type of conflict can cause a serious crash. According to the traffic situation and questionnaire survey from the road users, the roundabout must be provided with a separate lane between the motorcycle lane and the passenger car lane. These findings suggested that the roundabout designer must be concerned about the regulation design, physical design, and social impact on road users. The preliminary guidelines can be set by the following steps:

1) Simulate and analyze the design alternatives by investigating the traffic parameters affecting the traffic situation at the roundabout.
2) Design the experiment to the actual situation and investigate the real effects of the new design(s) on road users. This experiment included the test of regulation to use this roundabout, the traffic sign installation, and the physical enhancement of the roundabout. However, in this step, all stakeholders must cooperate to ensure the safety of the new design. Moreover, the designer must inform the road users of this project to the road users before starting the experiment. The preliminary list of concerns is shown as follows:
    a. The size of roundabout circulation must be optimized from both design speed and available space.
    b. The truck apron area should be installed considering the demand of road users, land use, and available space.
    c. The proper type and size of the truck apron area must be defined. This experiment suggested a declined truck apron island.

d. Channelizing physical islands need to be installed instead of painted road markings.
e. Roundabout signs and reflectors need to be provided at proper locations, clearly seen in advance, and standardized.
f. The motorcycle lane width needs to be tested for comfortable and safe riding.
g. The type of motorcycle separation lane needs to be discussed.
h. The priority rule of giving way must be clear for all road users.
i. Relocation of public facilities and parking areas is needed.

3) Experiment and collect the traffic data and the risk of potential crashes.
4) Analyze the real traffic condition compared to the simulation-based condition. Then, conclude whether the new design whether is good enough or not. If the design does not meet the requirement of the traffic performance and safety issues. The roundabout design must be modified and repeated from step 2) again.
5) Evaluate the road user perspective, environmental effects, and social impacts by public hearing from all stakeholders on the new roundabout design.
6) Build the new design roundabout and collect up-to-date data to evaluate the efficiency of the new design and check the safety requirement of the new design.
7) Frequently promote the knowledge of using roundabouts in the driving license program.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This project emphasized a roundabout investigation of post-society applications to evaluate traffic performance and safety issues which is one of the guild procedure standardizations. There were major concerns in both physical engineering design and road user perspective. Moreover, the education once public to the students who play an important context as road users that have less experience but need to better improve driver behaviors. The objective aims to rise driving skills by promoting awareness and international rules of roundabout rotation. The deficient right of way and traffic signs were surveyed to discover further improvements. Moreover, a new design concerning motorcycle users was proposed and asked for road user opinions.

The traffic trajectory paths showed that people drive unconscious, especially on the truck apron area, and ignore the correct lane keeping with the trend to follow ahead driver behavior. Based on the observed traffic flow during the evening peak, the traffic was mixed between dominant motorcycles and cars in all leg directions. The physical enhancement of the roundabout was introduced by installing the traffic cones to represent the raised island at the truck apron and channelizing guidance. The rotary speed in the roundabout significantly changed which could reduce the severity of potential crashes but still maintain traffic performance. The conflict level decreased according to the wider angle of a collision, which made people drive more carefully at a lower speed.

The education training for 818 participants which were mainly freshmen, the half proportion of males and females. The training started with an overview of fundamental traffic rules and then specified the roundabout problems revealing, enhancing an international rule, and showing good examples. According to 40% of students did not have a driver's license, which means they do not know about properly riding or driving. More than 60% have never learned about the roundabout, which means they possibly drive based on individual behavior instead of following the regulations. Due to the dominance of motorcycle users, they prefer to have shared motorcycle lanes for safety but not exclusive lanes.

The preliminary guidelines were proposed for further work improvement. Simulation-based physically enhanced roundabouts should be considered compared with the experiment design. The new motorcycle lane experiment had a limitation in this work because changing the main part of the physical design is a critical issue concerning safety. Therefore, all stakeholders including executives of the university, university professors, road designers, road operators, policemen, public servants, road users, etc. must be involved. All roundabout designs and right of way should be introduced to road users for a better understanding of the objective's design. Regulations should also be emphasized for safer driving behavior. These should be included in the driver's license training program.

5.2 Recommendations

5.2.1 Recommendations for the application of this research

This study is recommended for the roundabout that intends to design multiple lanes. Also, this study considers urban roundabouts that has mixed traffic. The existing roundabout can be investigated using recent technology which is the drone to provide proper traffic scene seeing from top views. Both traffic performance parameters and safety issues should be investigated simultaneously. The regulation educational is also important to express the engineering design meaning to the road users which is better to connect.

5.2.2 Recommendations for future research

Further research can be fulfilled by experimenting more on motorcycle lanes and analyzing the traffic parameters for practical comparisons. More details of traffic performance should be analyzed such as road capacity, delay, and queue length. Safety indicators should be deeply identified including, e.g., time to collision (TTC), Post Encroachment Time (PET).

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