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Development of Microscopic Simulation Model for Heterogeneous Traffic at Roundabout

(ラウンドアバウトにおける混合交通ミクロシミュレーションモデルの開発)

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Development of Microscopic Simulation Model for Heterogeneous Traffic at Roundabout

A dissertation presented

by

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"If I have seen further, it is by standing on the shoulders of giants."

- *Isaac Newton*

Abstract

While modern roundabout has been proven superior to signalized intersection in safety, delay, and capacity under homogeneous traffic, its merits in heterogeneous traffic are neither proven nor analyzed. Both unique characteristics and models to reproduce behaviors in simulation has not been discussed comprehensively, especially in the high proportion of two-wheeler (TW) condition. In this background, the study aims to answer the question of how to reproduce unique characteristics of TW at roundabout in simulation. In order to achieve the answer, the study has gone through the below procedures step by step.

Firstly, chapter 1 presents background, research needs, research gap, research question, objectives and scope. In chapter 2, the literature review section determined the two constitutions of mixed traffic that are the performance rule and the appearance of the small-sized vehicle. Traffic in Ho Chi Minh city, Vietnam, satisfies both two conditions and has a uniqueness that only one type of small-sized vehicle as well as non-lane-based vehicle, TW, also named as motorcycle, and its dominance in traffic proportion. Thus, roundabouts in the city are selected as case studies. Moreover, this section also goes through the concepts and techniques related to model development, collective behavior, two-player game theory, agent-based modeling.

Secondly, the surveyed videos are recorded by unmanned areial vehicle (UAV), DJI Phantom 4 Pro, and the trajectory data is extracted by using semi-automated software. The accuracy of extracted data is examined with under 3.4% error. From extracted data, the macroscopic and microscopic characteristics of TWs are analyzed. Chapter 3 highlights three points that are the exponential relationship between turning angle rate and speed, the small critical gap of TW, 1.25 seconds, and the oval shape of the following space.

Chapter 4 presents the model development in detail and its components. Based on the collective behavior and game theory, the TW's interaction model is built at the microscopic level, including regular movement model, conflict-solving model, and collective behavior model. The implementation of the model in traffic simulator is detailed in chapter 5. The simulator is built based on the multi-agent programmable modeling environment, Netlogo. The parameters are calibrated using half of the collected data.

Chapter 6 presented a series of results and indicators for validating the developed simulator. The remaining collected data is using for validation. Totally nine indicators are used for both macroscopic and microscopic validation. The total turning angle and low-speed duration are uniquely proposed in this study for validation. In total, the developed simulator is validated as good in representing both macroscopic and microscopic characteristics. The developed simulator is superior to the popular commercial software for heterogeneous traffic, PTV VISSIM, in simulating heterogeneous traffic at the roundabout.

Finally, chapter 7 concluded the study's achievements, contributions, and limitations. Concerning research interest, the study proposed the novel TW's interaction model at the individual level. The model potentially applies and expends in the future to improve the accuracy of the future microscopic simulations. In addition, the developed agent-based simulator also has practical contributions. It could be a useful tool for measuring the current roundabout performance under different schemes, or for policy test as well as new geometric design test.

Keywords:

Collective behavior model, Conflict-solving model, Two-wheelers, Roundabout, Heterogeneous traffic, Micro-simulation model.

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Glossary

Term	Definition
Turning Angle	The turning angle represents the change in the moving direction within the local frame of reference. It is not the steering angle of the handle or the front wheels but the angle between the current and previous moving directions. It is also named as veering angle, angular velocity. Unit: degree
Turning Angle Rate	the first derivative of the turning angle, which is called the turning-angle rate (T.A.R). The T.A.R is the rate at which a vehicle changes its moving approach. Unit: degree/second
Anticipation Movement	The movement of vehicle with an assumption that the vehicle will move towards its current direction with the same current velocity during the anticipation period *T*, here is *1.5 seconds*.
Throughput	The number of vehicles passed through the roundabout from entering to exiting approach. Unit: vehicle/hour

Abbreviation and Acronym

Term	**Full words**
MTW	Motorized Two-Wheeler
TW	Two-wheeler
T.A.R	Turning Angle Rate
TTC	Time-to-collision
ABM	Agent-based modeling
ABMS	Agent-based models
UAV	Unmanned Aerial vehicle
HCMC	Ho Chi Minh city
ZOR	Zone of repulsion in the collective behavioral model
ZOO	Zone of Orientation in the collective behavioral model
ZOA	Zone of Attraction in the collective behavioral model
ODD	"Overview, Design concept, and Details" protocol to design an agent-based model
OD	Origin-Destination
MAPE	Mean absolute percentage error
HCM 2010	Highway Capacity Manual 2010
HCMC	Ho Chi Minh city

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Chapter 1. INTRODUCTION

While modern roundabout has been proven superior to signalized intersection in safety, delay, and capacity under homogeneous traffic, its merits in heterogeneous traffic are neither proven nor analyze. Both unique characteristics and models to reproduce behaviors in simulation has not been discussed comprehensively, especially in the high proportion of motorcycle condition. The reason is that there is no means to evaluate the efficacy of roundabout under heterogeneous traffic. This section dedicates itself to the background, research needs, research gap, the motivation of the study, objectives, scope, and structure of the dissertation.

"*A roundabout that operates within its capacity will generally produce lower delays than a signalized intersection operating with the same traffic volumes*", Barker *et al.* (2010).

1.1 Background and research need

1.1.1 Raising necessary

Asian countries have been facing the problem of increased motorization is compounded by inadequate road infrastructure, unsafe vehicles, and driving behavior, sharing of the road surface, overcrowding of vehicles, inadequate traffic signals, signs, and traffic management, Asaithambi *et al.* (2016). The investment for the public transportation system has been considered as the possible answer to the current problems. However, this long-term solution has faced many troubles, from capital to social and documental issues. In that theme, Two-wheeler (TW), also called motorcycle, is still a favorable transport modal due to its advantages in low price, small size, high maneuverability, and great freedom on the road. Moreover, other reasons for its popularity are the low income, hot climate, and compact land use in urban areas. For these reasons, the only suitable means for commuting is small vehicles instead of car or larger vehicles, Taniguchi *et al.* (2014). Thus, TW is going to maintain a high proportion of transport modal in Southeast Asian cities in the near future.

Shiomi (2013) stated that the establishment of highway capacity manual for Asian countries for heterogeneous traffic is necessary. TW is a non-lane-based vehicle with distinctive behaviors and usually performs complicated movements. The heterogeneous flow, therefore, is quite dissimilar with the highway capacity manual for homogeneous traffic, TRB (2010).

Das and Maurya (2017) reviewed that the increasing share of MTW in many developing countries, especially Asian, raises the interest in modeling characteristics of MTW as well as its interaction with the rest of the traffic stream. The demand, for which appropriately analyzing traffic phenomena and forecasting the performance of new geometric design, is growing together with the raising of infrastructure. Traffic management needs a thriving tool for evaluating the new infrastructure under heterogeneous traffic conditions. However, most of the available models are designed for homogenous traffic and so are not fully capable of reproducing traffic patterns that emerge in the presence of mixed traffic conditions, as mentioned by Asaithambi *et al.* (2016).

In recent years, Giuffrè *et al.* (2016) mentioned that roundabouts have gradually gained great popularity worldwide as they represent a type of intersection control without traffic signals. Roundabout establishes a self-regulated intersection control system by making use of a circular geometric layout. The vehicles, entering the roundabout, conflict only with vehicles coming from the immediate left since roundabouts accommodate traffic flow in one direction around a central island. Compared to all-way-stop controlled intersections, roundabouts reduce speed as well as the number of conflict points. Moreover, safety and operational performance issues could also be enhanced by its design. There are controversies over converting signalized intersection to roundabout in many countries, United Kingdom, United State and European Union’s countries for example. Even though the conclusion is unclear at the moment, the number of new roundabouts has dramatically increased.

Even under homogeneous, Feng *et al.* (2007) emphasized that the variation in the proportion of long vehicles resulted dramatically impact on delay, queue length, and throughput. However, that variation is still in a smaller range than the distinction between lane-based and non-lane-based vehicles in heterogeneous traffic. In conclusion, since the huge differences were observed under variation of length among lane-based vehicles in homogeneous traffic, the differences between homogeneous traffic and heterogeneous traffic are, therefore, much more significant and worth investigating.

While roundabout has shown its merits in homogeneous traffic, these advantages are unproven in heterogeneous traffic condition. Especially, the comparison between roundabout and traditional signalized intersection design has not been discussed. Since their designs could be converted with an acceptable cost, the issue has got more attention. There is also no guideline for roundabout design under heterogeneous traffic. The reason for the lack of analysis of roundabout performance under heterogeneous traffic is the lack of an adequate tool for simulating the real heterogeneous traffic. The satisfactory model for simulating the heterogeneous has been requisite.

1.1.2 Why microsimulation?

Before starting to make a traffic simulation, a general question that should be answered is whether a distinctive simulation model is necessary and important for heterogeneous traffic? Which level of simulation is suitable if the answer to the former question is yes?

By function, traffic simulation plays a major role in allowing transportation engineers to evaluate complex traffic situations and recommending alternative scenarios Al-Obaedi and

Yousif (2009). Clark and Daigle (1997) reported that such simulation models provide the opportunity to evaluate traffic control and design strategies without committing a lot of expensive resources, including time, which are necessary to implement alternative strategies in the field. According to Kotsialos and Papageorgiou (2010) these models can be used for estimation, prediction, and control related tasks for the traffic process.

While building a new useful road system or applying a new efficient infrastructure operational system requires a number of field test. Computer simulation models can help in analyzing the performance in various designs or diverse traffic control systems. Microscopic simulation mimics the driver behaviors explicitly in a controlled environment. Driving behavior models are a crucial component of microscopic traffic simulation.

Specifically, micro-simulation is a versatile tool to model the complex system of a wide range of operational conditions. The results are more precise than macroscopic or mesoscopic simulation as regards comprehension characteristics (speed distribution, lane usage, lateral position distribution, travel time, travel cost) energy consumption and emission, safety. However, it has the drawbacks that are time-consuming, electricity-consuming, requisite of huge input data, lack of flexibility, and relying heavily on computer performance. Nowaday, owing to the development of computer technology, the boundary of micro-simulation has been expanded closed or overlap the traditional area of meso-simulation. It allows us to simulate the larger traffic network at the individual level.

Traffic safety evaluation has been the state-of-the-art application of the traffic micro-simulation. Mahmud *et al.* (2019) mentioned “the use of micro-simulation in traffic safety and conflict analysis has gained popularly due to recent developments, in human behavior modeling and real-time vehicle data acquisition”. However, from a detailed literature review, Mahmud *et al.* (2019) concluded that “No Asian countries except Japan has developed traffic safety simulation models for their own context”. It means that most of the model developments, application, calibration, and validation processes are conducted under the lane-based homogeneous traffic condition in developed countries, not the non-lane-based heterogeneous traffic in developing countries.

Furthermore, microscopic simulation is especially effective for mixed traffic, unsynchronized traffic, highly complex. While homogeneous traffic, which is highly imposed results, can be solved with mathematical models, the heterogeneous traffic often brings about the unpredicted result. The reason is that the result is neither simply the sum of individual's properties nor the same type with individual-level properties but is emerged - arise in relatively complex and unpredicted ways - from the individual's behaviors and environment's characteristics. Likewise, Arasan and Krishnamurthy (2008) also stated that "For highly heterogeneous traffic conditions, simulation has been found to be a versatile tool to model the characteristics of complex systems over a wide range of operational conditions".

In addition, Ni (2001) argued that the traffic simulation would continuously develop owing to five driving forces,

- The advances in traffic theory.
- The continuing improvement in computer hardware technology.
- The similar improvement in software technology.
- The development of the general information infrastructure.
- The society's demand for more detailed analysis of the consequences of traffic measures and plans.

From the market perspective, real-time traffic simulation is a recent trend and will have a huge demand in the near future. Pell *et al.* (2017) mentioned that "there are very limited real-world applications of real-time systems". It comes together with the intelligent transport system and quite successful when the road is blocked due to accident or incident events. The real-time simulation could test and analyze the proposed solution in a short time.

1.1.3 Potential of roundabout

Roundabouts have considerable advantages in respect of their safety record because they can improve vehicle safety by eliminating or altering conflict points, reducing speed differentials at intersections, and forcing drivers to decrease speeds when entering to roundabout. In United States, roundabouts are particularly successful in increasing traffic safety when the traffic flows are in balance on all approach legs, as mentioned by Barker *et al.* (2010).

Mensah and Eshragh (2010) proved that modern roundabouts are superior in safety and volume of traffic with less delay compare to signalized or all-way-stop-controlled. Barker *et al.* (2010) also reported that "A roundabout will always provide a higher capacity and lower delays than all-way-stop-control operating with the same traffic volume." and "A roundabout that operates within its capacity will generally produce lower delays than a signalized intersection operating with the same traffic volumes”.

Astarita *et al.* (2012) gave pieces of evidence roundabout is better in safety conditions compared with traffic signal intersections. Faghri (2013) stated that roundabout is safer than traffic signal intersection, especially when the electricity is cut off. It is a similar case with the driver does not strictly for the traffic regulations.

1.1.4 Motivation

While observing video of heterogeneous traffic at roundabout, I called videos from Nature channel, Thirteen New York. The movement of vehicles, specifically TWs, seems similar to the movement of creatures in nature, bird flock, school fish, or army ant for example. These creatures have an excellent moving pattern that could simultaneously avoid collision and keep close with flock-mates, align their moving direction with group direction, split into smaller groups in order to respond to surrounding agents. Figure 1.1 gives an overview of the similarities between two groups.

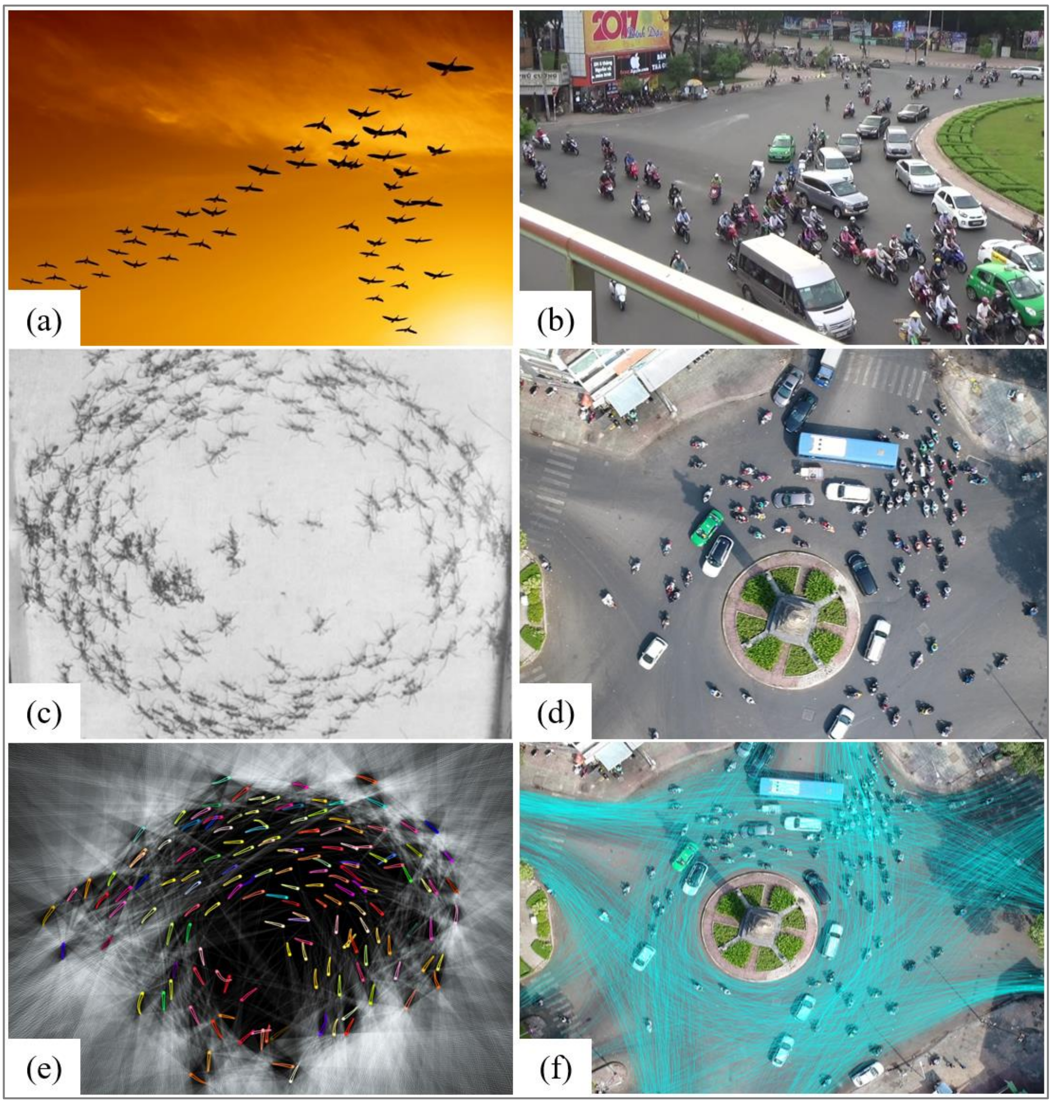


Figure 1.1. Overview of natural creatures group and heterogeneous traffic; (a) V-shaped bird flock, www.psb.org/ show/nature/; (b) Merging area of roundabout in HCMC; (c) Army ants circulating experiment, Couzin and Franks (2003); (d) Screenshot of roundabout in HCMC by UAV; (e) Visualization of fish school, Rosenthal et al. (2015) Appendix Fig. S17; (f) Trajectory of vehicles at roundabout in HCMC extracted by server www.datafromsky.com

On the purpose of comparing between nature creatures group and heterogeneous traffic, several factors are presented in Table 1.1. While the behavior rules are alike, the models of movement in heterogeneous traffic have not evolved as the models of natural creatures group. Heterogeneous traffic also has a trend to utilize the combining repulsive force, attractive force, oriented force, and to add goal-oriented force. In the over-crowded situations as heterogeneous traffic, the drivers tend to react logically to other drivers and the environment more than follow strictly the traffic rule. The intuitive reactions are, therefore, somehow similar to creatures' movement.

Table 1.1. Qualitative comparison between natural creatures group and heterogeneous traffic

	Natural creatures group	**Heterogeneous traffic**
Category	Self-organized system	Self-organized system
Behavioral rules	Avoid collisions and keep closed with flock-mates. Align with the average direction (grouping behavior). Split into several groups by individual response to surrounding information (diverging).	Avoid collisions and keep on the strategic route. Align with the similar objective vehicle (grouping behavior). Split into several groups by objective (diverging).
Leader	Deny any need for leaders.	Have a specific leader, who is an aggressive driver.
Properties	Collective motion Collective memory	Collective motion Collective memory and strategic orientation
Model of movement	Couzin and Krause (2003) combine three forces in a single model, • Repulsive force • Attractive force • Oriented force	Each of the three following forces were proposed discretely, • Nguyen *et al.* (2012) defined safety zone with repulsive force at a straight road segment. • Huynh *et al.* (2013) reproduce grouping behavior at a signalized intersection by using attractive force. • Vu and Shimizu (2010) analysis of inter-group interactions of two-wheelers, defined moving direction as one of the criteria determining group. This study case is at a signalized intersection.
Difference	Always try to make group	Continuously accumulate and divide by goal

From this observation and comparison, the study comes to the idea of utilizing the models of natural creatures group to simulate vehicles' movement at roundabout. However, in the decision-making process, drivers are rather both objective and intuitive. For this reason, applying the models also need to add the goal-oriented part and to modify the properties of entities, size, choice set, observation zone, reaction time, acceleration and deceleration, gap, headway and so on. The proposed unique model is expected to improve the accuracy of micro-simulation under heterogeneous traffic at roundabout in the future by capturing the human-like decision-making process of the drivers.

1.2 Research objectives

1.2.1 Research gap

To the best of the author's knowledge, none of the studies proposed the model to reproduce the TW's interaction, especially tackling conflict and grouping movement behavior, at roundabout under heterogeneous traffic. Several models proposed to simulate homogeneous traffic at roundabout. These models have focused on the interaction of lane-based vehicles in conflict area and have been regarded as the model of priority-control at intersection, specifically gap-acceptance model, as mentioned by Marczak *et al.* (2013); Guo *et al.* (2019). Thus, these models are based on the incoherent mix of sophistication and do not account for interaction between different elements, Wu and Brilon (2017).

In relation to modeling heterogeneous at roundabout, Asaithambi *et al.* (2016) emphasized that most studies related to conflict have employed gap acceptance models in the context of mixed traffic deal with yield controlled intersection crossing behavior. However, the gap acceptance decisions depend on the size of lag/gap, age of the driver, conflicting vehicle type, and vehicle occupancy. Therefore, the gap acceptance model in the context of heterogeneous traffic is limited and inappropriate.

The above argument is confirmed in the model of the popular commercial micro-simulations, AIMSUN and PTV VISSM. They are the two most popular for mixed traffic simulation and used to simulate traffic at roundabout by Giuffrè *et al.* (2018). The comparison between the current model of lane-based vehicle, non-lane-based vehicle and with the real world at merging area is presented in Table 1.2. There are two main gaps between current models and the real world. Firstly, the non-lane-based vehicle has freedom to maneuver. It results that the entering position is dynamic and the conflicting point is, therefore, varying in a wide area. Moreover, in order to tackle conflicts, drivers do not always yield priority rule but the first-come-first-serve principle. This phenomenon was also noticed in homogeneous traffic by Ma *et al.* (2017), namely limited priority by Lakoba *et al.* (2005), also called non-strict priority by Lin *et al.* (2016).

Table 1.2. comparison between the current model of lane-based vehicle, non-lane-based

vehicle and with the real world at merging area

	Model of lane-based vehicle in PTV VISSIM, AIMSUN	**Model of non-lane-based vehicle, TW, under heterogeneous traffic in PTV VISSIM**	**Real world non-lane-based vehicle, TW**
Entering position	Fixed	Fixed	Dynamic
Reaction before entering (there is a vehicle inside roundabout)	Stop or go (Fixed stop line)	Stop or go (Fixed stop line)	Slow down even stop. Maneuver to achieve higher utility. (No stop line)
Priority rule	Strong priority	Strong priority	Weak priority (based on a conflict situation)
Conflict point	Static conflict marker	Static conflict marker	Dynamic conflict point in a wide area.
Reference	SEPTARINA (2012); Silva *et al.* (2015); Zhou *et al.* (2016); Gallelli *et al.* (2014); Shaaban and Kim (2015); Trueblood *et al.* (2003)	Bharadwaj *et al.* (2017); Dodappaneni *et al.* (2016)	

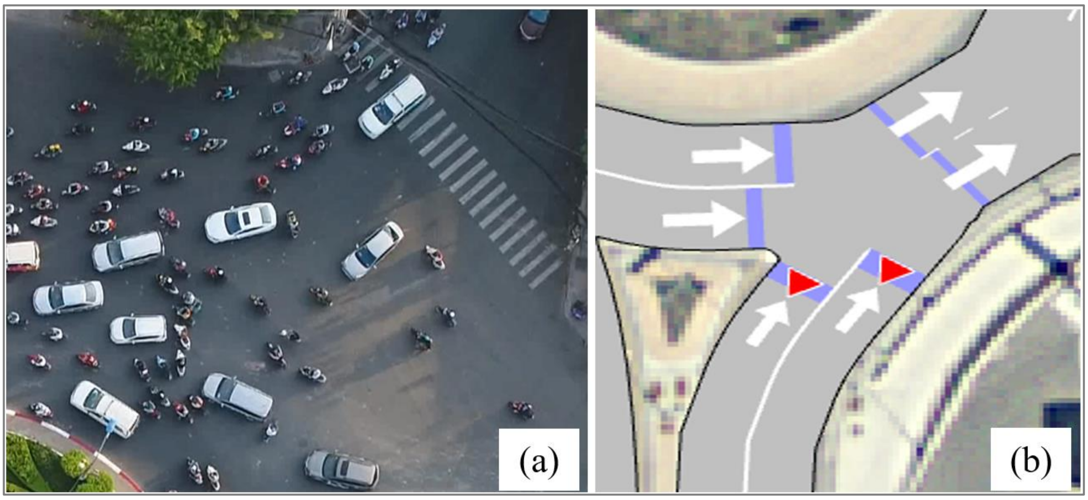


Figure 1.2. Differences in merging area of non-lane-based (real world screenshot) and lane-based (AIMSUN, by Zhou *et al.* (2016)*) vehicle*

1.2.2 Objectives

The ultimate goal covering this study is to propose a guideline for roundabout design under heterogeneous traffic. This dissertation is the beginning step in order to achieve the ultimate goal.

In the light of this background, the study hereby aims to address the specific above gaps. First, the main research question is stated:

- How to reproduce unique characteristics of TW at roundabout in a simulation?

  In order to clarify this research question, two detailed questions are added:

  - How does TW interact with the movements of the surrounding vehicles?
  - How to simulate these movements in the virtual environment at a microscopic level?

Second, in an attempt to answer these questions, the study set the two objectives as,

- To analyze the characteristics of TWs at roundabout.

  This step is mainly to analyze the macroscopic and microscopic characteristics of heterogeneous at roundabout. From analysis results, the study aims to identify the complex behaviors and to figure out some basic rules that each individual behaves to attribute those complexity movements.

- To propose a psychological reaction model of TW in order to reproduce conflict-solving and grouping behavior.

  In order to simulate roundabout, this study not only proposes the model but also develops a simulator to prove the effectiveness of the proposed model. The interaction in group and avoiding collision with vehicles while merging, circulating, and diverging of vehicles are described by the basic rules and formulated in the models. The proposed model is developed based on the conflict-solving and collective behavioral model.

1.3 Scope and limitations

The scope of this study is classified into academic and practical field. Related to academic field, the present study attempts to answer the conceptual questions that are why this topic? and so what if it has been accomplished? The present study simulates TWs' movement at roundabout under heterogeneous traffic in order to find out the effective model to reproduce complex movements of vehicles at roundabout. So that the study contributes a better understanding heterogeneous traffic and the model could be applied in other study cases or even in the future scenarios where human-driven vehicle interacts with connected and autonomous vehicles.

Bridged to practical filed, the developed simulator itself is expected to be an effective tool to forecast roundabout performance under different schemes or designs. So that the current situation could be improved and new alternative solutions could be validated accurately in the virtual environment. The model also has potential application in:

- Improving the simulation of lane-based homogeneous traffic.
- Evaluating safety of roundabout.
- Optimizing the design of roundabout.
- Examining the new traffic regulations.
- Simulating for future transportation network where human-driving vehicles and semi-autonomous vehicles collaborate.

Beside significant contributions, the study also has its limitation due to the focus of the objective.

- The variables and parameters are calibrated for the case study area, a roundabout in HCMC, Viet Nam. The future application should modify these values from the field survey.
- The aggressive behaviors, which usually happen irrationally, for example, dangerous overtaking, violate the traffic rules and so on, are not taken into consideration. The study concentrates solely on performance functions.
- The lack of flexibility and other functions is a limitation of the developed simulator. The simulator is developed firstly for studying the simulation of roundabout. It currently does not have a wide range of functions like commercial softwares, astonishing graphical motion, fuel consumption, safety evaluation to name a few. Moreover, even though it belongs to microscopic level, the developer's viewpoint is to observe the entire movements inside roundabout not to observe individual movements from the driver's field of view as the driving simulator. Input variables are reduced owing to the simplifications and research objectives.

1.4 Outline of the dissertation

Firstly, the overview of this study is provided in section 1.1. After a brief summary of research needs and motivation on this topic, the research gaps are pointed out as the background to define research objectives. The research question is stated together with the answer is the objectives of the study. This section is fundamental to clarify which aspects should be focused on this study and why they should be considered.

Second, the literature review section determined the two constitutions of mixed traffic that are the performance rule and the appearance of small-sized vehicle. Ho Chi Minh city, Vietnam, satisfies both two conditions and has uniqueness that only one type of small-size as well as non-lane-based vehicle, TW, also named as two-wheelers, and its dominance in traffic proportion. Thus, roundabouts in the city are selected as case studies. Moreover, this section also goes through the concepts and techniques related to model development, collective behavior, two-player game theory, agent-based modeling.

Third, the surveyed videos are recorded by UAV and the trajectory data is extracted by using semi-automated software. The accuracy of extracted data is examined and the effect of lens distortion is also clarified. From extracted data, the macroscopic and microscopic characteristics of TWs are analyzed. Chapter 3 highlights three points that are the exponential relationship between turning angle rate and speed, the small critical gap of TW, 1.25 seconds, and the oval shape of the following space.

Chapter 4 presents the model development in detail and its components. Based on the collective behavior and game theory, the TW's interaction model is built at the microscopic level. The implementation of the models in a traffic simulator is detailed in chapter 5. The simulator is built based on the multi-agent programmable modeling environment, Netlogo. The parameters are calibrated with half of the collected data.

Chapter 6 validated the simulated result based on the remaining data. The innovative microscopic indicators are employed for validation. They are traffic flow, speed distribution, travel time, area occupancy, and trajectory map. The results show that the simulator could be considered as good in representing the traffic condition.

Finally, chapter 7 concluded the study's achievements, contributions, and limitations. Concerning research interest, the study proposed the novel TW's interaction model at the individual level. The model potentially applies and expends in the future to improve the accuracy of the future microscopic simulations. In addition, the developed agent-based simulator also has practical contributions. It could be a useful tool for measuring the current roundabout performance under different schemes, or for policy test as well as new geometric design test.

Chapter 2. LITERATURE REVIEW

This chapter firstly reviews the definition of the homogeneous traffic and heterogeneous traffic in order to highlight the uniqueness Ho Chi Minh city as a study case. Properties and geometries of roundabout designs are portrayed in detail. The concepts, techniques related to model development, collective behavior model, two-player game theory, and agent-based modeling are also discussed critically.

2.1 Heterogeneous traffic

2.1.1 Homogeneous and heterogeneous traffic

On the one hand, homogeneous traffic is a popular term used to describe the traffic state in developed countries. This definition includes two fundamental characteristics: cars are the dominant vehicle type and drivers follow lane discipline. Arasan and Krishnamurthy (2008) defined homogeneous traffic state as “traffic movement under fairly homogeneous traffic conditions with cars constituting about 80% or more of the vehicles displays lane discipline.” When all vehicles obey the lane regulations, there is a synchronized movement on the road.

On the other hand, heterogeneous traffic, also called mixed traffic, is a popular technical term used to describe the state of traffic in developing countries, e.g. Matsuhashi *et al.* (2005); Lee *et al.* (2009a); Wong *et al.* (2016); Vu and Shimizu (2010); Asaithambi *et al.* (2016); Kiran and Verma (2016); Das and Maurya (2017). The map of heterogeneous traffic countries is depicted in Figure 2.1, referred Group (2019); World Health Organization (2018). The countries are mostly located in South-Easts Asia area. Heterogeneous traffic is a complex system, even for mid-blocks or intersections. Furthermore, mixed traffic at roundabouts represents an immensely intricate situation; owing to the numerous interactions among vehicles travelling in different directions, having a wide range of characteristics, and rescinding lane discipline. They represent a non-signalized intersection that employs the yield on entry and circulation rules TRB (2010). This intricacy motivated us to investigate the characteristics of mixed traffic flow at roundabouts. Vietnam was selected as a case study, as it exemplifies the foregoing complex characteristics.

Figure 2.1. Map of heterogeneous traffic (www.mapchart.net)

Heterogeneous traffic is more complex due to the increase in the types of vehicles and the changes in performance rules. Vehicles vary with regard to dimensions (e.g., lateral and longitudinal size) and performance capabilities (e.g., acceleration, deceleration, desired speed, and maneuvering capabilities). Many types of vehicles that are smaller than cars can gain more freedom in their lateral movement by disregarding the lane rule. By utilizing the advantages of static and dynamic characteristics, small vehicles can occupy empty space on the road surface to maximize their utility. This practice results in the behaviors reported by Lee (2007), such as filtering, swerving or weaving, tailgating, oblique following, and maintaining a shorter headway when aligning with the lateral edge of the preceding vehicle. Similarly, overtaking behavior was described by Asaithambi and Shravani (2017), and the accumulation at the stop line was described by Haque et al. (2008). This traffic stream finally results in unsynchronized movement, unorganized traffic under traffic rules' viewpoint, and self-organized traffic under individual interaction's viewpoint.

2.1.2 Constitutions of heterogeneous traffic

There are two important characteristics that distinguish mixed traffic flow from homogenous traffic: the presence of a mix of widely variable vehicle types, and organization of lane-less traffic, Asaithambi *et al.* (2016).

Many researchers have attempted to define the mixed traffic state in their studies. Taylor and Mahmassani (1999) conceptualized heterogeneous traffic according to its mixed nature, as bicycles, TWs, and cars share road space. Hsu et al. (2003) described a measurement method for mixed traffic characteristics in Taiwan, which involves calculating the ratio of the number of TWs to the volume of traffic. It emphasizes the mix essence of TWs and other vehicles. Chandra and Kumar (2003) examined the mixed traffic in India, which includes various vehicles. Minh et al. (2007) studied traffic in Hanoi and Ho Chi Minh (HCM) City in Vietnam, where TWs account for more than 80% of transportation. It is emphasized that the mixed traffic should be considered with a sufficient TW volume. Tang et al. (2009) investigated the heterogeneity of mixed traffic in China, including the vehicle heterogeneity and speed heterogeneity. In most of the aforementioned studies, mixed traffic was considered as traffic with a wide variety of vehicles having different characteristics, all sharing the road surface. Lane discipline was not considered as a critical factor affecting mixed traffic behavior in these studies.

More recently, mixed traffic has been defined as a lack of lane discipline and a variation in vehicular characteristics. Venkatesan et al. (2015) stated that large variations in speed and vehicle dimensions lead to difficulties in following lane discipline. Small vehicles often occupy any available space on the road to maximize their utility. Asaithambi et al. (2012) characterized mixed traffic in developing countries as traffic having a lack of lane discipline, varying constituent vehicle types, and a significant disparity in the characteristics of the vehicles within each class. Shiomi et al. (2012) characterized the characteristics of traffic flow dominated by TWs free from lane restrictions and examined the differences in the field of view, size, weight, maneuvering methods, turning radius, and acceleration and deceleration between passenger cars and TWs.

Furthermore, Kiran and Verma (2016) used the terms “heterogeneous disordered traffic” and “mixed traffic” to describe the traffic scenario in developing economies. The two characteristics distinguishing this type of traffic from homogeneous traffic were identified as a wide variety of static and dynamic characteristics and the absence of lane discipline. These two factors were confirmed via microsimulation, which indicated that they have significant effects on the capacity and jam density Lenorzer A *et al.* (2015). The combination of these two effects results in the unsynchronized movement of vehicles. Poorly performing vehicles present considerable resistance to the movement of high-performing vehicles, and the entire stream becomes difficult to predict. Thus, many distinctive behaviors have been identified during surveys of mixed traffic: overtaking, which was mentioned by Asaithambi and Shravani (2017), oblique following Lee (2007), swerving movement Nguyen (2012), vehicle filtering, creeping, cut-tail, giving way, accumulation and dispersion at intersections, and many others, as identified by Trinh et al. (2018).

The foregoing literature review raised some arguments that must be clarified. First, what would the traffic state be if there was a wide variety of vehicle types, ranging from small to large, and all of them followed lane discipline? In this scenario, the type of vehicle factor is activated, and the performance rule factor is deactivated. This scenario may describe the traffic state of developed countries, such as the United States of America or Japan, where small vehicles still obey lane-based movement. Thus, it is classified as homogeneous traffic according to the traffic's synchronized movement. Second, what scenario would develop if we limited the categories of vehicles to one (four-wheelers), but rescinded the lane discipline? Here, the first factor is deactivated, and the second factor is activated. This scenario is represented by traffic at non-lane-marked roundabouts in developed countries. The homogeneous traffic state remains, and no mixed traffic characteristics are observed. This could be because four-wheelers (and larger vehicles) cannot utilize small spaces on road surfaces, owing to their limited maneuverability. The third scenario concerns limiting the categories of vehicles to one (TWs) and rescinding lane discipline. This scenario is represented by Vietnam, where TWs account for up to 80% of traffic. Most of the characteristics of mixed traffic have been observed there.

Thus, it can be concluded that the two fundamental factors causing mixed traffic are the performance rule and the appearance of small vehicles. If only one of these factors is active, traffic will not exhibit heterogeneous traffic characteristics. Large vehicles (cars, trucks, and buses) cannot utilize small spaces on road surfaces, owing to their limited maneuverability, even when lane discipline is revoked. Additionally, small vehicles, such as TWs and three-wheelers, cannot perform complex maneuvers if they are forced to follow lane discipline.

2.1.3 Case study and other heterogeneous traffic cities

In order to compare Ho Chi Minh with other mixed traffic cities, data on the traffic composition in mixed traffic cities were collected, as shown in Table 2.1. We considered the following issue: when choosing data for a country, a city, a town, or even the same road, the traffic proportions of different locations are highly diverse. For comparison, we selected the highest proportion of non-lane-based vehicles among the study sites from each country.

In accordance with the proposals of Hsu et al. (2003) and Tang et al. (2009), this paper suggests that two indicators should be used—the number of non-lane-based vehicle types and the proportion of non-lane-based vehicles in the traffic—to quantitatively characterize mixed levels in traffic. Regarding the appearance of non-lane-based vehicles, it is clear that as the number of non-lane-based vehicles increases, the traffic becomes more complex. Owing to the larger variations in their dimensions and performance capabilities, the interactions between different types of vehicles and their behaviors become more sophisticated. Regarding the proportion of non-lane-based vehicles, the higher proportions, the more the characteristics of mixed traffic are revealed. According to the data in Table 2.1, the cities defined in this study were characterized using two indicators, as shown in Figure 2.2. The horizontal and vertical axes are assigned to these two indicators.

Table 2.1. Comparison between traffic composition in mixed traffic cities

City and Country	**Traffic composition (%)**				**Type of non-lane-based vehicle**	**Reference**
	TW	**Three-wheeler**	**Bicycle**	**Lane-based vehicle**		
HCM City Vietnam	89.5	-	-	10.5	TW	Trinh *et al.* (2018)
Ha Noi Vietnam	92.7	-	-	7.3	TW	Nguyen and Sano (2012)
Taipei Taiwan	35.7	-	-	64.3	TW	Wong and Liao (2012)
Tainan Taiwan	36.4	-	-	63.6	TW	Lee and Wong (2016)
Penang Malaysia	66.0	-	-	34.0	TW	Ahmed *et al.* (2015)
Pakem, Region of Yogyakarta Indonesia	87.2	0.1	1.4	11.3	TW, Three-wheelers, Bicycle	Hidayati *et al.* (2012)
Bangkok Thailand	55.3	2.6	-	43.1	TW, Three-wheelers	Transport Statistics Group (2018)
Chennai India	56.0	13.0	-	31.0	TW, Three-wheelers	Bharadwaj *et al.* (2017)
Dhaka Bangladesh	50.3	6.0	-	43.7	TW, Three-wheelers	Bureau of Statistics (2019)
Kathmandu Nepal	65.3	1.7	-	33.0	TW, Three-wheelers	Timalsena *et al.* (2017)

Considering the horizontal axis of Figure 2.2, there are two extremes: no non-lane-based vehicles and all non-lane-based vehicles. The former extreme is the state of synchronized traffic in developed countries. The latter extreme describes the chaotic state of traffic that has not yet been discovered. In Figure 2.2, HCM City is the second-closest city to the latter extreme case; TWs comprise 89.5% of the traffic flow. Thus, HCM City is considered to be the representative of the latter extreme. Moreover, the city has only one type of non-lane-based vehicle (TWs), making it relatively easy to study TW's interactions. The other cities were located between the two extremes. Hence, by understanding the mixed traffic in HCM City, the characteristics of the other mixed traffic cities can be inferred.

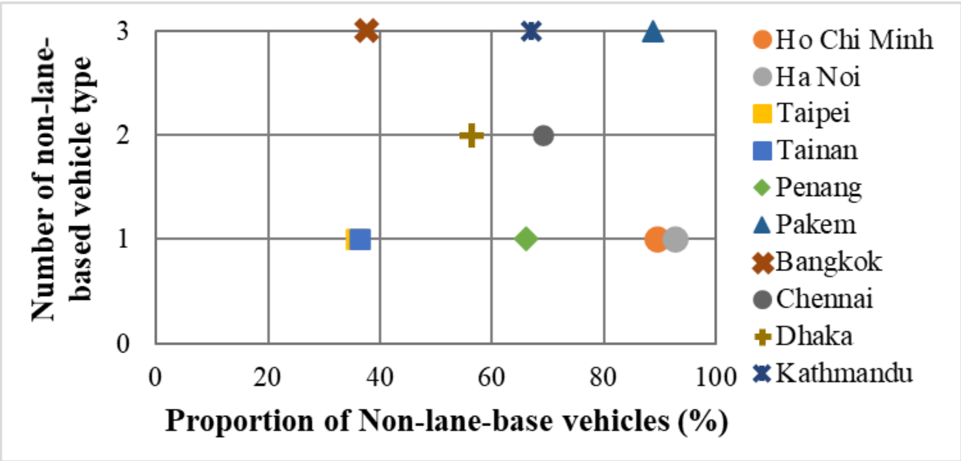


Figure 2.2. Comparison of mixed traffic cities

As shown in Figure 2.2, both HCM City and Ha Noi belong to the mixed traffic group; both are characterized by the predominance of TWs, which characterizes the properties of the entire traffic stream. This state is close to the second aforementioned extreme, i.e., the chaotic traffic state. Priority is usually ignored owing to the high density of TWs. Instead, the common features are a high level of interaction and the negotiation of priority.

2.2 Roundabout

2.2.1 Modern roundabout

Formerly, roundabout was defined as a circular intersections with specific design and traffic control features. Aty and Hosni (2001) added two other characteristics of modern roundabouts that are prohibiting both parking on the circulating roadway and pedestrian activities on the central island. However, with these definitions, roundabouts are a subset of a wide range of circular intersection forms. Rodegerdts *et al.* (2007) indicated three key features of roundabouts are distinguished from those of other forms of traffic circles, such as rotaries, mini-traffic circles, and other non-modern roundabouts. These features are the yield-at-entry rule, channelized approaches, and geometric curvature designs to slow down the speed. Barker *et al.* (2010) lately specified these features include yield control of all entering traffic, channelized approaches, and appropriate geometric curvature to ensure that travel speeds on the circulatory roadway are typically less than 13.9 m/s (50 km/h).

Modern roundabouts, throughout the document, is named interchangeably with roundabouts, has been proven its advantages in safety, delay, capacity, and required land resource over two-way stop control (TWSC), all-way stop-control (AWSC), or signalized intersection. Faghri (2013) reported that roundabout increases throughout flow and reduces delay compared to traffic signal. Mensah and Eshragh (2010) concluded that roundabout is superior in safety and capacity compared to AWSC. Barker *et al.* (2010) wrote that roundabout offers lower overall delays than TWSC and signalized intersection under the same traffic volumes. Astarita *et al.* (2012) assert the superior in safety of roundabout compared to signalized intersection by observing three indicators, time-to-collision, deceleration rate to avoid crash, and proportion of stopping distance through 10 cases of micro-simulation. Last but not least, roundabout even works under blackout mentioned by Faghri (2013). Similar with road signs, roundabout does not need electricity to operate and therefore suitable to evacuation scenarios.

On the other hand, roundabout has been noticed with a significant drawback. It does not give the traffic management full control the priority and demand. When the unequal flow of entering approaches occur, morning rush hour for example, roundabout causes tailbacks on the high flow approach.

2.2.2 Roundabout in Ho Chi Minh city

ALMEC (2004) summarized the layout and operation of roundabout in HCMC as the followings. As regards layout,

- Many roundabouts are formed by adding central islands.
- There are large unregulated areas that allow irregular traffic streams.
- Curb layouts are irregular.
- Traffic engineering design is minimal.
- Priorities are not defined on the approach arms.

- The central island is often not well-located to effectively guide vehicles in forming a regular traffic stream.
- The central island is often too small to encourage regular traffic stream.

In regard to operation, the details are presented as,

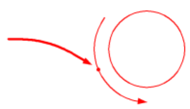
- A central island is created for all traffic to move in a counterclockwise direction. The main objective is to remove crossing conflicts and require vehicles to merge and diverge from the circulating flow.
- Traffic enters in a free-for-all manner.
- System works on a *first-come-first-served basis* and priority rule is ignored.
- It is up to the vehicles to take evading action in order to avoid collisions.
- TWs take the shortest route to avoid going around the island, thus disrupting the traffic streams that conform to the required flow.
- 4-wheelers vehicles encounter great problems when crossing the dominant stream of 2-wheelers vehicles.

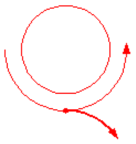
To summarize above conclusion, roundabouts in HCMC were not designed and operated properly according to the current guideline, even though the guidelines based on lane-based vehicle characteristics. Moreover, they are not designed to take full advantage of the characteristics of the TW-oriented heterogeneous traffic in HCMC. TWs, which have higher degrees of freedom in movement and more-complex social interactions, were not taken into consideration when designing the layout and operational regulations.

2.2.3 Basic movement rules

Suzuki *et al.* (2015) classified the movement phases for homogeneous traffic in Japan as in Table 2.2. In heterogeneous traffic, the vehicles also follow similar movement phases but with high variety of paths.

Table 2.2. Basic movements classification

Category	Illustration	Simulating model	Purpose
Merging movement		Conflict-solving model	Adjust moving direction and speed to enter and merge with circulating flow. Avoid crash with other vehicles.

Circular movement		Roundabout-traveling model	Travel inside roundabout. Follow, make group and maintain safe space with surrounding vehicles.
Diverging movement		Goal-oriented model	Split into small group by exiting road. Avoid crash with other vehicles
Weaving movement		Do not considered because of its low frequency and high complexity	Take over other vehicle by aggressive maneuver

2.3 Simulation methodology

With the advancements in computational technology over the last few decades, microscopic traffic simulation has become a popular tool among researchers for the evaluation of different alternative design and management strategies for a road network before adopting full-scale real-life implementations. Rakha *et al.* (1996) stated that field implementations generally have legal and financial constraints associated to them while traffic simulation is a cost-effective, objective, and flexible approach to analyze and evaluate transportation systems. Compared to analytical models, microscopic simulation models can keep track of individual vehicle movements and interactions on a second to sub-second basis and they are quite helpful in realistic representation of complex traffic behaviors mentioned by Dowling *et al.* (2004a). In developing countries, Mathew and Radhakrishnan (2010) gave an example of India, the absence of lane marking, non-lane based traffic, and disorganized movement of a varied mix of vehicle types are commonly observed scenarios. They are, however, difficult to replicate using traditional analytical models. That creating necessity for microscopic simulation models, Maheshwary *et al.* (2019).

Dealing with non-lane-based lateral movements, the solution can be either in a discrete form, splitting the lanes into narrow strips where vehicles can occupy several strips and change lane easily as Mathew *et al.* (2015), or in a continuous way like Lee (2007) by introducing a turning angle and update the lateral position and lateral speed. Similar to the strip-based approach, the cellular automata model with smaller cells and vehicles can occupy multiple cells at a time has been proposed by different authors, e.g. Yao *et al.* (2009); Vasic and Ruskin (2012). The dissertation follows the continuous manner that using turning angle and update position by speed and moving direction.

2.3.1 Agent-based modeling

Another promising approach to simulate non-lane-based movements has gained much attention is agent-based-modeling. Many researchers have attempted to build a complex and unorganized traffic system for conducting microsimulations of traffic flows. One distinguishing approach in this regard is “to treat vehicles as individual units instead of a continuous flow and see what behavior emerges when vehicles are given simple rules to follow” Ghadai *et al.* (2016). Based on this idea, agent-based modeling can be used as a thriving modern tool. By definition, agent-based modeling “is a microscopic computer simulation technique focusing on simulating the actions and interactions of clusters of computational agents” Lee (2007). The traffic flow on the road is also regarded as a combination of vehicle movements. Each moving vehicle is regarded as an individual agent. Thus, many researchers have successfully presented agent-based models for use in traffic simulations Erol *et al.* (2000); Champion *et al.* (2005); Lee (2007); Grether *et al.* (2012); Ksontini *et al.* (2014); Ghadai *et al.* (2016).

By definition, Wilensky and William (2015) stated that “an agent is an autonomous computational individual or object with particular properties and actions”. Agents are parts of an environment and they can sense their environment. An agent has a goal and it is programmed to behave in the best way to achieve its goal while interacting with other agents and its environment. A vehicle on the road can also be lookup as an agent in the field of moving, reacting to other vehicles, sensing the surrounding information, road surface, curb, road signs, lane marker, road divider to name a few, and making a decision to reach a particular destination.

Agent-based modeling (ABM) is an approach to simulate the behavior of the complex system in which the agents interact with each other and with their environment using simple local rules of interaction. It is also defined as “a form of computational modeling whereby a phenomenon is modeled in terms of agents and their interactions” by Wilensky and William (2015). ABM differs with other models in that it supports as a tool to address the problem that concern emergence by the advantage of across level model. That means what individuals do will affect the system and any change of the system will affect the individuals, Railsback and Grimm (2012). Furthermore, addressing system complexity and dynamics that arise from components' interaction, including the system's individuals and what they do, is another advantage of ABM. That is exactly matched with the traffic simulator's requisite, where interactions of vehicles are significant to simulate traffic status.

Regarding conventional models, using sets of tractable mathematical formulas, typically produce only one outcome for determined inputs. However, instead of describing a system only with representing variable, ABM is superior in modeling individuals and producing many kinds of results that arise in complex and unpredicted ways.

2.3.2 Netlogo modeling environment

In association with ABM language, there are several opened-sources and freely available packages, for example, SWARM mentioned Minar *et al.* (1996), MASON mentioned by Luke *et al.* (2005), Repast Eric *et al.* (2006),   NetLogo by Wilensky (1999), and so forth. Among all of them, Netlogo has been the most popular free license and the state-of-the-art language so far.

NetLogo, Wilensky (1999), is a programmable modeling environment for simulating natural and social phenomena. It was authored by Uri Wilensky in 1999 and has been in continuous development ever since at the Center for Connected Learning and Computer-Based Modeling. It is particularly well suited for modeling complex systems developing over time. Modelers can give instructions to hundreds or thousands of "agents" all operating independently. That makes it possible to explore the connection between the micro-level behavior of individuals and the macro-level patterns that emerge from their interaction. NetLogo is the next generation of the series of multi-agent modeling languages, including StarLogo and StarLogoT.

As regards the research objectives, a microscopic traffic simulator has been developed using the *NetLogo*. The simulation could reproduce the vehicle with the features, size, shape, position, turning direction, and the rest. The environment are included geometric layout, lane divider, traffic light, and all others facilities at roundabout. The TWs and cars are represented as agents' properties, movement and interaction with each other inside environment.

2.4 Concept of shared space

Another keyword related to the conflict between mixed vehicle types on the road surface is shared space. Shared space was once defined by Schönauer *et al.* (2012) as a common space that the divide between motorized and nonmotorized traffic is removed. That creating an integrated space without traffic signs or signals, curbs, and road markings. The traffic flows are controlled by social interactions and supported by intelligent infrastructure, such as colored floors or bollards. Lacking of such binding elements, people are thought to become higher safety conscious and focus on the behavior of the others. The potential conflict between types of road users is thought to be higher but the serious conflict is lower. Contrasting with conventional road design, conflicts between distinctive road users, for example, car, bus, pedestrian, and bikes, are avoided by separating traffic flows. Pioneers of shared space approach, Clarke (2006) argued that this is an outdated concept and results in the following consequence,

- Users of one mode pay less attention to those in other modes because they feel safe and privileged on their assigned part of the road.
- Cars, as well as bikes and other motorized traffic, exceed the speed limit and concentrate on their part of the road, putting pedestrians at higher risk.
- Although modal splits are moving away from individual motorized traffic, current street designs are not flexible enough to adapt to unexpected shifts and tend to prioritize such traffic, hindering the development of green transport.

In associated with implementation, Hamilton-Baillie (2008) shared that street designs based on this concept have evolved rapidly in Demark, Germany, Sweden, the northern part of Holland, France, Spain, United Kingdom, and other European countries. Several practical analyses have shown the advantages of performance compared to traditional design.

In fact, this concept does share fundamental principles with roundabout regulations. Firstly, the lane-based and non-lane-based vehicles share the space and there is no lane stripe inside roundabout. Secondly, utilizing social interactions instead of strictly priority rule to raise the safety attention and reduce severe conflicts. In fact, due to similar basic principles, the success of shared space concept consolidates our beliefs on the efficacy of roundabout under heterogeneous traffic.

2.5 Modeling heterogeneous traffic

Examining the nature of the conflict between distinctive vehicle types, the conflict between each entering flow and circulating flow could be considered similar to the conflict of major and minor flow at T-intersection. Thus, review the model of heterogeneous traffic at intersection is requisite and helpful for the model development.

2.5.1 Vehicle interaction

Several studies have also examined the interactions between TWs and other vehicles within intersections. A simulation model was proposed for a non-crossing flow at a signalized intersection in terms of the queue density and dissipation under heterogeneous traffic Asaithambi and Ramaswamy (2008). The relationships between the grouping behavior and conflict inside an intersection were clarified through a statistical analysis Phan and Shimizu (2011). A social force has also been applied to describe the grouping behavior of TWs at signalized intersections Vu and Shimizu (2010); Huynh et al. (2013). However, none of the studies above discuss a way to solve head-on conflicts or consider the opportunistic behaviors when there is no priority but the first-come-first-serve principle.

2.5.2 Conflict-solving model

Tackling the conflict, the gap acceptance principle has been popularly utilized at intersections, Pollatschek et al. (2002). It has been theorized that vehicles should only be allowed to enter an intersection when the time gap between two vehicles is sufficient to allow an insertion into or the crossing of a flow. Numerous studies have followed this theory in analyzing the gap acceptance for homogeneous lane-based traffic, Daganzo (1981); Choudhury *et al.* (2007); Hidas (2005a); Cassidy *et al.* (1995); Mahmassani and Sheffi (1981); Ragland *et al.* (2006).

However, under heterogeneous traffic, most studies have considered a gap acceptance model that concentrates on crossing and merging behaviors at an intersection, Asaithambi et al. (2016). Whereas several studies have employed a constant critical gap, Popat et al. (1989), depending on the vehicle categories, driver age, vehicle lane conflicts, conflicting vehicle types, and vehicle occupancy, other studies have considered the variation in the critical gap through a neuro-fuzzy technique as Sangole et al. (2011), probability density function, Hossain (1999) as Raff method, logit maximum likelihood, lag, or Ashworth method as Patil and Pawar (2015). An alternative to gap acceptance, which is the minimum required time gap for clearing an intersection between vehicles on major streets, was applied to truly reflect the priority rule, Ashalatha and Chandra (2011).

In terms of the merging behavior, which is similar to merging at roundabout, the gap acceptance approach has been utilized in the development of probabilistic merging models at unsignalized T-intersections, Kanagaraj et al. (2011); Kanagaraj et al. (2015b). Although the gap acceptance has become a popular approach, a limitation remains, namely, it is based on the priority rule, Prasetijo et al. (2016), which is obeyed by lane-based vehicles and limits the flexibility of TWs under the assumption that all drivers conform to the traffic rule. Besides, Wu and Brilon (2017) proposed the conflict technique as the state-of-the-art model for describing limited priority phenomena and precisely estimating roundabout capacity.

While the above mentions are only one-dimensional simulation models, where turning vehicles only move along a determined trajectory and use stop-and-go strategy. The two-dimensional model, controlling both longitudinal and lateral movement, was firstly introduced for the lane-based vehicle by Ma et al. (2017) to solve the crossing conflict at a signalized intersection. Making use of the plan-decision-action framework, the model obtains the value of acceleration and angular velocity in each simulation step during the turning process. The model transcended the lane-based and priority limitation regards to reproducing the variation of trajectories, psychological effects of drivers in the decision-making process, non-strict priority rule, and multi-task driving process.

Nevertheless, the variation of trajectory comes from the variation of the dividing point, the connecting point between the curve and the straight segments, of the desired trajectory, not the dynamic of conflict. It means when the TW has a fixed dividing point, current position, speed, and moving direction, there is no variation of trajectory even with distinct conflicts. Although untying the priority rule, the model is still constructed based on this rule. No priority situation, such as in TW-dominated heterogeneous traffic, could not benefit from the model. Last but not least, due to focusing on lane-based vehicle, the model mentions neither capability of modifying the position of crossing point by intensively maneuvering nor the opportunistic behavior of TW. It means the model could not simulate the situation when a TW speeds up and maneuvers to pass the conflict area before a priority vehicle.

Besides the priority rule, another approach to solving conflicts with pedestrians has been introduced by Asano *et al.* (2010). The anticipation approach and two-player game theory were also applied to build a microsimulation model for pedestrian movement. However, the subject of the study was pedestrian and the scope was limited to Japan. The developed model must also be restructured before being applied to a TW. For example, the differences in size and shape lead to differences in the specific pedestrian-to-pedestrian and vehicle-to-vehicle distances.

Anticipation movement and discrete choice approaches have been recently employed to depict the intricate movements of a TW Shiomi *et al.* (2012). The model reproduces several behaviors of a motorized two-wheeler, its following behavior, and interactions with other

TWs and passenger cars, among other factors. The results indicate that this approach can capture both the high flexibility and perception of the traffic surrounding a TW. However, the study focuses on TW behaviors at mid-block, and thus, a head-on conflict was not considered.

Finally, the conflict-solving model at signalized intersection developed by Trinh (2017) has effectively reproduced the conflict and decision-making process of drivers to tackle the conflict. This model is continuously developed and utilized as one of the core models in the study.

2.6 Game theory

In association with the models of road user behaviors, Elvik (2014) stated that a large number of statistical models have been developed, but it is not clear that these models reveal the causal relationship. The statistical models show that variables are related; they do not show how road users interact in complex traffic environments. Lately, behavioral models, Fuller (2005); Shinar (2017); Vaa (2007), have been proposed to describe driver behaviors at a very general level; however, they can not predict road user's actions in a specific situation due to lack of theoretical foundation.

At the same time, the game theory offers a rich set of models for studying interactions between road users. Elvik (2014) reported that game-theoretic models are suited for modeling the interaction between road users, such as the choice of speed, giving way in junctions. They may explain why informal norms, conflicting with formal regulations, develop and are sustained often by road user. However, that game theory cannot serve as a general theory of road user behavior. It is best suited to situations where road users interact, for example Wang *et al.* (2015), not where single user has no interaction. Furthermore, it is based on an assumption of rationality that may not apply fully to all road users. For example, the levels of rationality between children and adults are dissimilar.

According to Eric (2006), game theory is the formal study of interactions among decision-makers who are conscious that their actions affect each other. The concept of game theory gives a language to model the strategic scenario, which deals with the making decision process in the highly interactive environment. The essence of game theory springs from the core of conflicts and cooperation motions, Ungureanu (2017). It is characterized as theory of mathematical models of decision making in the process of conflict and cooperation. As regards to type of problem, it could be classified as multi agents and single objective problem. Osborne and Rubinstein (1998) stated that “Their abstractness allows this theory to be used in a wide range of phenomena”. Owing to the prediction of the player’s behaviors and the final outcome, the game theory is applied in various fields from economics, political science, psychology to computer science. In this study, the game theory also is employed for analyzing the vehicles’ interactions at intersection.

Although the situation for applying game theory is closed to the applying decision theory, there are some differences between two cases. While the decision theory analyses how one person makes a decision when he faces with uncertainty or disregard the reactions of others situation. The game theory is concerned with the action and the effect of this action on each other. Parsons and Wooldridge (2002) also stated that the game theory focuses on the interactions between self-interested agents. However, the decision theory concentrate on identifying the optimal decision in uncertain conditions and the outcome has not been taken into account.

In order to describe the game of the study, the following characteristics will be clarified. First, the number of players is considered as two, a pair of drivers (i, j). The reasons is that the amount of time that driver has to make a decision is not long enough to consider much players, Schonauer (2017), and at serious conflict, the driver focuses only on the most influential conflict. Second, the number of iterations is only one. The single sequential game - Stackelberg game - for each pair of the agents is taken into consideration. The reason is that the duration for making a decision is short and the decision is made independently. The leader, who is assumed to pass the conflict first, selects his strategy and informs to the other player. Third, the game is defined as perfect information. All the agents understand the situation of the other agent is facing, the strategy set, and the payoff function of the other. Finally, all the agents cooperate with the other. The leader maintains its speed and direction. The follower gives way to the leader by altering speed, direction or both. In short, the game is specified as cooperative, two agents, perfect information, and no repetition.

2.7 Collective behavior

Collective behavioral model is a self-organizing model of group formation in space and has been successfully used to investigate the spatial dynamics of animal groups such as fish schools and bird flocks by Couzin *et al.* (2002), army ants by Couzin and Franks (2003), wildebeest and pedestrian trail by Couzin and Krause (2003), baboon by Strandburg-peshkin *et al.* (2015), caribou by Couzin (2018). The models have the ability to reproduce the major group-level behavioral transitions according to minor changes in individual-level interactions.

Moreover, Couzin *et al.* (2005) stated that the model also effectively on imitating information transferring pattern within groups and a process of making consensus decisions in the absence of individual information on its current position among the group or the quality of its informed information. In other words, each individual acts to form the group's pattern based on its local rules and information without knowing the role it is going to play.

Reynolds (1987) emphasized on three basic behaviors that governed individual steering among the flock,

- Avoid collision or close encounters with flock-mates.
- Align with the average direction of your neighbors.
- Stick together: steer towards the average center of gravity of its neighbors.

These rules are model under three non-overlapped zone, zone of repulsions (ZOR), zone of orientation (ZOO), zone of attraction (ZOA) as in Figure 2.3.

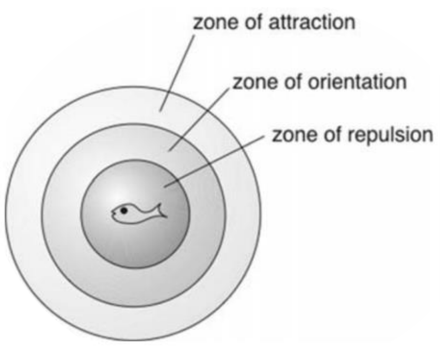


Figure 2.3. Model of three spherical zone Ball (2009)

Collective behavior models have been widely applied to traffic simulation. Thanks to their allowing the user to specify his own psychology and view himself as a part of the whole simulation, Paruchuri *et al.* (2002). Thus, collective behavior is suitable to simulate the drive decision-making procedure.

Couzin *et al.* (2002) stated two behavior rules which are similar and, therefore, applied in the model development:

- Individuals aim to maintain a minimum distance to others during moving. This rule has the highest priority in order to avoid collision, Krause and Ruxton (2002).
- If individuals are not performing an avoidance maneuver, they tend to be attracted towards other individuals by moving close or align the similar direction, Partridge (1982).

As concluded in section 2.1.1, the traffic stream of the study case is unorganized traffic and could be seen as the traffic patterns determined by the collective behavior of various agents rather than by some traffic rules. Hence, the study makes use of the collective behavior model in developing the traffic simulator under heterogeneous traffic.

Chapter 3. DATA COLLECTION AND ANALYSIS

This chapter covers details of the survey site, methodology of data collection and data extraction. Using UAV for data collection is introduced in section 3.2. The issue of lens distortion in data extraction is also presented in this section. Section 3.1 detailed the survey site, including geometries, characteristics, and collected date and time. Section 3.3 discusses the data extraction method and the accuracy of data extraction. The extracted data then is then analyzed at both microscopic and macroscopic level. Characteristics of heterogeneous traffic at the roundabout are exposed. The relationship between turning angle rate and speed, the small critical gap of motorcycle, and the oval shape of the following space, are unveiled and discussed.

3.1 Survey site

3.1.1 Site selection and geometric characteristics

The traffic in HCM City exhibits both the aforementioned features of mixed traffic: the revocation of lane discipline and the appearance of non-lane-based vehicles. Although the city's traffic is dominated by TWs (>90% in this study), it is a good representative of mixed traffic. Additionally, HCM City is a major city, contributing more than half of Vietnam's gross domestic product, and is the representative city in Vietnam for a mixed traffic status. Thus, it was selected as a case study to examine the microscopic characteristics of mixed traffic.

Figure 3.1. A map of survey site (Google maps)

The survey site was the small signalized roundabout in HCM City, Vietnam, Figure 3.1. The roundabout is circular in shape, with six legs for both entry and exit, as shown in Figure 3.2. The diameters of the central island and inscribed circle are 15.2 and 51.7 m, respectively. It has no lane markers, which gives drivers freedom to maneuver inside the roundabout. The national driving regulations stipulate that traffic should drive in a counterclockwise circular direction and should obey the "give-way" rule, which requires drivers to yield to traffic that is already in the roundabout. The study area also conforms to the right-hand traffic rule. Four-phase signal is assigned to the combination of entering approach. The cycle duration is 80 seconds with four phases as listed in Table 3.4.

Table 3.1. Traffic signal phase information at survey site

Phase	Duration (second)	Signal on approach 1, 2, 4	Signal on approach 3, 5, 6
1	43	Green	Red
2	3	Amber	Red
3	31	Red	Green
4	3	Red	Amber

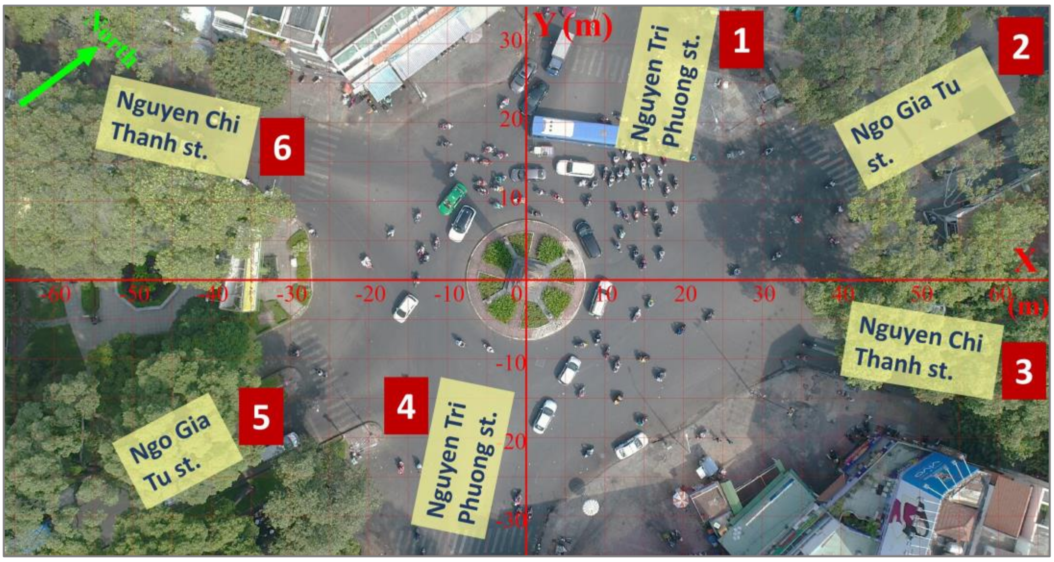


Figure 3.2. Surveyed site with coordination systems

This roundabout was selected owing to several factors. First, its design is typical for roundabouts in HCM City, with regard to the number of legs, refers Table 0.4 for more detail. In developing countries, owing to the limited space in urban areas and the limited infrastructure investment for multi-level intersection options, roundabouts are frequently used where intersections with more than five legs are needed. This design is also suggested to improve the operation efficiency of the same-pave-area multi-leg intersection AASHTO (2011). Moreover, it is one of the main connectors of road networks. Three four-lane arterial roads, which have four-lane widths and two-way traffic, are connected by the circular roundabout. These legs likely have similar widths, numbers of lanes, and traffic flow. Finally, the roundabout has the advantage of permitting a large circulating road width and can be considered as a three-lane roundabout. This provides abundant space for TWs to take full advantage of their mobility; hence, the behavior desired in the study is likely to occur.

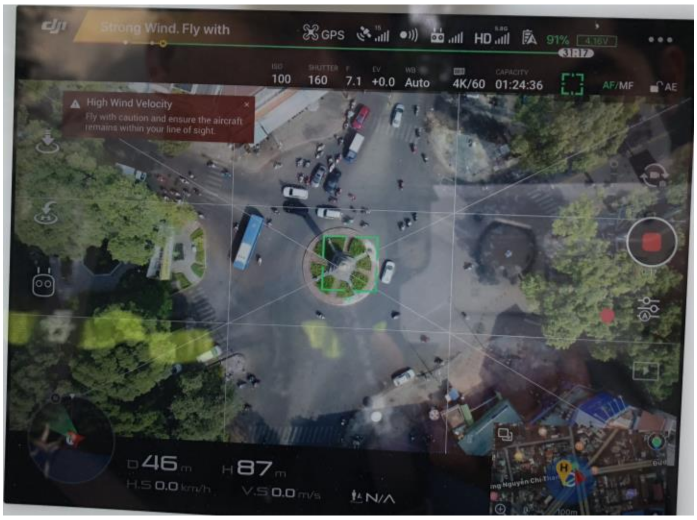


Figure 3.3. Screenshot of video recording information

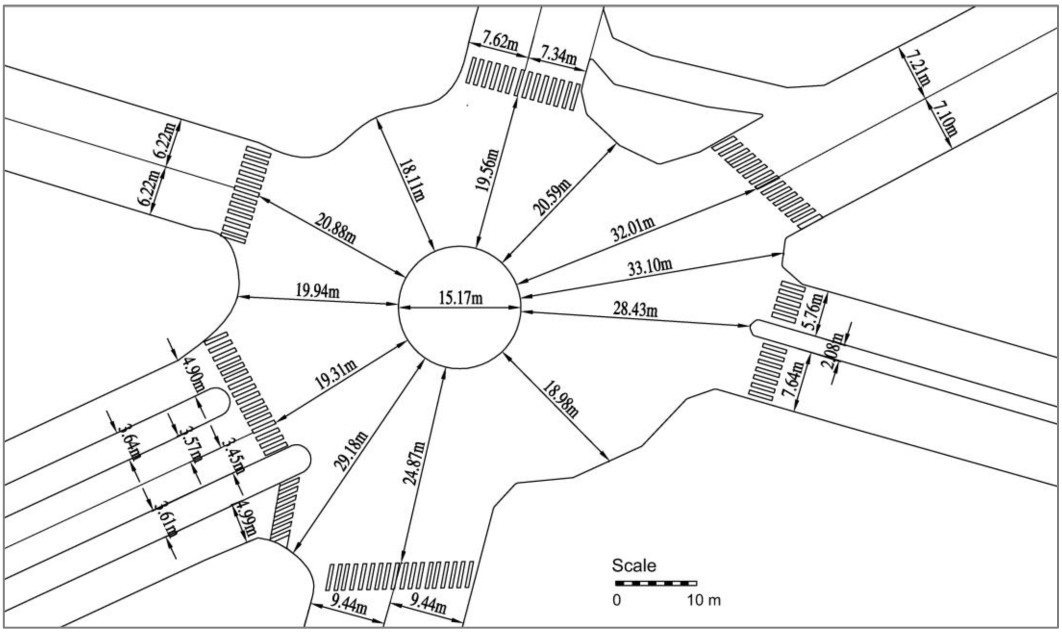


Figure 3.4. Dimensions of the surveyed site

3.1.2 Survey detail

Videos of traffic at the roundabout were recorded during the peak rush hour (9:00 AM to 10:30 AM) on March 1, 2018, as listed in Table 0.1. They were recorded using an unmanned aerial vehicle (UAV): the quadcopter DJI Phantom 4 Pro portraited in Figure 3.5. Quadcopter DJI Phantom 4 Pro devices. The UAV’s field of view covered the whole roundabout area (132.84 × 70.05 m), as shown in Figure 3.2. The dimensions of the roundabout are shown in Figure 3.4. The UAV’s height above ground level was maintained at 87 m during the recording, and the auto-adjust position was used to keep the UAV stationary above the center of the roundabout. To ensure sufficient detail, the videos were recorded in 4K ultrahigh-definition resolution, 4096 × 2160 pixels, at 60 frames per second, as showed in Figure 3.3. The spatial resolution of the captured field was approximately 0.032 m/pixel.

Figure 3.5. Quadcopter DJI Phantom 4 Pro devices

3.2 Data collection

3.2.1 Unmanned Arial Vehicle (UAV)

Traffic surveillance and monitoring has been one of the main tools for Transportation Managers and Engineers for years and an integral part of traffic management and control strategies, Papageorgiou *et al.* (2003). In order to collect visual information, stationary cameras have been a successful practice for years. Nonetheless, several practical issues emerge and require a superior collecting approach, e.g. monitoring a large area, gathering data of unexpected events at any time and location, real time surveyed data, mentioned by Puri *et al.* (2007), high cost, mentioned by Salvo *et al.* (2014b), and especially difficult to identify TW, non-lane-based vehicle, mentioned by Taniguchi *et al.* (2014). Beside stationery method, the Manned Aerial Vehicles (MAV), usually helicopters, could overcome many mentioned points. However, it is extremely costly and not always feasible due to the high risk for operators.

Nowadays, Unmanned Aerial Aircraft systems (UAS) have raised up as a novel solution that get over the shortcomings of current practices. Emmanouil N. Barmpounakis *et al.* (2016) emphasized that free-site-selection, large observation area, and top-view make it became a new effective tool. The system is also cost-effective, eco-friendlier energy Gupta et al. (2013), and a replacing method the conventional data collection using pre-installed cameras.

Compared to the conventional method as in Kanagaraj *et al.* (2015a); Vlahogianni (2014), it has four main advantages. Firstly, this method is independent from the high building, which is a thorny constraint of preceding studies. Since flying vehicles untie restriction of camera setting position, the researchers are free in choosing survey sites. It offers an opportunity to reach the previous unfavorable locations, which have no high place to set the camera or high-risk for researcher. Secondly, the adjustable flying height resolves the covered area issue. With the same field of view, higher flying height gives the wider covered area. However, the same video resolution for the wider area leads to the video's details matter. Owing to the modern camera sensor technology, video resolutions has been improved dramatically, up to 4K quality. That helps to ensure the detail in recorded videos for the large area. Thus, the size of site is not a problem anymore. The third advantage related to the accuracy of extracted information from the video. In transportation research, videos of survey site are often exploited for traffic flow characteristics, for example, speed, density, traffic flow, travel time, to name a few. The top-view of UAV camera eliminates close sight effect in video. This point is essential to increase the accuracy in data extraction. Finally, the UAV has merit of comparatively small size. It can reach to many small space area, e.g. urban areas with tall buildings. It also eliminates the intrusion while recording traffic phenomena, Emmanouil N Barmpounakis *et al.* (2016).

Despite of various advantages, Nguyen *et al.* (2019) discussed some remained drawbacks. The limited recording duration is the biggest drawback. Due to the battery capacity, the device has to land to replace battery after a period of time, around 20 minutes for the conducting device. The recorded videos are not continuous for a long duration. Others are dynamic position, engine vibration, shake due to strong wind. The researchers, who want to utilize this modern methodology, need to address all the mentioned problems.

Due to these above advantages, the UAV is employed to record the traffic data in the research project. The Phantom 4 Pro, mentioned in section 3.1.2, is a specific device that the data collection team employed. Due to the objective of microscopic behavior, the data insists on detailed and high accuracy trajectory data. The study, therefore, makes use of the semi-automatic data extraction.

3.2.2 Lens distortion

In the context of rapid development of intelligent transport, traffic monitoring depends strongly on the quality of record videos. Hence, the precision of the image has attracted more and more attention. In the technical side, the pre-processing step for collected videos has to deal with two main issues that are lens distortion and image stabilization. Accurate camera calibration of an imaging device is extremely important, especially in various applications that involve quantitative measurements. The vibration effect, which is the main issue of stabilizing image, has been minimized by a component named gimbal and stabilizing algorithms in software. DJI (2017) mentioned that three-axis gimbal on Phantom 4 Pro provides a steady platform for setting the camera. The stabilizing utilizes artificial intelligence and machine learning technique to reduce the negative shaking effect. While the stabilizing image has been minimized by both hardware component and software solution, the lens distortion is an innate hardware problem of the lens. Software solution has been the only possible solution so far.

3.2.2.1 Definition

Peatross and Ware (2015) defined lens distortion, other names are fish-eye effect or radial distortion, as a visual aberration that the magnification of a photo varies depending on the distance to the center of a photo. In other words, the photo is stretched or compressed as it approaches the edges of the frame, as stated by Dobbert (2013). As the field of view becomes larger or smaller, the magnification from the center to corner of a photo also changes much faster. Peatross and Ware (2015) stated that there are two common types of distortion, “barrel” and “pincushion” as exposed in Figure 3.6(b) and Figure 3.6(c). Barrel distortion is observed if the magnification decreases as the distance from the center increase. The image, therefore, is compressed at its corners. On the other hands, when the magnification increases from the center outwards, it called pincushion distortion. The effect results that a straight line out of optical axis of the object is imaged as a curve not a straight line any more.

Dereniak and Dereniak (2008) explained the cause of lens distortion is the position of aperture stop and the lens in the image space. When the aperture stop is in front of the lens, the image is distorted in barrel manner. On the opposite, when the aperture stop stands in the back of the lens, pincushion distortion is formed. Dereniak and Dereniak (2008) mentioned that beside the distance of aperture stop, aperture size also contributes to the magnitude of distortion. This factor is represented in the value of focal ratio, which determines the field of view size. Focal ratio also is called in other names, f-number, f-ratio, f-stop, or relative aperture. When aperture size becomes larger, the magnification from center to corner of a photo also changes much faster, the more severity of distortion results in photo.

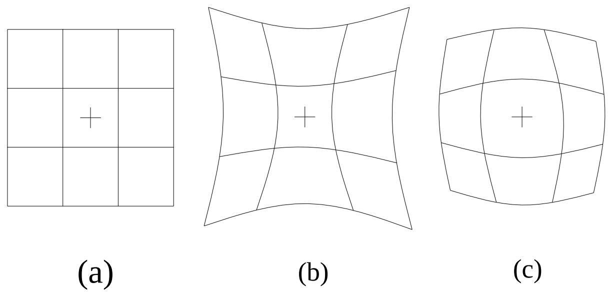


Figure 3.6. Distortion category, (a) normal object, (b) pincushion distortion, (c) barrel distortion by Dereniak and Dereniak (2008)

3.2.2.2 Experiment procedure

The paper uses a unique method, which is a similar manner to Shah and Aggarwal (1994), in order to estimate the distortion of the lens system in DJI Phantom 4 Pro. The procedure is presented in this section as the following. The first step is designing and printing sheet in A0 paper size, 841×1189 mm. The sheet, which is used as a target for a camera shot, includes parallel horizontal and vertical crossing lines, as in Figure 3.7. The distances between these lines are fixed value, 0.01 m. In the second step, the target sheet is pasted on a flat and vertical surface, the wall, for example. The importance is to ensure the flat and vertical of the paper on the wall. The third step is setting up the DJI Phantom 4 Pro in a tripod to satisfy the constraint that the center of camera has the same height with the center of the target sheet. To ensure the parallel between the sensor of the camera and the target sheet plane, several test shots and careful adjustment is required. In the fourth step, the whole sheet is shot in a range of preset focal ratio. The photo resolution is set as same as recording value, 3840×2160pixels, 4K quality.

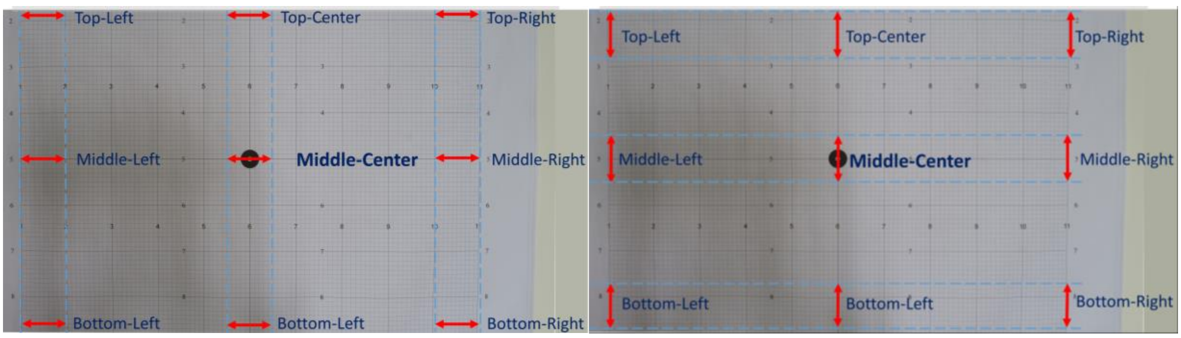


Figure 3.7. Horizontal and vertical measurement from the target sheet

These photos are lately processed in Adobe Photoshop software. For each focal ratio value, the length of a fixed segment, 0.1meters, at nine spread positions in these photos are measured in pixel. The difference in length is an indication of the degree of lens distortion. Dobbert (2013) stated that a light passes through the center of the stop is the least bending light. It means that the length at the middle-center position is not affected by lens distortion. Therefore the study compares the length in middle-center position with the other positions in both horizontal and vertical direction. Figure 3.7 depicts the measuring position and direction in taken photos of the plaid sheet. The variation of the number of pixels of the fixed-line segment between two positions is the error caused by distortion as in the following formula,

$$error = \frac{l_i - l_{middle\_center}}{l_{middle\_center}} \times 100\% \tag{3.1}$$

where,

l_i : the number of pixels of the line segment at position *i*

l_{middle_center} : the number of pixels of the line segment at position middle-center

3.2.2.3 <u>Measurement result</u>

From the process of following the steps above when applying to the Phantom 4 Pro device, the following results with the focal ration F/7.1 are obtained when the camera is set to record the results at an intersection as Table 3.2 and Table 3.3. The results show that all of the values are negative and tend to become larger in the corner of the sheet, the farthest position from the center. That matches the theoretical explanation of barrel distortion. The largest values of horizontal and vertical approaches are -3.4% and -2.7%, respectively. Both of them are in the same corner of the target sheet. These errors are included, lens distortion of the camera, flatness of target sheet plane, print system error, and human error. Among them, lens distortion contributes to the highest proportion of total error.

Table 3.2. Measurement of lens distortion in horizontal at focal ratio F/7.1

	Length of segment (pixel)			Error compare with the Middle-Center		
	Left	**Center**	**Right**	**Left**	**Center**	**Right**
Top	408	411	406	-1.0%	-0.2%	-1.5%
Middle	398	412	400	-3.4%	-	-2.9%
Bottom	408	411	398	-1.0%	-0.2%	*-3.4%*

Table 3.3. Measurement of lens distortion in vertical at focal ratio F/7.1

	Length of segment (pixel)			**Error compare with the Middle-Center**		
	Left	**Center**	**Right**	**Left**	**Center**	**Right**
Top	408	406	411	-1.2%	-1.7%	-0.5%
Middle	407	413	411	-1.5%	-	-0.5%
Bottom	408	412	402	-1.2%	-0.2%	*-2.7%*

In order to calibrate the camera, the distortion is estimated under the entire range of focal ratio of the camera, from F/2.8 to F/11.0. Each ratio value is estimated in the same process of the F/7.1. The summary result of lens distortion measurement is shown in Table 3.4. As in the result, even though there is some noise, the smaller value of focal ratio still results the higher error. From F/2.8 to F/11.0, the average errors gradually decrease. That matches with the optics theory, the smaller the focal ratio the more severe the fish eye effect in video. The focal ratio F/2.8 has the highest error and too far to other ratios.

Table 3.4. Summary error of lens distortion measurement in range of focal ratio

	F/2.8	**F/5.0**	**F/7.1**	**F/9.0**	**F/11.0**
Average error in vertical (%)	-1.6	-1.0	-1.0	-0.7	-0.9
Maximum error in vertical (%)	-6.8	-2.7	-2.7	-1.9	-2.2
Average error in horizontal (%)	-0.7	-1.7	-1.6	-1.7	-1.6
Maximum error in horizontal (%)	-4.3	-4.1	-3.4	-4.1	-3.4

In this study, the collected videos are recorded at the focal ratio F/7.1, as exposed in Figure 3.3. The error caused by lens distortion is examined to be below 3.4%. This value higher than the calibrated error after correcting, 1.6%, mentioned by Shah and Aggarwal (1994). However, it is not high enough to require an image correction process.

3.3 Data extraction

3.3.1 Methodology

Numerous UAV-based studies, specifically for traffic analysis, have been conducted in the past few years, e.g. Coifman *et al.* (2006). They can be generally broken down into two groups according to the video processing technique, i.e. (i) manual or semi-automatic data extraction and (ii) automatic data extraction. Khan *et al.* (2018) stated that the former group, the semi-automatic approach, has shown high accuracy, but requires a great deal of time for processing. Vehicles have to be detected and tracked by experimenters for a number of frames. As a representative for the group, Salvo *et al.* (2014a) used UAV to observe a stop-controlled intersection and determines the gap-acceptance, waiting time of vehicles from the videos. Salvo *et al.* (2014b) also extracted flow rate and velocity from UAV-acquired data. Emmanouil N Barmpounakis *et al.* (2016) extracted vehicle trajectories and various traffic parameters with high accuracy.

Besides the semi-automated approach, the automatic approach promises a quick processing and analysis procedure. A number of studies using the state-of-the-art object detection and tracking algorithm to get trajectories data and traffic parameters, included Khan *et al.* (2017); Jiří Apeltauer *et al.* (2015); Gao *et al.* (2014); Oh *et al.* (2014); Zheng *et al.* (2015). However, the detail and accuracy of trajectory data is now unsatisfied for microscopic behavior analysis.

In the dissertation, vehicle trajectories were extracted from the videos using a semi-manual data extractor software named Trajectory Extractor, made by Lee et al. (2008). The software is highly accurate and can reliably extract precise trajectories. As Wong et al., (2016) remarked, the vehicle trajectory dataset offers innovative opportunities to investigate heterogeneous traffic characteristics at various levels of traffic density, such as lane choices, lateral position distribution, and spacing distribution.

Figure 3.8. A sample screenshot of data extraction process

This method is time-consuming and not the state-of-the-art approach. The human power per time ratio is approximately 1:100. It means that 1-hour-video data cost 100 hours of an expert to extract data. However, it ensures the accuracy of data by eliminate the effect of small UAV’s small motion and reduce the mis-detection error in automatic extraction algorithm. And it is appropriate to observe the microscopic behavior of the chaos traffic flow in a short time period.

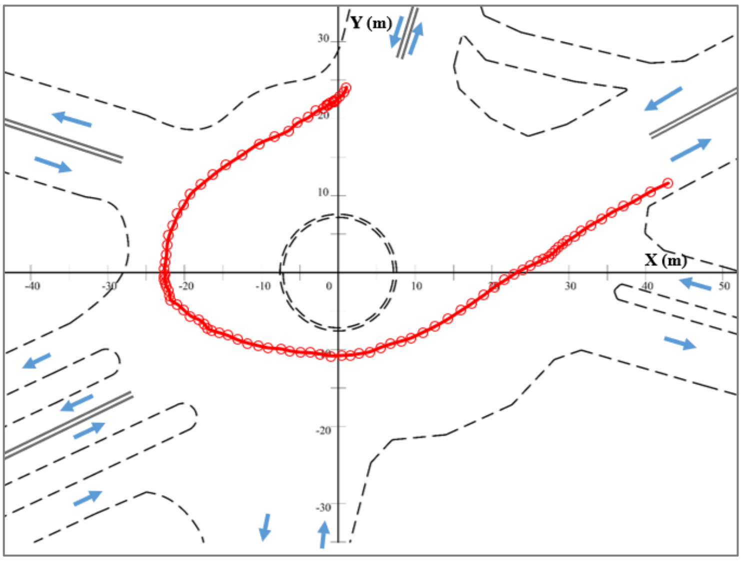


Figure 3.9. Sample of reconstructed trajectory from extracted data

3.3.2 Accuracy of extracted data

Follow a manual video-based data extraction method, a 40-inch monitor (3840 × 2160 pixels) was used to detect the positions of vehicles at each frame of the videos. For each period of 30 frames, the experimenter clicks once at the vehicle on the video. Based on the attached coordination system, the XY coordinates of the position are calculated. In order to eliminate the error caused by UAV's small motion, the coordination system is updated manually in accordance with the change in the scene. The final combination of all the detected locations on the XY coordinate system formed the trajectory of the vehicle's movement. Under the assumption that the human detection error on the monitor was 0.001 m, the accuracy of the extracted data was approximately 0.14 m. This value is much smaller than other studies using automatic data extraction method, e.g., 0.5-0.6m by Kim *et al.* (2019), 0.54m by Guido *et al.* (2016), and 1.045 m by Jiri Apeltauer *et al.* (2015).

The time step for the data extraction process was chosen to capture all changes in drivers' behavior. In association with the general driver's response duration, Koppa (1975) described perception and reaction time of car's drivers as log-normally distribution, mean 1.3 s and standard deviation (STD) 0.61 s. Lerner et al. (1995) lately proposed a shorter reaction time, 0.54 s, for evasive maneuvering. Green (2000) reported that the fully aware driver took 0.7 - 0.75 s to brake. Schweitzer *et al.* (2007) stated the experiment results on total braking time as mean 0.678 s and STD 0.144 s. Svetina (2016) mentioned that the reaction time was relatively constant across age in the single-task condition and the smallest mean is 0.59 s. In specific surveys for TW, Tang (2003) concluded the response duration ranges from 0.7 to 0.9 s. Minh *et al.* (2007b) found from the extracted data in HCM that the mean and STD of reaction time distribution was 0.79 and 0.24 s. From the above reasons, the value 0.5 s could be considered as reasonable and, therefore, is chosen for data extraction.

Table 3.5. Accuracy of extracted data follow manual video-based data extraction approach

Monitor	Size (pixel)	Size (Inch)	Size (m)	Pixel dimension (inch)	Pixel dimension on monitor (m)	Field of view (m)	Convert 1mm on monitor to ground truth (m)
Diagonal	4406	40					
Height	2160	19.61	0.50	0.00908	0.00023	70.05	0.14
Width	3840	34.86	0.89	0.00908	0.00023	132.84	0.14

3.4 Macroscopic Characteristics

The macroscopic level focus on the entire flow characteristics like traffic flow, stream phenomena, density, and mean speed of traffic stream. They are frequently observed by former studies. This section concentrates on the three macro-characteristics, traffic flow, speed, and area occupancy.

3.4.1 Traffic flow

While collecting data, the flow was classified into two groups: TWs and cars. Cars in this study included all four-wheelers, including buses and trucks. The traffic flow of each vehicle entering approach was counted, as shown in Table 3.6. TWs dominated (~90%) for all the entry approaches. This result is similar to those of previous studies performed in Hanoi and HCM City. For example, Huynh (2016) reported a TW proportion of 95.7%. Moreover, the Origin–Destination (OD) matrix of entry and exit at the survey site is presented in Table 3.7. It is easy to recognize the flow of the main roads, where traffic enters and exits along the same road. These roads contribute significantly to the total flow (>50%) and are represented by the flow from approaches 1 to 4, 2 to 5, and 3 to 6.

Table 3.6. Traffic flow of entering approaches

Approach	Duration	Traffic flow (vehicle/h)	Proportion (%)
1	TW	2748	89.11
	Car	324	10.51
	Others	12	0.39
2	TW	1620	91.84
	Car	132	7.48
	Others	12	0.68
3	TW	2748	93.85
	Car	156	5.33
	Others	24	0.82
4	TW	3612	90.94
	Car	288	7.25
	Others	72	1.81
5	TW	2172	93.30
	Car	144	6.19
	Others	12	0.52
6	TW	3108	91.84
	Car	264	7.80
	Others	12	0.35

Others: includes bus, truck, van, bicycle.

Table 3.7. OD Matrix of the survey site

		Exiting Approach					
		1	**2**	**3**	**4**	**5**	**6**
Entering Approach	**1**	-	3.9	17.9	60.3	9.6	8.3
	2	3.0	-	0.0	18.5	48.9	29.6
	3	28.1	0.5	-	3.1	8.7	59.7
	4	64.1	18.9	4.3	-	0.7	12.0
	5	18.8	64.1	14.9	2.2	-	0.0
	6	5.8	19.7	47.1	23.9	3.5	-

Unit: %

3.4.2 Speed distribution

Speed is one of the important macro characteristics. In order to calculate speed distribution, 13600 data collected points, 360 TWs form 6 approaches are tracked. TW is tracked inside roundabout from the entering to the exiting moment. Collected locations cover the whole roundabout not a specific location. The travel speed is calculated based on TW traveling distance in each 0.5 seconds. Even though assigned at the spot, the speed represents for traveling speed of the segment. The speed distribution graph is shown in Figure 3.10. The calculated average speed is 3.61 m/s, standard deviation is 1.82 m/s. From the graph, the highest frequency speed ranges from 2-6 m/s and covers 77.14% cumulative.

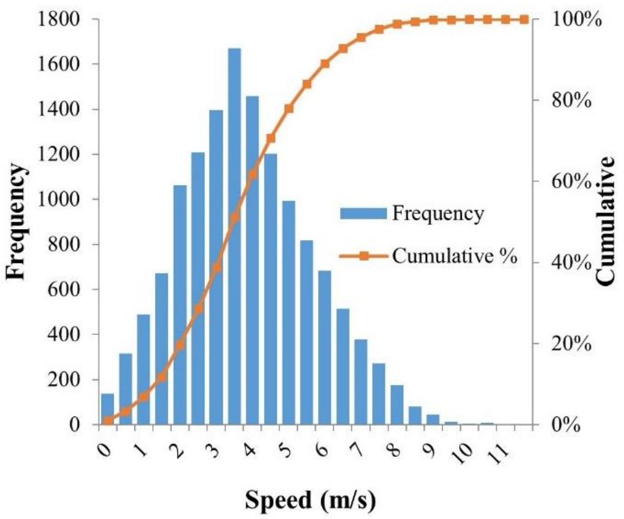


Figure 3.10. Histogram of TW speed distribution

In attempt to expose the stream speed of entering flow, circulating flow, the magnitude of speed is represented by the gradient color in the geographical background. Only the main road flow from approach 1 to approach 4 are shown in Figure 3.11. The entering flow mostly belongs to range 10-15km/h and the markers are close and light color. The exiting flow is mostly over 25km/h, which markers are dark color and sparse. The circulating flow has a wide range of speed from 10-20km/h, which has the lightest and the widest marker area. The marks of entering and circulating flow are close and mostly light color. In terms of circulating flow, while the high-speed flow concentrates closely to the central island, the lower speed flow is distributed far from the center of the roundabout.

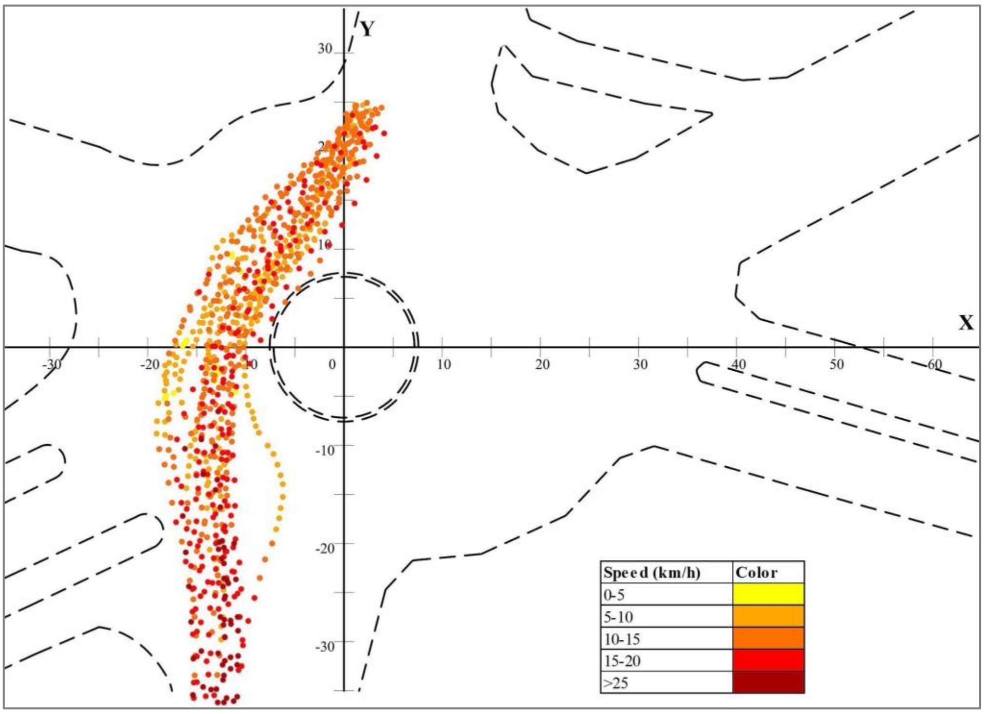


Figure 3.11. TW speed scatter diagram from approach 1 to approach 4

3.4.3 Area Occupancy

Density is one of the essential macroscopic traffic characteristics showed traffic status. Accompany level of service and delay, this indicator has been used widely in facility assessment under homogeneous traffic. The conventional density is defined in TRB (2010) as "the number of vehicles occupying a given length of a lane or roadway at a particular instant". However, in TW-oriented heterogeneous traffic scenario of Vietnam, this definition shows its weakness and inappropriate. In a wide variation of vehicle's static and dynamic characteristics, the total number of vehicles is meaning less without the composition of vehicle. Therefore, at mostly the same time, Mallikarjuna and Rao (2009) and Arasan and Dhivya (2008) developed the concept of area occupancy in efforts to overcome the density's limitation. Area occupancy considers both vehicle's width and length, thus, represent the heterogeneous traffic status competently. It also takes into account the time as the third dimension in depicting collective behavior. Kiran and Verma (2016) formally stated the definition of area occupancy is "the proportion of time the set of observed vehicles occupy the given stretch of the roadway". At mid-block, Wong *et al.* (2016) concluded that density is no substitute for by comparing for the same data set.

On the other hand, Bharadwaj *et al.* (2017) also gave a comprehensive review of several density estimation methods. However, these methods are proper for mid-block only and face difficulties for the roundabout. Due to the study case, roundabout, and data collection method, recording videos by UAV, the area occupancy again shows its appropriateness. Thus, the study adapts Kiran and Verma (2016) definition to calculate the area occupancy. The result of this study site is 0.36, calculated by the following formulation,

$$AreaOccupancy = \frac{\sum_i t_i a_i}{TA} \tag{3.2}$$

where,

t_i - occupancy time, time during a stretch of the roadway is occupied by vehicle *i* in second;

a_i - projected area of the vehicle *i* on the road surface in square meter;

T – total observation period in second;

A - total area of the entire roundabout road surface under observation in square meter. The total area includes entire road surface of roundabout from the edge of pedestrian zebra crossing and exclude the unused central island area as exemplified in Figure 3.12.

Figure 3.12. Total area of the roundabout

The area occupancy of this study site is 0.0974 with standard deviation 0.0115. The highest value is 0.1120. This value is much higher than the highest value from Wong *et al.* (2016), 0.21. However, this distinction could come from the difference between the study case, between roundabout and mid-block.

No.	Motor Area (m^2)	Total Motor Area (m2)	Car Area (m2)	Total Car Area (m2)	Roundabout Area (m2)	Area Occupancy
1	1.32	107791.00	8.05	107791.00	2650.50	0.1120
2	1.32	120400.00	8.05	120400.00	2650.50	0.0858
3	1.32	115517.00	8.05	115517.00	2650.50	0.0943
4	1.32	115679.00	8.05	115679.00	2650.50	0.1067
5	1.32	115059.00	8.05	115059.00	2650.50	0.0883
					Mean	0.0974

3.5 Microscopic Characteristics

The microscopic level concentrate on the individual characteristics or the detail of vehicle's movement, including headway, individual speed, spacing, lateral position, lane usage, individual travel time, Wong *et al.* (2016). They are much more suitable for obtaining a comprehensive understanding of the interactions, behaviors, and mechanisms of decision-making processes. The microscopic characteristics are far more practical and meaningful for understanding and modeling vehicle movements than the macroscopic one.

However, in a previous study on heterogeneous traffic at a roundabout in Taiwan, Lo (2017) only focused on macroscopic characteristics. The microscopic characteristics are still remaining. Therefore, the present study makes an effort to address this limitation by emphasizes on microscopic characteristics. This section presents the findings of this study, by analyzing five microscopic characteristics of TWs, acceleration and deceleration, turning angle rate and speed, critical gap, following space, and trajectory map, as described in Figure 3.13. Furthermore, the characteristics of heterogeneous traffic at the roundabout were found to be dissimilar to those of heterogeneous traffic at mid-blocks and other types of intersection, and differed significantly from those of homogeneous traffic at roundabouts.

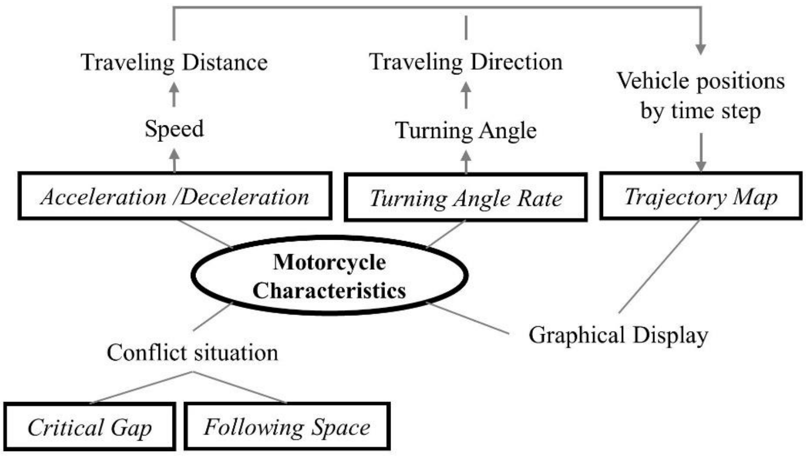


Figure 3.13. Conceptual framework of the analyzed microscopic characteristics

3.5.1 Acceleration and deceleration

TWs have a high power-over-weight ratio and are lightweight. This allows them to easily speed up or brake, which results in them continually altering their speed. The acceleration and deceleration of TW are collected and plotted as a histogram in Figure 3.14. The highest-frequency group was of those that were slightly accelerating or decelerating (from -0.4 to 0.4 m/s^2); this group encompasses 74.8% of the data. The groups of hard brake or speed up contributed to only a small part of the histogram. The groups of less than –1 m/s2 and more than 1 m/s^2 occupied only 4.2%. These findings support the characteristics of TWs, frequently altering their speed, and emphasize that the change in speed is usually minor. The deceleration in this study ranged from 0 to –1 m/s^2, whereas that reported by Minh *et al.* (2007a) ranged from 0 to –2 m/s^2. With regard to acceleration, the results of the two studies were similar, they mostly ranged from 0 to 1 m/s^2. This could be owing to the distinctive speed at roundabouts, which is 3.61 m/s on average (almost half of the average speed at mid-blocks, i.e., 6 m/s). Lower speeds result in a lower required deceleration rate under the same period of time to stop. Additionally, maneuverability is higher at lower speeds, allowing more time for the driver to react. Therefore, drivers prefer soft braking at roundabouts and hard braking at mid-blocks.

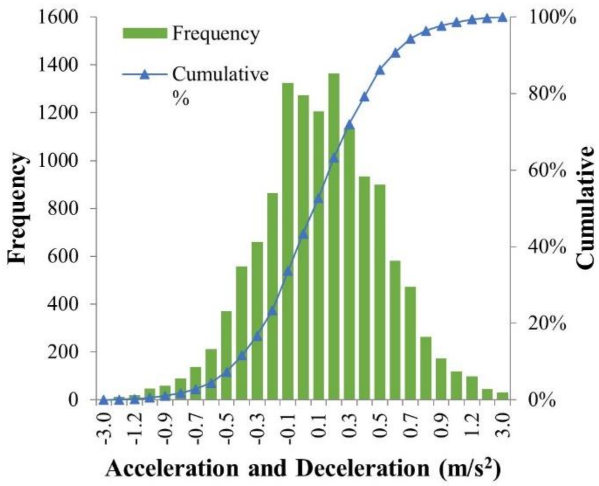


Figure 3.14. Histogram of the acceleration deceleration of TWs

The acceleration–deceleration and speed profiles of a single TW are shown in Figure 3.15. In the first 20 s, the speed continuously fluctuated between 0 and 0.4 m/s. This indicates that the driver faced complex situations and was continuously accelerating or decelerating to respond. Consequently, the TW exhibited continuous changes in both its moving direction and its speed.

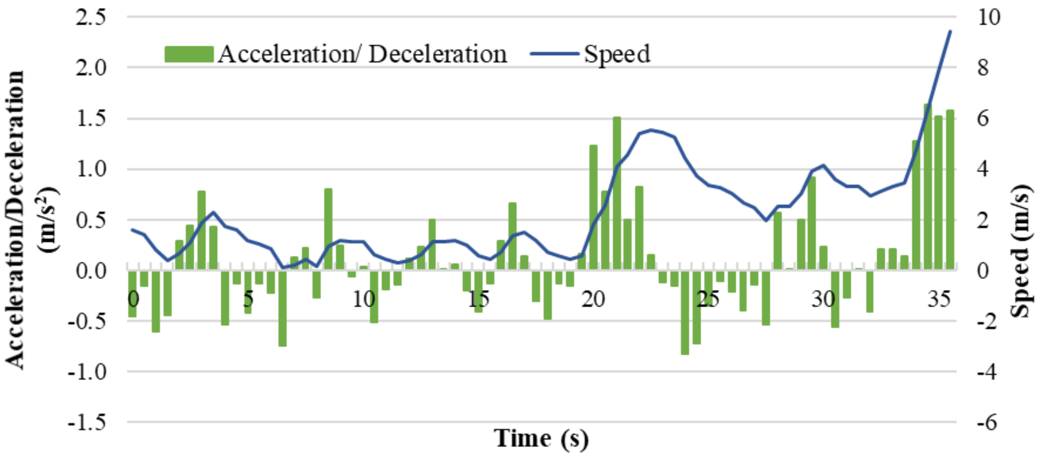


Figure 3.15. Acceleration-deceleration and speed profiles of a TW

The positions at which TWs often speed up or brake were considered. Thus, the acceleration and deceleration scatters were plotted with color gradient. An example of TWs traveling from approach 1 to approach 4 is shown in Figure 3.16. The color in the diagram represents the magnitude of the speed change. The results indicate that at the circular flow, TWs did not exhibit hard braking or quick acceleration; rather, they decelerated and slightly accelerated. At this location, the motorcyclists had already matched their speed with the flow; therefore, there were few significant speed changes.

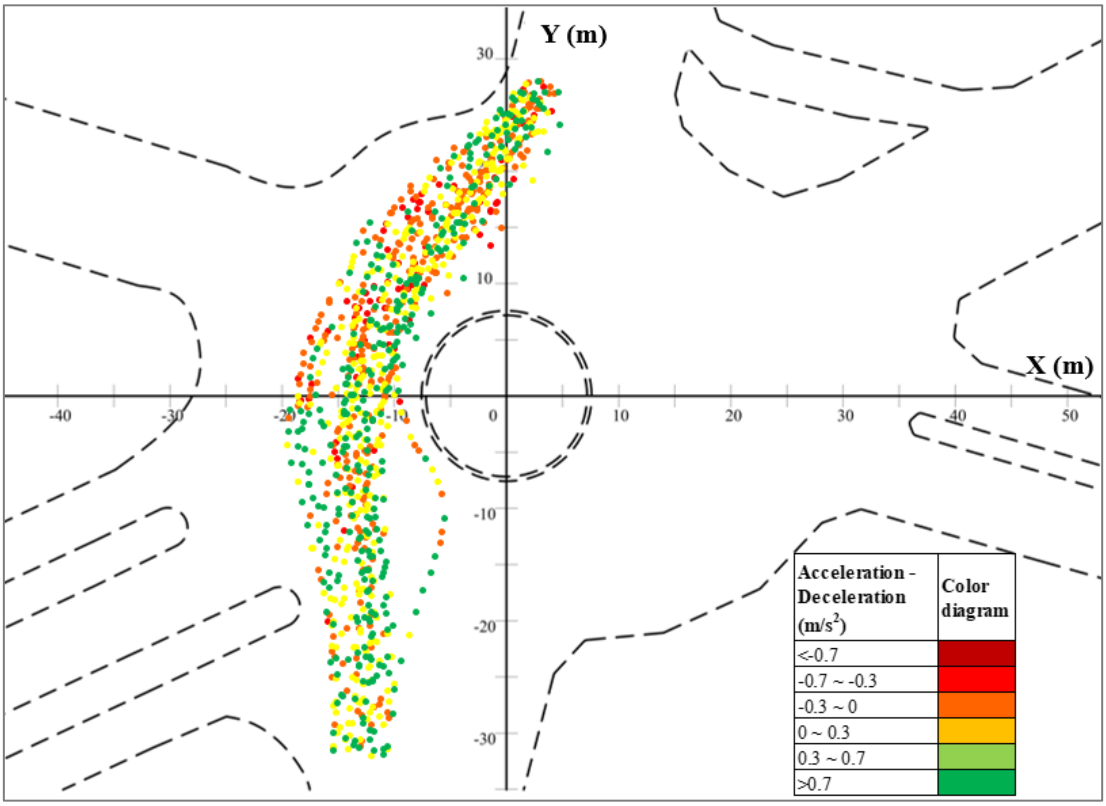


Figure 3.16. Acceleration and deceleration scatter plots

3.5.2 Turning angle rate and speed

The turning angle represents the change in the moving direction within the local frame of reference. It is not the steering angle of the handle or the front wheels but the angle between the current and previous moving directions. It is one of the key parameters of the turning process Ma *et al.* (2017). The turning angle describes the magnitude of the change in the moving direction. It was described by Lee (2007) and was called the “veering angle” by Lenorzer A et al. (2015) and the “angular velocity” by Ma *et al.* (2017). However, in none of these studies was this quantity calibrated or modeled. The present study presents the first derivative of the turning angle, which is called the turning-angle rate (T.A.R). The T.A.R is the rate at which a vehicle changes its moving approach. It is calculated as follows:

$$T.A.R = |dir_{current} - dir_{previous}| / time\_step \quad (3.3)$$

The unit for the T.A.R is degrees per second (degree/s). $dir_{current}$ represents the current moving direction in the global coordinate system. It is the angle between the unit vector which pointed of the North of the map and the speed vector of the vehicle at the calculating moment *t*. Its value is in the range [0, 360]. $dir_{previous}$ represents the previous moving direction in the global coordinate system. It is the angle between the unit vector point of the North of the map and the speed vector of the vehicle at the previous calculated frame, i.e., at time (*t - time_step)*. *time_step* represents the period of time between two frames that are used for tracking the vehicle's position (unit: seconds).

This paper presents the first examination of the relationship between the T.A.R and the speed. The maximum value of the T.A.R, which was dependent on the traveling speed, was formulated. This inspection can facilitate the calibration in future modeling studies. Figure 3.17 shows >14000 coupled data points for the T.A.R and speed. Generally, at low speeds, the T.A.R is high; the inverse is also true. At high speeds, the maneuverability of TW is limited by physic rules, e.g. owing to the inertial restriction. The driver intends to perform large-angle maneuvers at a low speed. This is also shown in Figure 3.17. Thus, the boundary of the data, rather than the central tendency, is the main focus of this investigation.

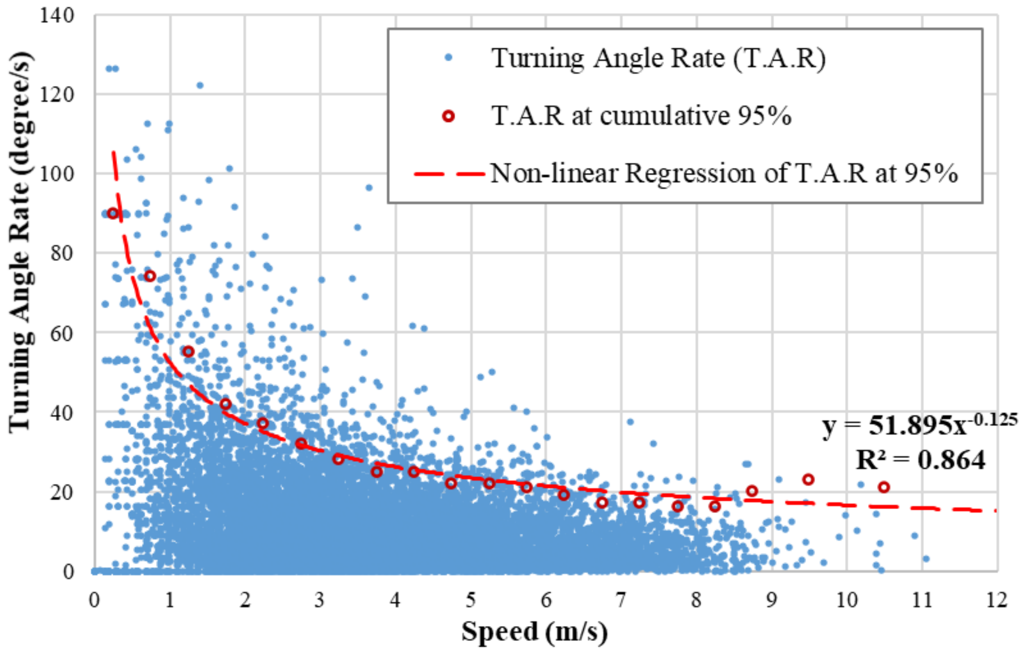


Figure 3.17.Relationship between T.A.R and speed

To clarify the relationship between the T.A.R and the speed, the data were first filtered by eliminating the most dispersed part (~5%). As the boundary of the T.A.R was the main focus, 95% of the data were considered to be valid. Binning the speed into small intervals (of 0.5 m/s) allowed the data distribution to be calculated more easily. In each interval, the representative horizontal value was the mean speed of the segment. In the vertical direction, the values of 95% of the cumulative distribution of the turning angle rate were considered to be representative values; they are displayed as red circles in Figure 3.17. These values were employed to estimate the fitting curve. The results of regression analysis and curve estimation, which were performed using the IBM Statistical Package for the Social Sciences (SPSS) software, are presented in Table 3.8 and Table 3.9.

Table 3.8. SPSS regression analysis results.

Curve estimation	R	R-Squared	Adjusted R-Squared	Std. Error of Estimate
Power	0.929	0.864	0.856	0.188
Exponential	0.776	0.603	0.581	0.321

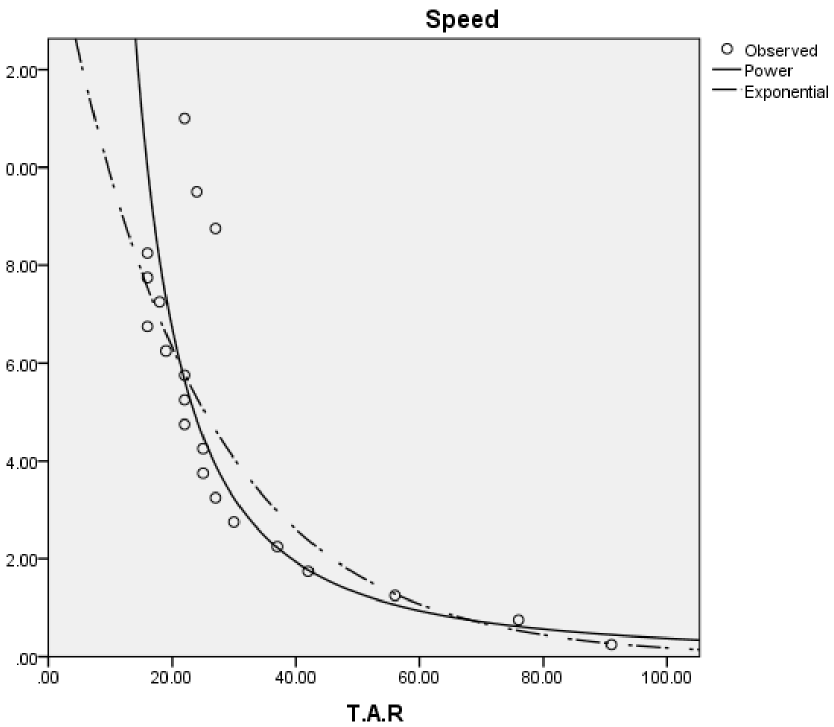


Figure 3.18. Regression result of fitting power and exponential curve in SPSS

Owing to the roughness of the data, the power curve and the exponential curve were estimated. The T.A.R and speed exhibited a very strong correlation in both cases, with R values of 0.929 and 0.776, respectively. The R-squared value for the power model was significantly higher than that for the exponential model (0.864 vs. 0.603). Moreover, the power curve is valid in speed range from 0.5 m/s to 11 m/s. When speed of vehicle becomes too small, less than 0.5

m/s, the turning angle rate will take the maximum value of turning angle rate for motorcycle, which is 90 degree/s. Regarding the exponential curve, even the curve has a good limit in both side of the speed, close to 0 and infinity, the value of the curve when speed is over 12m/s and less than 0.5m/s is unreasonable. Thus, the power model provided a more accurate estimation. The high adjusted R-squared value (0.856) confirmed that the power curve fits well with the data. The standard error of the estimation was minimal compared with the range of the T.A.R (0.188 vs. 0–140). This suggests that the error for the power-curve estimation was small. Moreover, the significance levels of the variables were close to zero and were significantly smaller than 0.05. Thus, all of our B coefficients were statistically significant. The estimated curve (the red dashed line) and its formula are shown in Figure 3.17. The maximum value of the T.A.R can be calculated as follows:

$$T.A.R = \begin{cases} 51.895\, v^{-0.125}, & v \le 0.5 m/s \\ 90, & v < 0.5 m/s \end{cases} \tag{3.4}$$

Where,

v (m/s) : represents the current speed of the vehicle.

Table 3.9. Coefficients of power regression curve estimation using SPSS

	Unstandardized Coefficients		**Standardized Coefficients**	**t**	**Sig.**
	B	**Std. Error**	**Beta**		
In(Speed)	–0.125	0.032	–0.776	–5.227	0.000
(Constant)	51.895	7.301		7.108	0.000
The dependent variable is In(T.A.R)					

The size of the roundabout also influenced the T.A.R.; a smaller central island resulted in a more significant effect of the circulating movement on the vehicle turning angle. Thus, the T.A.R of the same vehicle is higher in a smaller roundabout. For determining the maximum T.A.R (which was dependent on the speed) and utilizing this effect, the selected site, i.e., a small-sized roundabout, was appropriate.

To validate the estimated curve, the data-splitting technique Snee (1977), which is one of the accredited methods for obtaining a good internal validation Giancrisotofaro and Salmaso (2003), was employed to divide the samples into two sets. Fitting samples accounted for 75% of the original samples, and the other 25% of the samples were validation samples. Four goodness-of-fit measures, which were used for measuring simulation of heterogeneous traffic, were also utilized: the mean absolute percentage error (MAPE) Babu *et al.* (2015); Swamidass (2000), mean absolute deviation (MAD) Swamidass (2000), root-mean-square error (RMSE) Toledo and Koutsopoulos (2004); Dowling *et al.* (2004b), and root mean square normalized error (RMSNE) Hourdakis *et al.* (2003); Toledo *et al.* (2003); Ma and Abdulhai (2002). Especially, the MAPE and MAD were used appropriately to evaluate the goodness-of-fit between the predicted and actual data by Swamidass (2000).

Table 3.10. Validation results for the estimated curve

Estimated Curve	MAPE	MAD	RMSE	RMNSE
Power	0.188	4.311	5.089	0.031

The validation results for the estimated curve are presented in Table 3.10. According to Lewis' scale of interpretation for the MAPE, the model was validate as good, as the MAPE (18.8%) was in the range of 11%–20% Lewis (1982). The RMSE and RMSNE, which were 1.57 and 0.45, respectively, indicated that the overall performance of the estimated curve was good. The MAD (4.311) was small compared with the range of the data (from 0 to >100), confirming the accuracy of the estimated curve.

3.5.3 Travel time

The travel time, hereby, focuses on non-lane-based vehicles with complicated movement. It is the duration from the moment vehicles pass through the pedestrian zebra crossing to enter roundabout until the pass again to exit. The results from extracted data are presented in Table 3.11.

Table 3.11. Mean travel time of TW from real data

		Exiting Approach						Mean
		1	**2**	**3**	**4**	**5**	**6**	
Entering Approach	**1**	-	40.4	32.9	18.6	16.2	9.0	23.4
	2	8.4	-	0.0	26.5	25.1	21.2	16.2
	3	11.8	4.5	-	31.4	29.6	19.2	19.3
	4	18.9	11.9	8.3	-	29.8	36.1	21.0
	5	18.9	20.7	11.9	23.8	-	0.0	15.0
	6	25.2	27.7	22.5	12.3	4.8	-	18.5

Unit: second

3.5.4 Critical gap

The critical gap and follow-up headway are the major gap-acceptance parameters that explain the interaction of the merging flow and circulating flow at roundabouts Giuffrè *et al.* (2016). A gap is an opening distance or time in the circulating flow that an entering vehicle can exploit. When the driver of the entering vehicle refuses to merge with the circulating flow, the gap is denoted as a "rejected gap." When the driver considers the gap safe enough to merge, the gap is denoted as an "accepted gap" (Shaaban and Hamad (2018). The critical gap refers to the specific gap size for than which a driver would accept if it were larger and would reject if it were smaller. Fitzpatrick *et al.* (2013) stated that even though the accepted gap has been used as the critical gap for estimating the capacity at roundabouts by TRB (2010), it is unreasonable to ignore the rejected gap. Thus, in the present study, Raff's method Raff and Hart (1950) was used to estimate the median critical gap, in accordance with the spatial and temporal gap analysis approach of Fitzpatrick et al. (2013). Owing to the nature of the non-lane-based vehicle, the follow-up headway was unsuitable and was replaced with the following space defined in section 3.5.5.

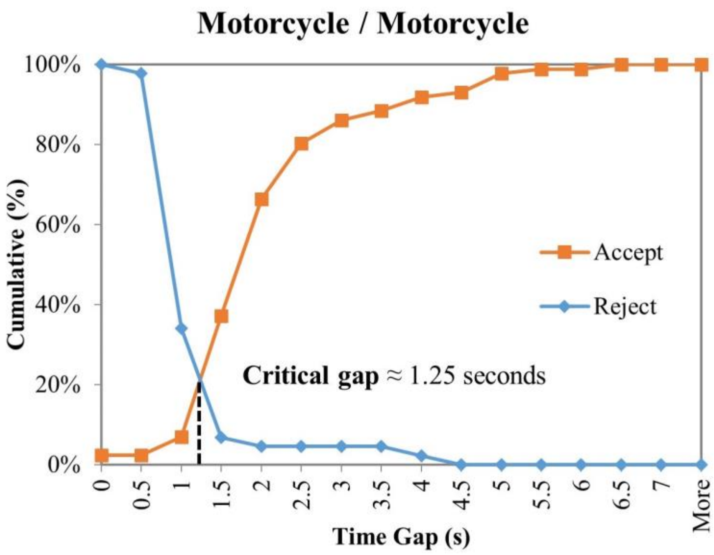


Figure 3.19. Critical gap for a TW facing a TW

The critical gap of a TW facing a TW is shown in Figure 3.19. The cumulative line of the accepted gap rises sharply in the range of 1–2.5 s. The majority of drivers (80.23%) accept the gap when it is >2.5 s. The cumulative line of the rejected gap falls significantly, even in the shorter range of 0.5–1.5 s. Most of the drivers (93.18%) reject the gap when it is <1.5 s. These shapes are similar to those observed by Dodappaneni *et al.* (2016). It can be inferred that TWs are highly sensitive to small gaps. The critical gap is the crossing point of the cumulative lines of the accepted and rejected gaps. The critical gap in the present study (1.25 s) was shorter than those previously reported Dodappaneni *et al.* (2016); Arroju *et al.* (2015). The reason could come from the conclusion of former studies Dodappaneni *et al.* (2016); Patel and Khode (2016) that the lower critical gap was found under smaller-traffic volume conditions. The TW volume in this research is about triple compared to Dodappaneni *et al.* (2016). In addition to the traffic volume, the traffic composition affects the critical gap. With a higher proportion of TWs, the critical gap is smaller. The proportion of TW in this study is higher from 4.5-36.3% compared to Dodappaneni *et al.* (2016). This once again emphasizes the advantages of TWs with regard to utilizing a small gap. Thus, it is concluded that a large traffic volume with the dominance of TWs results in a short time gap.

3.5.5 Following space

The "follow-up time," which is also called the "follow-up headway" in spatial measurements Zheng *et al.* (2012), is the longitudinal time gap between two queued vehicles entering a roundabout Dahl and Lee (2012). When considering the grouping behavior of non-lane-based vehicles, the longitudinal gap is insufficient. Thus, in the present study, both the longitudinal and lateral gaps related to the following space are considered.

TWs have the unique following behavior: they usually maintain a clear space around themselves. This behavior was first described in a study on heterogeneous traffic characteristics in mid-blocks Lee *et al.* (2009b). That study emphasized that TWs follow cars with an extremely small safety headway when traveling close to the edge of the car and with a larger headway when aligned with the center. Thus, the minimum following space from the rear of the preceding vehicle has the shape of a triangle. Even though this following space is defined by the preceding vehicle, the paper pointed out the distinctive shape of the following space. Nguyen et al. (2012) replaced the safe headway with a safety space, which had a half-ellipsoid boundary. The size of the ellipse depends on the traveling speed, the reaction time, the vehicle's dimensions, the types of vehicles, the longitudinal and lateral distances to the influential vehicle Nguyen *et al.* (2012).

This raises the question of how the following space changes when TWs approach roundabouts, rather than mid-blocks. We attempted to answer the foregoing question by calibrating the following space at the studied site. TWs were observed when they performed the following behavior. Other behaviors (e.g., when they faced conflicts) were not considered. The relative positions of the surrounding vehicles were accumulated via time series, as shown in Figure 3.20. The data were categorized into three groups according to speed. The first, second, and third groups' initial speeds were 0–2.78 m/s (0–10 km/h), 2.78–4.17 m/s (10–15 km/h), and >4.17 m/s (>15 km/h), respectively. In each time, only TWs at the first boundary, which had a significant influence on the subject vehicle, were tracked. The others, which were hidden from view, were neglected.

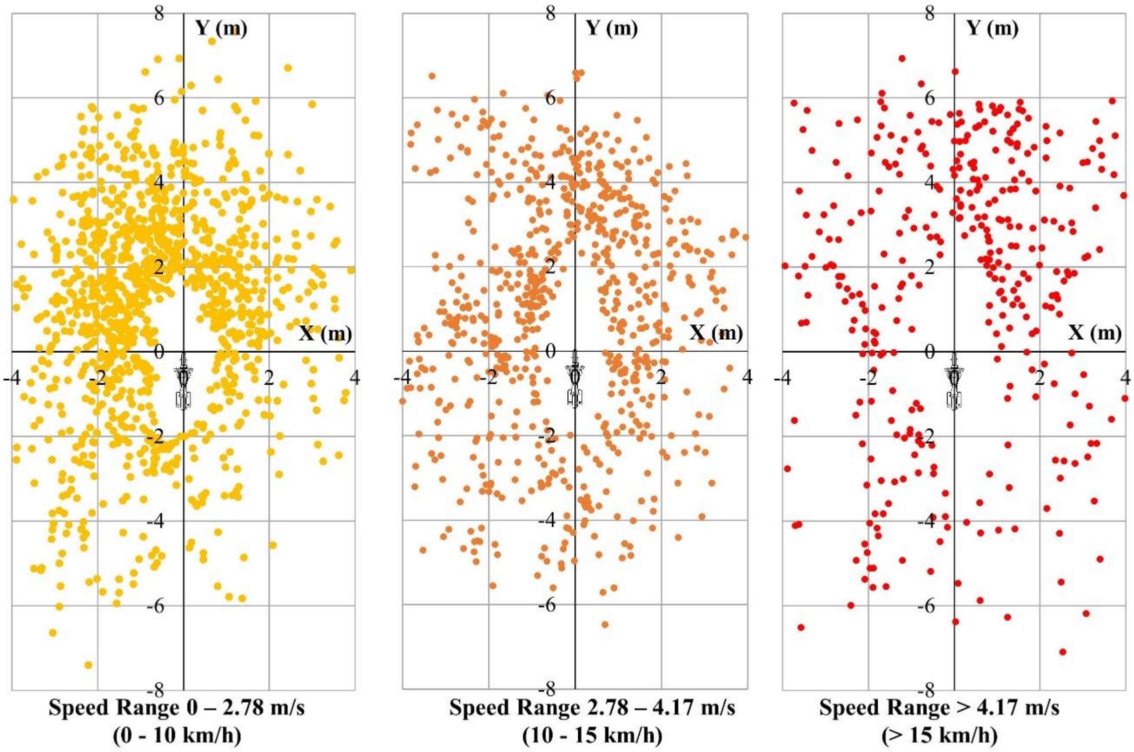


Figure 3.20. Following space of the TW

The distributions of the relative positions are shown in Figure 3.20 in the local Cartesian coordinate systems of the subject TW. All the markers in each of the graphs were tracked from the middle-front point of the vehicle. The middle-front point of the subject TW is represented by the origin (0, 0). The oval-shaped clearance in the middle of three of the graphs supports the theory of safety space. The size of this space increases as the speed increases. These results agree with the dynamic lane width reported by Minh et al. (2007) across these three speed ranges. However, compared with the size of the safety space suggested by Nguyen et al. (2012), the lateral dimension was larger and was independent of the speed (1.5 m compared with 2.6 m). The longitudinal dimension was larger at higher speeds and was also larger than that of the safety space (1.74 and 2.88 m at speed range 0-2.78 m/s and 2.78-4.17 m/s, compared with 1.39 and 2.08 m at the same speed range for the safety space).

This distinction is attributed to the speed and road type. The average speed in this study was 3.61 m/s, whereas that calibrated by Nguyen et al., (2012) was 8.33 m/s. Even though both studies were conducted in HCM City, the survey site in the present study was a roundabout, whereas previous studies focused on mid-blocks. Moreover, in the low-speed range, vehicles were denser near the boundary of the clearance, compared with the higher speed range. At higher speeds, the drivers preferred to maintain the desired gap, rather than the minimal gap. Therefore, the density at the following space's boundary was lower than that at lower speeds.

3.5.6 Trajectory map

A trajectory map was drawn by connecting the consecutive positions of the vehicles over time. Most of the vehicle trajectories were smooth, indicating that they were reasonable Figure 0.3.shows the trajectory maps of 100 TWs from approach 1 (green path) and approach 4 (red path). The trajectories were dispersed and covered the entire width of each approach when vehicles entering or exiting the roudanbout. The lateral position of each TW at any cross-section as also exposed in Figure 6.3. Moreover, the trajectories were complex and unpredictable. This is in accordance with the unique characteristics of TWs, which frequently maneuver inside the roundabout; however, it presents a challenge for conventional models to reproduce these trajectories.

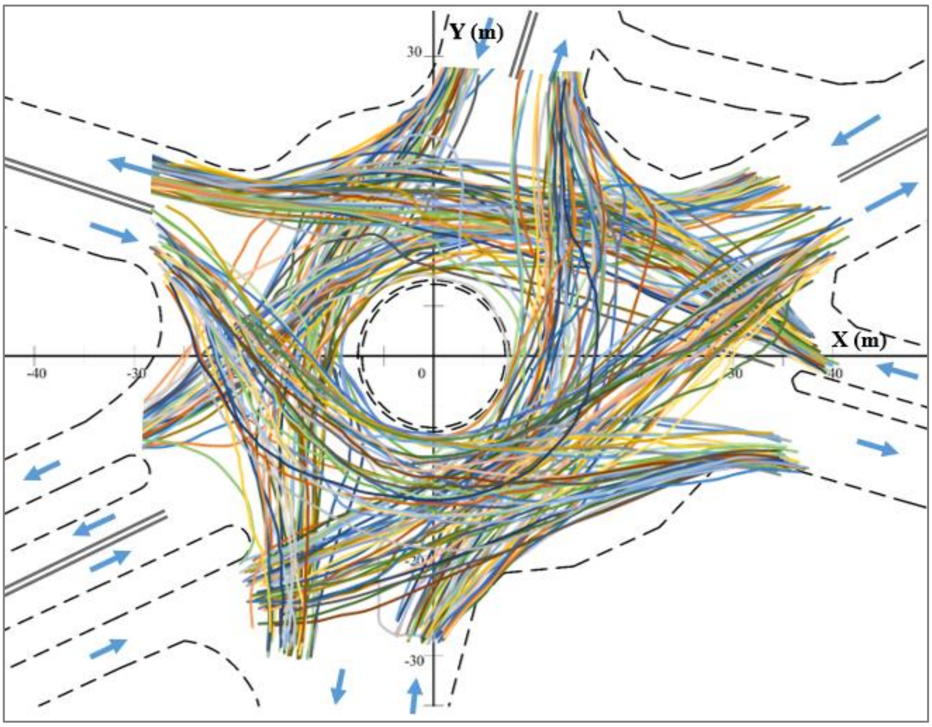


Figure 3.21. Trajectory map of 250 TWs from six approaches

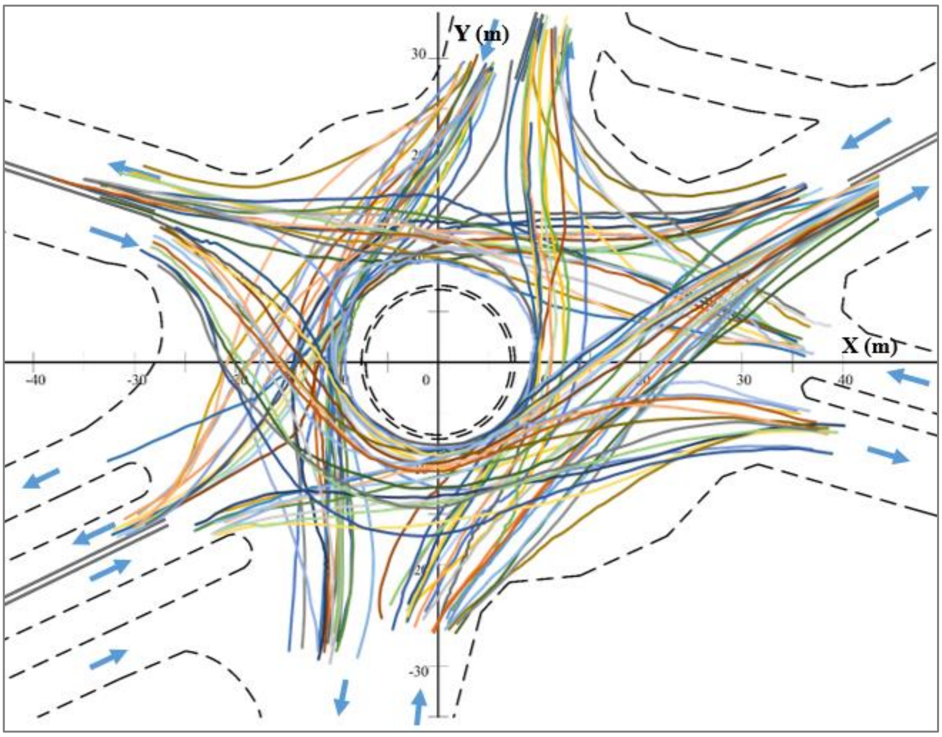


Figure 3.22. Trajectory map of 100 cars from six approaches

Chapter 4. MODEL DEVELOPMENT

This chapter makes efforts to clarify the proposed vehicle interaction model. The three main models, that are regular movement model, conflict-solving model, and collective behavior model, are constructed from the concepts, structure, formulations to the final combining. The description of each model and how they work together will be discussed in detail. This chapter contributes to the primary novelty of the study.

4.1 Preliminaries

To develop a rigorous study, the study makes the following assumptions and simplifications. Firstly, the assumptions are listed as the following,

- Generated time gap and position of vehicles are assumed to be random values and follow normal distribution.
- Vehicle only recognizes and interactions with other vehicles inside its observation zone or conflicting groups.
- Solving conflict to avoid the crash has the highest priority in the decision-making process. The grouping behavior is the second order of priority.

Secondly, some simplifications in the model are,

- Vehicles react based on the collected information of the surrounding environment without considering the drivers characteristics (gender, age, driving skill, emotion, fatigue, alcohol, drugs, personality, personal intention).
- The reaction is made independently after a period of time step, based on the collected information at that moment.
- In order to deal with the continuity of time, time is partitioned into discrete time steps, 0.1 seconds. The value is much smaller than driver reaction time, reviewed in section 3.3.2. When all the discrete time steps are connected in its order, it becomes a series of times steps. If the period of time step is small enough, hereby enough to capture the driver's reaction, it could be considered as a continuous time flow.
- The vehicle’s movement is controlled by two variables, speed and moving direction. After every time step, the vehicle’s position is updated based on how fast - speed - and which way - moving direction - it moves. Thus, the developed simulator focus on formulas calculating these two parameters.
- The model’s outputs are acceleration and turning angle. These two parameters control the value of speed and moving direction. Thus, the model focus on calculating these parameters after every time step.
- In the conflict-solving model, the acceleration and deceleration duration between stop status and the current speed is ignored. In order to reduce the sophistication and improve the applicablity of the model, the vehicle is simplified to has two states, stop or traveling

at current speed, without transition state. In other words, in the space-time diagram of each angle, vehicle's movement are forecasted by only straight segments, not by curves.

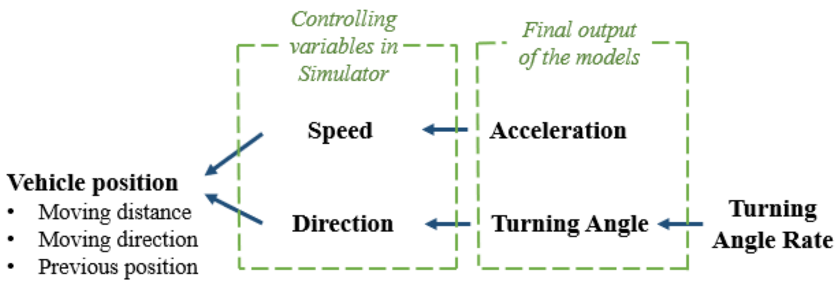


Figure 4.1. Parameters in simulator and model's output

4.2 Regular movement model

4.2.1 Movement phases

By and large, without any interruption, vehicles from entering flow usually go through three moving phases before exiting to another approach. They are merging, circulating, and diverging one after another, as exposed in section 2.2.3. The sequential three phases can sometimes be shortened due to positions of entering and exiting approach, for example, flow from approach 1 to 6. When ranges of these phases are overlapped, the later phase has a higher priority. This section devotes how to determine moving phases for entering approach 1 in detail, based on the observation of the trajectory map and the following simplifications. Other approaches have used the same method and simplifications.

In entering approach 1, the entering flow, except for exiting approach 6 – from approach 1 to 6, firstly merging with the circulating flow inside the roundabout. The merging zone results are simplified that at the vehicle at the road divider in entering approach finishes merging phase at the tangent point at the curb of the central island, as the green line in Figure 4.2. The thick green line from the center of the roundabout is the separated line for the merging phase of entering approach 1. This separated line is matched with the collected trajectory from the real data. After the merging phase, the vehicles start the circulating phase. This phase is the middle between merging and diverging phases. Its range is, therefore, the remaining space between the two phases.

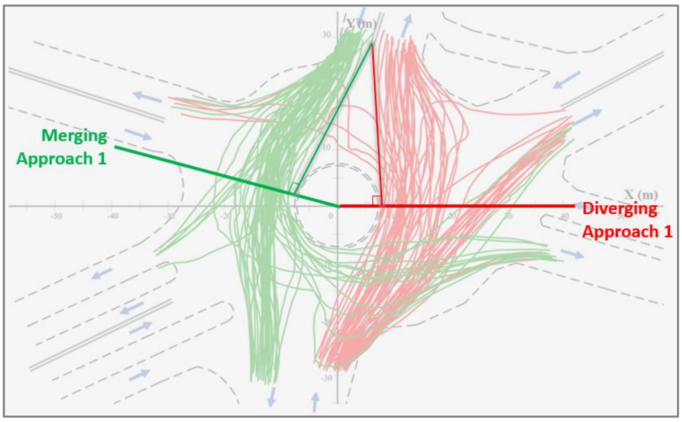


Figure 4.2. Separated line for merging (green line) and diverging (red line) area of approach 1

The third phase before exiting is diverging. The zone of this phase for approach 1 is determined by the similar manner with entering approach. The vehicles at the curb of the central island result in the position of road divider in the exiting approach as the thin red line in Figure 4.2, Figure 4.3. The thick red line from the center of the roundabout crossing tangent point of the red line is the separated line for the diverging phase of exiting to approach 1. This separated line is also applied for vehicles from other approaches exiting to approach 1.

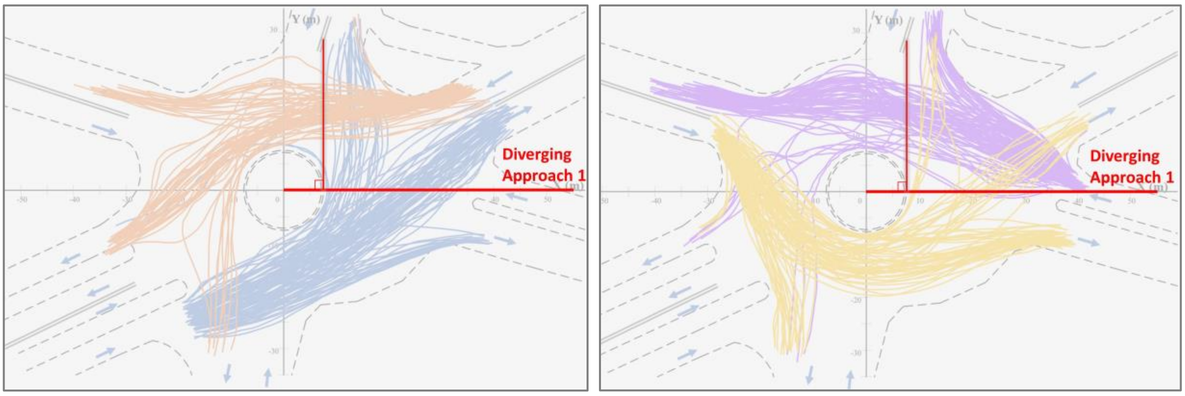


Figure 4.3. Separated line (red line) for diverging area of approach 1 from approach 2, 4, 3, and 6

A similar manner to determine the merging and diverging zone is also employed for the other approaches. The examples are illustrated for approach 2 in Figure 4.4 and approach 3 in Figure 4.5.

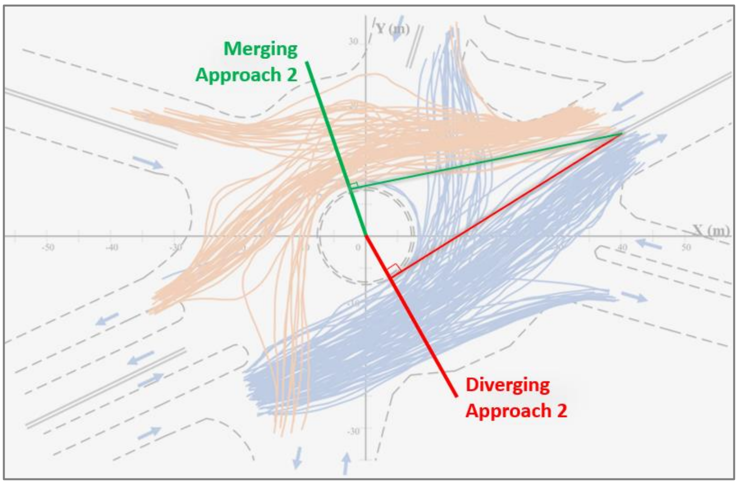


Figure 4.4. Separated line for merging (green line) and diverging (red line) area of approach 2

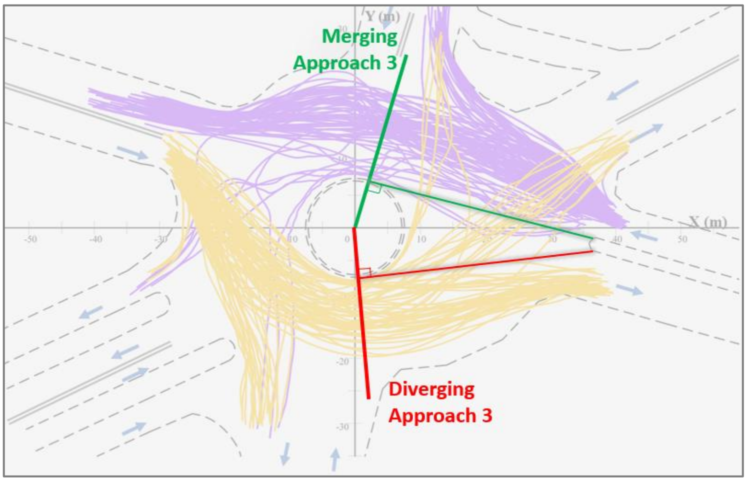


Figure 4.5. Separated line for merging (green line) and diverging (red line) area of approach 3

4.2.2 Desired direction

The desired direction, more detail in section 4.2.2, is the direction guides the vehicles moving inside roundabout to reach the destination. This direction is updated after every time step based on the moving phase, current position, velocity, moving direction, and entering and exiting approaches. Following this direction, the resulted trajectory of TW is the most referable path from the origin to the destination.

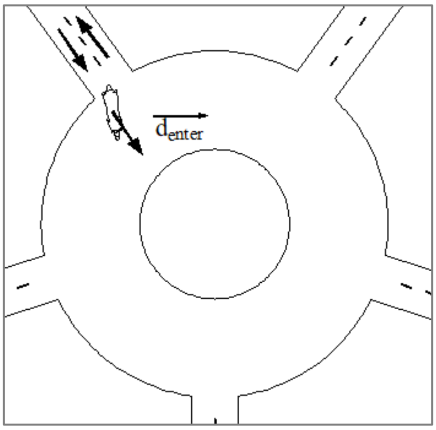


Figure 4.6. Entering direction of the merging phase, a vector has similar direction with the entering approach.

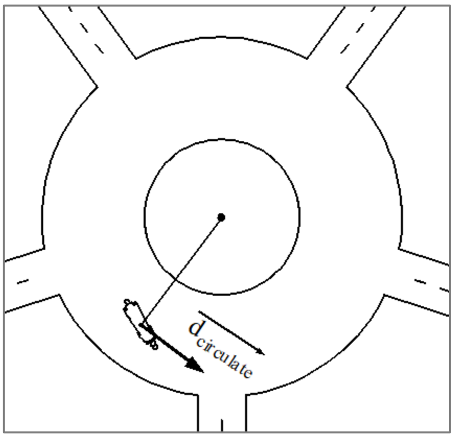


Figure 4.7. Circulating direction of the circulating phase, a tangent vector of the virtual circle going through the current position of individual i and centered on the center of the roundabout

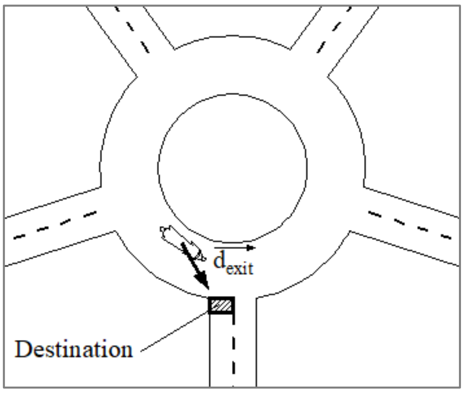


Figure 4.8. Merging direction of the merging phase, face towards the destination.

The desired direction is calculated as the following equation,

$$\overrightarrow{d_{desired}(t+\tau)} = w_4\,\overrightarrow{d_{enter}} + w_5\overrightarrow{d_{circulate}} + w_6\overrightarrow{d_{exit}} \tag{4.1}$$

where,

w_4 : the weighting term of the entering direction
d_{enter}: entering direction, the direction leads vehicle go inside the roundabout. It has similar direction with entering approach
w_5 : the weighting term of the circulating direction.
$d_{circulate}$: circulating direction, the direction that makes an individual move around the circle (circular motion). This direction parallels with the tangent line to the positional circle and faces towards the moving way. The positional circle is the virtual circle going through the current position of individual *i* and centered on the center of the roundabout.
w_6 : the weighting term of the exiting direction.
d_{exit}: exiting direcion, the direction leads the vehicle go out of the roundabout. It starts from the center of the vehicle and faces towards the destination.

4.3 Conflict detection

4.3.1 Anticipation movement approach

The anticipation movement is the intended trajectory of a vehicle with a constant velocity and moving direction during the anticipation period *T*. In calculation procedure, TW takes into account its surrounding conditions such as the movement in the anticipation period *T* of other vehicles. During the anticipation period *T*, all TWs are assumed that they will consistently move in the same direction and velocity as time *t*. This idea is assigned to the simulation by using the environmental layer. Specifically, each vehicle inside the intersection has its own anticipation line, drawn in the environment layer. It is a straight line from the middle point of the vehicle towards the moving direction. The length of this line equals the anticipation movement length, which is calculated as the following equation,

$$L_{anticipation} = T \times V_{current} \tag{4.2}$$

where,

$L_{anticipation}\ (m)$: the anticipation movement length

$T = 1.5\ seconds$: the anticipation period

$V_{current}$: the velocity at the calculation time

The cross between two or more anticipation lines is the sign of the conflict area. The crossing point is employed as an indicator of the potential accident recognition, as exemplified in Equation (*4.2*). The presented conflict detection technique is classified as a nominal projection method Daalen (2010). The method remains a main limitation in that a conflict could likely be missed. The developed simulator overcomes this limitation by setting a small time step of 0.1 seconds, which means increasing the frequency of searching and reducing the likelihood of missing a conflict. Thus the simulation using the crossing point as an indicator for conflict area recognition due to its simplicity and effectiveness. This manner is exemplified in Figure 4.9.

The position of the TW is considered the center point. For this reason, both the accident and conflict areas are parallelograms. The accident area, which is the potential crashing area of two TWs, is contributed to by the lateral dimensions of the two conflicting TWs. The conflict area is contributed to by the longitudinal dimensions of the two conflicting TWs. This area limits the conflict with the entrance and exit positions of the conflicting TWs. Here, l_{11} and l_{12} indicate the distances of the subjective TW *i* at its current position to the entrance and exit positions of conflict area 1. These positions are determined when the front and rear of the TW reach the accident area. The times during which the TW *i* travels distances l_{11} and l_{12} are t_{11} and t_{12}. Similarly, l_{21} and l_{22} are the distances of the subjective TW *i* from the current position to the entrance and exit positions of conflict area 2, and t_{21} and t_{22} correspond with the traveling period. This is mostly the same for the conflicting TW *j* as l_{j1} and l_{j2}, and t_{j1} and t_{j2} and the conflicting TW *k* as l_{k1} and l_{k2}, and t_{k1} and t_{k2}.

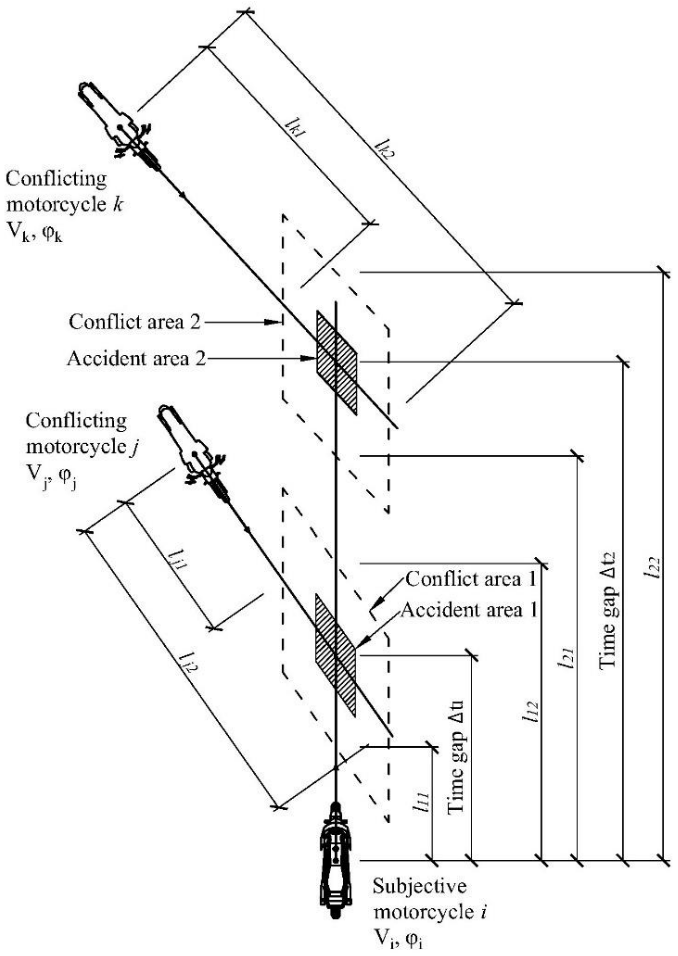


Figure 4.9. Double conflicts situation

4.3.2 Game-theoretic implementation

In order to understand game theory, the core of conflict and cooperation motions should be firstly explained. In general, Ungureanu (2017) described the definition of conflict as "a situation in which beings have to fight for limited resources to satisfied their needs" and the notion of cooperation as "a situation in which beings act jointly for a fair division of limited resources". Game theory lately springs from the conflict and cooperation motions as theory of mathematical models describing how intelligent rational players make decisions. The intelligent players herein are the persons who have exhaustive knowledge. Rational players are assumed as the persons always maximize their pay-off. Decision-making process is simplified as choosing a decision from a set of admissible decisions. The intelligent rational players are assumed will choose the optimal decision with regard to a set of criteria.

Applying game theory in the study has to be amended for TW conflicts. Players are the drivers of conflicting TWs. The game, which is similar to Schonauer (2017), is presented in the following five aspects, number of players (agents), number of repetitions until the conflict is settled, conveying information (transparency of decisions), type of cooperation, and symmetry of the game.

First, the only two players are taken into consideration in the game. The games are assumed to be independent from one another even though each player could face a number of conflicts. In the reality, a driver usually focuses and resolves effectively only the most urgent conflict within a short period of time, a time step 0.1 s. Most of the driver would keep their eyes on the most influential vehicle until they feel safe or that vehicle is not the highest risk anymore. That psychological reaction gives an idea for the consideration only the most unsafe conflict. Therefore, the two-player game theory is employed to reflect the conflicted situation inside roundabout. While multi-player game theory considers a number of TWs, the two-player game theory only considers the subjective and the most influential TW. The two-player game theory thus has an advantage of calculation cost and driver's psychological reflection to deal with the conflict. This swift and efficient approach is highly competitive for applying in the simulation.

Second, there is only a single game for each player pairs in the conflict. The duration between making decisions is short, 0.1 s in the simulation, not enough to make multiple decisions or continuously update the game state. Thus, for a driver, only a non-repetition game is considered.

Third, the game can be specified as perfect information. The pay-off matrices are transparent and the players have all information of the game. Both drivers can understand the situation that the other is dealing and know the strategies of each other.

Fourth, the players do not cooperate to achieve the optimal total utility but try to maximize their own utilities. Observing the real world, it is popular that one of the road users, who has advantages, initializes the reaction. By eye contact, the other road users know the announced strategy and react to it. In the simulator, an asymmetric hierarchical game is applied. The leader, who comes to the conflict area at first, selects a strategy and achieves optimal utility. The follower reacts based on the leader's announced strategy.

Finally, the game is classified as symmetry for conflict between TWs and asymmetry for conflict between car and TW. In the former situation, both of the players share the same probability of keep going. The first-come-first-sever principle is lately applied to determine which player has to give way. The game, which does not set any difference between two players, hence, is symmetry game as Eric (2006). However, in the latter situation, cars usually give way to TW owing to the comparative size, power-to-weight ratio, and maneuverability. TWs usually utilize their advantages to achieve better payoff, keep going, and force the car to give way. This situation is considered a asymmetry game. To sum up, the game here-in is characterized as 2 players, no repetition, perfect information, non-cooperation, leadership, and symmetric game.

Table 4.1. Qualitative payoff matrix for two-players game

		Subjective TW	
		Give way	**Keep going**
Conflicting TW	**Give way**	(*Continue to give way and can not reach destination*) 0 0	1 0
	Keep going	0 1	(*Collision*) 0 0

The qualitative payoff matrix for the two-players game is presented in Table 4.1. For the top-left case, both the subjective TW and the conflicting vehicle give way by changing direction. As the non-cooperative game, player makes decision based on behaviors of other players. This situation, therefore, could lead to the case that both two TWs continuously give way but could not solve the conflict. It ends up that both two TWs can not reach the destination. In the bottom-right case, both two TWs keep going on the same direction. It results to the potential crash of the vehicle. These two extreme cases are avoided by employed the first-come-first-serve to determine the leader and follower. The game finally results in one of two remaining cases.

4.4 Conflict-solving model

This section provides a deep look inside the conflict-solving model rather than the entire simulator. The module simulates the decision-making procedure used to reach a destination while avoiding a collision with other vehicles. According to human-like driving concept Ma *et al.* (2017); Asano *et al.* (2010); Schonauer (2017), the module is also structured into three levels, namely, a strategic level, a tactical level, and an operational level.

It is assumed that a TW wants to move toward its desired direction as far as possible. A situation in which the TW travels inside the roundabout without conflict is less complex than with conflicts. With a potential conflict, the movement of the TW becomes a challenge to predict. Based on the observed situation, the constraints from the strategic and tactical levels, and the capability of the TW itself, the final decision at this level is determined as the algebraic value of the acceleration and turning angle rate, also termed as angular velocity Ma *et al.* (2017). Finally, the velocity and turning angle are smoothly changed by updating the acceleration and turning angle rate after 0.1 seconds each.

When facing two conflicts as in Figure 4.9, a driver usually focuses first on the most severe conflict. This behavior is imitated in the model by considering the smallest time gap. The time gap Δt_1 is taken into consideration. It is assumed that the subjective TW *i* shows a "*giving way*" behavior, and the conflicting TWs *j* and *k* insist on their current direction and velocity. The subjective TW *i* has 61 options in the set of choices Ω to stay away from the collision. The maximum moving distance of TW *i* in direction θ_m, which is denoted by $L_j^i(\theta_m)$, is calculated within the anticipation period *T*. This calculation is taken under the assumption that the velocity of TW *i*, namely V_i, is a constant during the anticipation period *T*. Each option θ_m in the set of choices Ω is calculated to find the possible moving distance along the desired direction. To maximize the moving distance toward the desired direction φ_d, the optimal direction θ_{opt} is chosen as the farthest distance along the desired direction φ_d among the set of choices as the following equation,

$$\theta_{opt} = max_{\theta_m \in \Omega}\left(L_j^i(\theta_m)\ \cos(\theta_m - \varphi_d)\right) \tag{4.3}$$

where,

θ_{opt} : the optimal angle in the choice set Ω

$L_j^i(\theta_m)$: the maximum moving distance of TW *i* at the direction θ_m

θ_m : one of direction in the choice set Ω

φ_d : the desired angle

Figure 4.10 shows six examples of calculating the optimal direction θ_{opt} when subjective TW *i* comes into conflict with two TWs, namely, *j* and *k*, in direction θ_m. Despite the application of the two-player game theory, the anticipated movement of the second conflicting TW k is also considered to calculate the optimal direction θ_{opt}.

The acceleration toward the optimal direction in this model is calculated by assuming that the TW wants to minimize the number of changes in its velocity. Consider case 1 in Figure 4.10, the optimal velocity is chosen as a dashed line instead of a continuous line. If there are no expected collisions during the anticipation period T, the TW continues to go along its desired direction and speed ups until reaching the desired velocity. Finally, this behavior results in the maximum moving distance toward the desired direction φ_d within the anticipation period T with the velocity below the desired level.

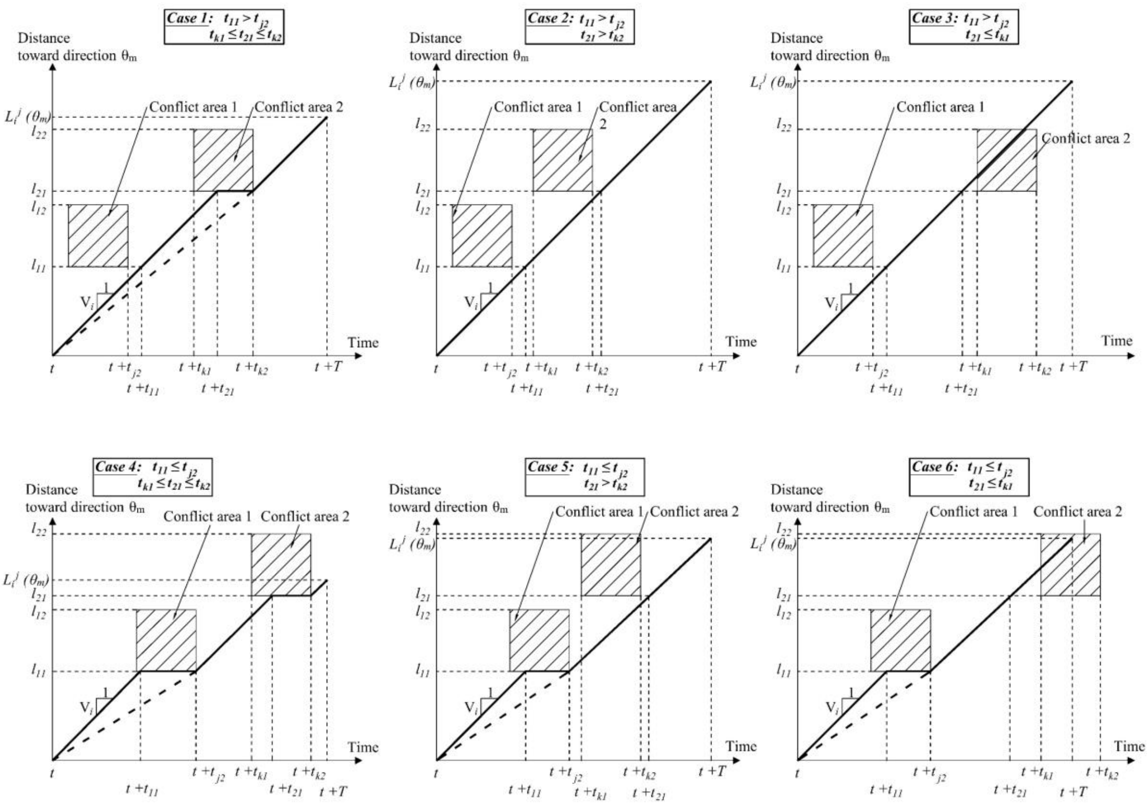


Figure 4.10. Six example cases of calculating of maximum moving distance

Considering the case of the two conflicting areas, there are six possible conflict situations. In each case, the TW reacts in a different way. The equation of the maximum distance is also split into six small cases based on the value of the anticipation period T. The value of T can belong to one of the following intervals: $[0, t_{j1}]$, $[t_{j1}, t_{j2}]$, $[t_{j2}, t_{k1}]$, $[t_{k1}, t_{k2}]$, or $[t_{k2}, \infty]$. The specific equations are presented in Table 4.2 and Figure 4.10.

Table 4.2. Equations of maximum moving distance

Case	t_{11} and t_{j2}	t_{21} and t_{k1}, t_{k2}	**T (with the below values)** (4.4)				
			0	**t_{j1}**	**t_{j2}**	**t_{k1}**	**t_{k2}** ∞
1	$t_{11} > t_{j2}$	$t_{k1} \le t_{21} \le t_{k2}$	L = TV ($0 < T \le t_{k1}$)			L = l_{21} ($t_{k1} < T \le t_{k2}$)	L = $l_{21} + (T - t_{k2})V$ ($t_{k2} < T$)
2		$t_{21} > t_{k2}$	L = TV				
3		$t_{21} < t_{k1}$	L = TV				
4	$t_{11} < t_{j2}$	$t_{k1} \le t_{21} \le t_{k2}$	-	L = l_{11} ($t_{j1} < T \le t_{j2}$)	L = $l_{21} + (T - t_{j2})V$ ($t_{j2} < T \le t_{k1}$)	L = l_{21} ($t_{k1} < T \le t_{k2}$)	L = $l_{21} + (T - t_{k2})V$ ($t_{k2} < T$)
5		$t_{21} > t_{k2}$	-	L = l_{11} ($t_{j1} < T \le t_{j2}$)	L = $l_{11} + (T - t_{j2})V$ ($t_{j2} < T$)		
6		$t_{21} < t_{k1}$	-	L = l_{11} ($t_{j1} < T \le t_{j2}$)	L = $l_{11} + (T - t_{j2})V$ ($t_{j2} < T$)		

4.4.1 Choice set

In the field, a TW usually turns within its turning capability and the speed is usually below the desired speed. To reduce the calculation cost and achieve a pragmatic replication of the maneuvering capability, two constraints, velocity and moving direction, are adapted,

- The velocity of the TW can change during the anticipation period but remains under the desired velocity $0 \le V(t+i) \le V_{desired}$.
- The possible direction of movement is arranged from $\varphi_i(\mathrm{t}) - \psi$ to $\varphi_i(\mathrm{t}) + \psi$ for each degree.

This study makes use of a discrete choice approach to reproduce the set of choices of the TW. A driver can choose one direction from a set of choices Ω, as shown in Figure 4.11. A chosen direction is calculated using Equation (5.2).

$$\theta_m = \varphi_i(t) + \frac{2m-n}{n}\psi \quad ; m \in \mathbb{Z} \mid m \in [0, n] \tag{4.5}$$

where,

- θ_m : the chosen direction
- $\varphi_i(\mathrm{t})$: the moving direction at time *t* (current direction)
- $\psi = 30°$: the maximum possible angle for one side

- $n+1=61$: the number of options in a choice set Ω
- m : the variable determined selected option among the choice set Ω in iterative calculation

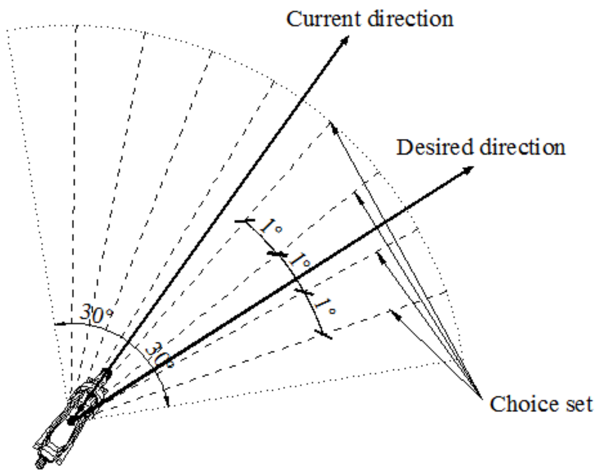


Figure 4.11. Choice set and desired direction of TW

4.5 Collective behavioral model

The model goals to reproduce the grouping behavior of TW in the simulation. The behavior is defined by the surrounding vehicles and the drivers' target. In each time step, TW assesses the positions and directions of its neighbors based on the three non-overlapping zones as in Figure 4.12. This information, grouping guide direction, combined with geometric guided direction is used to calculate the desired direction. The concept of three zones is inspired by Couzin *et al.* (2002). However, the shape, size, open angle, formulation forces for these zones are determined by this study. The study proposes a novel model based on the observation field, real data, and the driver's psychology.

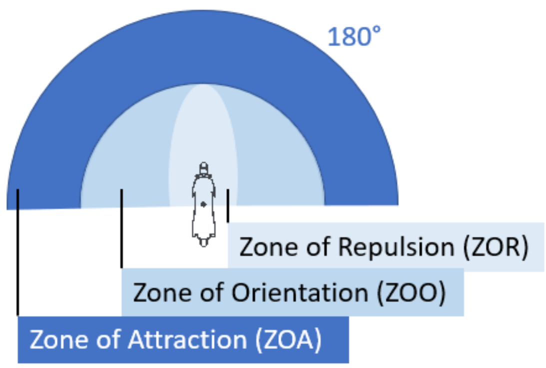


Figure 4.12. Representation of a TW with three non-overlapped zones, ZOR, ZOO, ZOA

4.5.1 Zone of repulsion (ZOR)

As revealed in section 3.5.5, while moving inside roundabout, TW maintain a clear space around itself. This space is modeled in the simulator by ZOR. The ellipse formulation is used to approximate the ZOR in Figure 4.13.

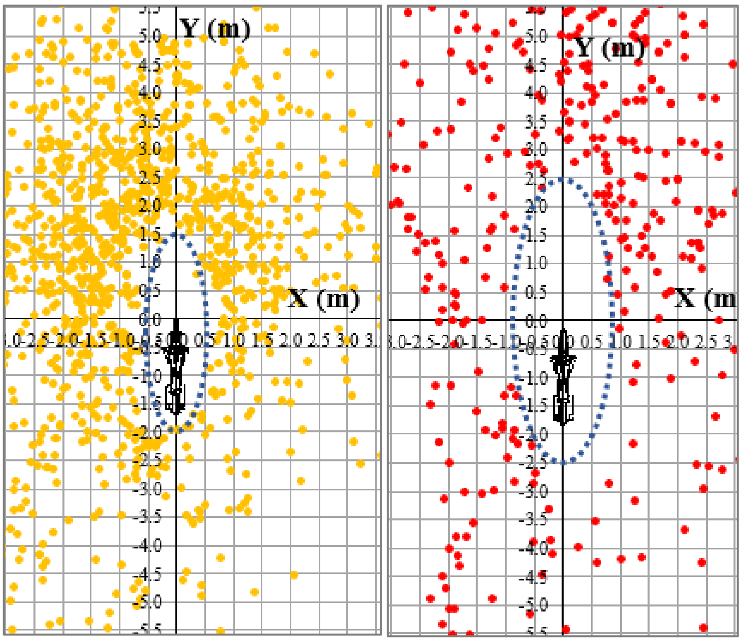


Figure 4.13. Approximating ZOR when speed < 2.78 m/s (left graph) and when speed ≥ 2.78 m/s (right graph)

Vector of repulsive force is calculated by the following equation, Couzin *et al.* (2005),

$$\overrightarrow{d_r(t+\tau)} = -\sum_{j\neq i}^{n_r} w_1 \frac{\overrightarrow{c_j(t)} - \overrightarrow{c_i(t)}}{\left|\overrightarrow{c_j(t)} - \overrightarrow{c_i(t)}\right|} \quad (4.6)$$

where,

- $\overrightarrow{d_r(t+\tau)}$: the calculated vector of individual *i* move away from its neighbors n_r in the ZOR.
- d_o : the calculated direction of individual *i* align itself with its neighbors n_r in the zone of orientation
- d_a : the calculated direction of individual *i* move forward to its neighbors n_r in the zone of attraction
- n_r : the number of neighbors in the zone of repulsive at time *t*

- $\overrightarrow{c_i(t)}$: the positional vector of individual *i* at time *t*
- $\tau = 0.1\text{sec}$: the time step, corresponding to the response latency – reaction time
- w_1 : the weighting term of the repulsive force

Calculated acceleration

$$A\, exp\left(-\left(\frac{x^2}{(\tau_\alpha v_\alpha)^2} + \frac{y^2}{(W_\alpha + d_y)}\right)/B\right) + \varepsilon \tag{4.7}$$

where,

- A = 4.031: parameter represents the magnitude of the safety level
- B = 0.470: represents the effect of stretching out the value of safety level.
- x, y: the distances between subjective vehicle and nearby vehicle on local x-axis and y-axis
- τ_α = 0.5s: relaxation time.
- Vehicle size: dx = 1.9m, dy = 0.7m

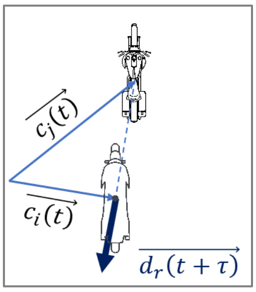


Figure 4.14. Example of Repulsion direction

4.5.2 Zone of orientation (ZOO)

In order to reproduce the grouping behavior, the ZOO is approximated as the same shape with ZOR but offset from the center of vehicle an anticipation movement length, section 4.3.1. This direction target to reproduce the behavior that vehicles strengthen the group connection. The vehicles align their direction to the group direction to achieve higher utility by following the group's direction. The oriented vector is calculated as the following equation, Couzin *et al.* (2005),

$$\overrightarrow{d_o(t+\tau)} = \sum_{j \neq i}^{n_o} w_2 \frac{\overrightarrow{v_j(t)}}{\left|\overrightarrow{v_j(t)}\right|} \tag{4.8}$$

where,

- $\overrightarrow{d_o(t+\tau)}$: the calculated direction of the individual i align itself with its neighbors n_r in the ZOO.
- n_o : the number of neighbors in the zone of orientation at time *t*
- $\overrightarrow{v_j(t)}$: the unit of directional vector of individual *j* at time *t* .
- w_2 : the weighting term of the orientating force.
  $w_2 = 0$: If the vehicle *j* and *i* have distinctive moving phases.
  $w_2 = 1$: in other cases

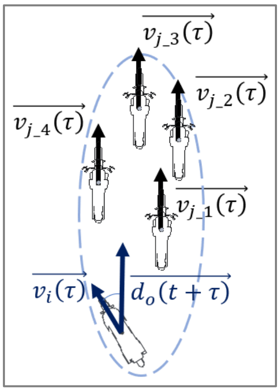


Figure 4.15. Example of orientation direction

4.5.3 Zone of Attraction (ZOA)

This direction aims to reproduce the phenomena that vehicles have the same short-term objectives. For example, vehicles from an entering approach, who are trying to merge with the circulating flow, make group to get advantages in conflict and feel confident, Vu and Shimizu (2010). The equation to calculate the attractive force is as the following, Couzin *et al.* (2005),

$$\overrightarrow{d_a(t+\tau)} = \sum_{j\neq i}^{n_a} w_3 \frac{\overrightarrow{c_j(t)}-\overrightarrow{c_i(t)}}{\left|\overrightarrow{c_j(t)}-\overrightarrow{c_i(t)}\right|} \tag{4.9}$$

where,

- $\overrightarrow{d_a(t+\tau)}$: the calculated direction of the individual i attracted by its neighbors n_a in the ZOA
- n_a : the number of neighbors in the zone of attraction at time *t*
- w_3 : the weighting term of the attractive force.

$w_3 = 0$: If the vehicle *j* and *i* have distinctive moving phases.
$w_3 = 1$: in other cases

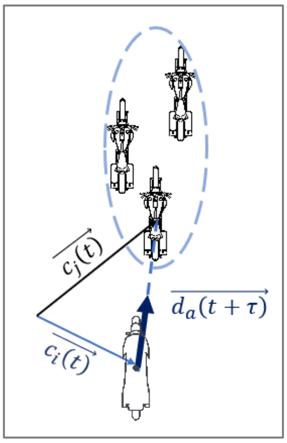


Figure 4.16. Example of attraction direction

4.6 Combining model

The entire model includes three sub models, regular movement model, conflict-solving model, and collective behavior model, that calculates three dissimilar directions. Each of them responses to a specific behavior. They are developed based on the bottom-up approach and arranged in a hierarchical structure, as in Figure 4.17. The first basic model is the regular movement model. Without this model, the simulator does not work. The second level is conflict-solving behavior model, which response to overlapping and complex maneuver of motorcycles. Missing this model, the simulator, the vehicles will only move in their desired path without considering other vehicles and the overlapping phenomena happen usually. The last level is the collective behavior model, which responses to relative position and direction of vehicles in the same group. Missing this model, the simulator does not expose the grouping behavior but still works. Thus, it is the fundamental model of the simulator. This section explains the manner in the controller to combine the result of all three models to determine the final acceleration and direction.

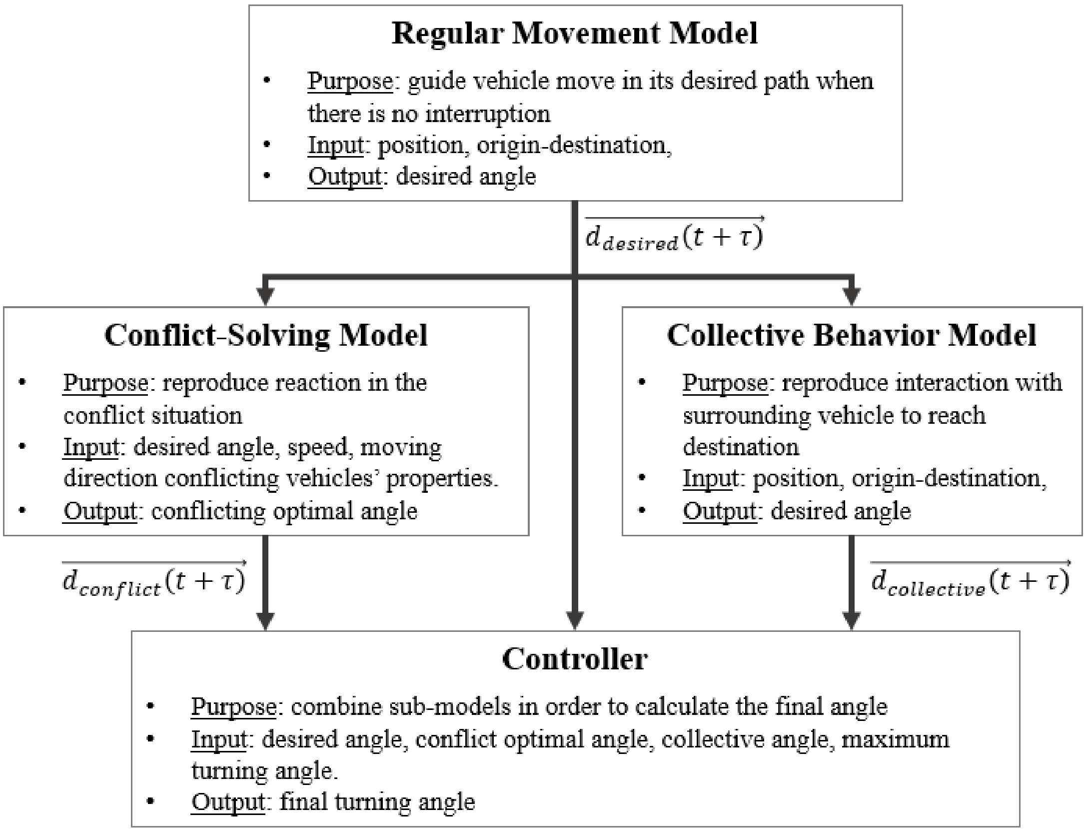


Figure 4.17. Combining three sub-models

As stated in the assumption that solving conflict to avoid the crash has the highest priority, the combining model is separated into three cases as the following.

- Case 1, the conflict-solving model is activated:

$$\overrightarrow{d_{final}(t+\tau)} = \overrightarrow{d_{conflicting}(t+\tau)} \qquad (4.10)$$

- Case 2, the conflict-solving model is inactivated but the collective behavior model:

Firstly, the collective direction, $\overrightarrow{d_{collective}(t+\tau)}$, by the collective behavioral model and desired direction is computed as the following,

- If there are vehicles inside the zor : $n_r \neq 0$:

$$\overrightarrow{d_{collective}(t+\tau)} = \overrightarrow{d_r(t+\tau)} + \overrightarrow{d_{desired}(t+\tau)} \qquad (4.11)$$

- If there is no vehicle inside the zor: $n_r = 0$:

$$\overrightarrow{d_{collective}(t+\tau)} = \overrightarrow{d_o(t+\tau)} + \overrightarrow{d_a(t+\tau)} + \overrightarrow{d_{desired}(t+\tau)} \qquad (4.12)$$

Secondly, the final direction is calculated as,

$$\overrightarrow{d_{final}(t+\tau)} = \overrightarrow{d_{collective}(t+\tau)} + \overrightarrow{d_{desired}(t+\tau)} \qquad (4.13)$$

- Case 3, both the conflict-solving model and collective behavior model are inactivated:

$$\overrightarrow{d_{final}(t+\tau)} = \overrightarrow{d_{desired}(t+\tau)} \qquad (4.14)$$

The calculation process of main model is summary in the Figure 4.5.

Chapter 5. TRAFFIC SIMULATOR

The proposed models are implemented into a traffic simulator for a roundabout in Ho Chi Minh city. The simulator is build based on the multi-agent programmable modeling environment, Netlogo. This chapter presents the framework, geometry setup, vehicle generation, and input variables.

"*Traffic simulation is one of the most complex simulation projects that can be undertaken.*"
Kotusevski and Hawick (2009)

5.1 Developing traffic simulator

Paruchuri *et al.* (2002) pointed out the main issues are modeling of autonomous behavior of drivers, modeling of their interaction, simulating the traffic, and procure reliable realistic results. Organized traffic with drivers heeding to well-defined traffic rules is less dynamic and erratic than modeling unorganized traffic. Wherein the drivers either do not heed to well-defined traffic rules, or there are no traffic rules in place. This paper shows the viability of applying multi-agent simulation for unorganized traffic.

5.2 Framework

In fact, Railsback and Grimm (2012) concluded that the current conventional conceptual model protocol and many other descriptions of ABMs are wordy and incomplete. That causes difficulties to reimplement or replicate the models and results. In the effort to standardize the description of ABMs, a huge group of experienced modelers, Grimm and Railsback (2005); Grimm *et al.* (2006); Grimm *et al.* (2010), introduced the "Overview, Design concept, and Details" (ODD) protocol. The ODD is quick to establish, easy to grasp, complete, and organized framework of ABMs. This study, thereby, is applied the protocol to structure and describe the simulator.

Table 5.1. Clarification of ABM following the ODD protocol

Elements	**Explanation**
Overview	
Purpose	To reproduce the interaction of TWs at the roundabout by using the collective behavior model and simulate in a multi-agent environment. To observe the emerged behaviors and the change in traffic condition due to these interactions.
Entities, state variables, and scales	There a two type of vehicle, called entities, will be built inside roundabout that is the lane-based and non-lane-based vehicle. The environment that vehicle move includes geometric infrastructure design, traffic regulation (right-hand driving, traffic signal, roundabout rule), and other vehicles. State variables are entering, circulating, merging, diverging, avoid-crash, and exiting. Dimension of simulation, 160×128m ~ 800×640 patches Simulating period, 10minutes Convert unit:

	Temporal, 1 tick = 0.1 seconds Spatial, 1 patch = 0.2×0.2 m^2

Process overview and scheduling	The model describes the interaction of vehicles on the road surface to reach the destination. The interaction of vehicles in the decision-making process is to avoid the accident and optimize the traveling path by continuously modify speed vector, represented by two parameters speed and direction.
	Procedure order:
	
	`Breed`
	`Cars-own[ ]`
	`Motor-own[ ]`
	`Patches-own[ ]`
	`Globals[ ]`
	`To setup`
	`To setup-globals`
	`To setup-patches`
	`To setup-agents`
	`To setup-traffic-lights`
	`To go`
	`To manage-traffic-light`
	`To gen-motors`
	`To gen-cars`
	`To draw-anticipation-line`
	`To move-cars`
	`To move-motors`
	`To moving-status`
	`To identify-conflict`
	`To circulating`
	`To merging`
	`To diverging`
	`To remove-anticipation-line`
	`To remove-vehicles`

Design concept	
Basic Principles	**Conflict-solving model:** Two-player game theory, Nominal project approach, Discrete choice approach **Roundabout-traveling model**: Individual interaction based on Collective behavior. **Goal-oriented model**: Destination attraction. Vehicle is updated its new position from the previous position after a period of time step based on speed and moving direction. Speed and moving direction is calculated from acceleration/deceleration, turning angle, previous speed, and previous moving direction.
Emergence	An important model output is the movement of vehicles. It is a collection of updated positions after a period of time step.
Adaptation	Try to make group, moving towards the destination, circulating, avoid crashes with other vehicles. Information transfer from strategic level to tactical level to operational level. Calculate the longest possible line along the desired direction among the choice set.
Objectives	Enters the roundabout and align moving direction with others Move closer to the exiting point. Move along the reference direction. Speed up if possible close to the desired speed. Move with a similar objective group.

	Solve the conflict to avoid crashes with other vehicles and boundaries.
Learning	No
Prediction	Based on the anticipation line in the environment of vehicle. Decide who will give up and who will go straight. Based on the desired speed. Get information in the observation zone.
Sensing	Observation zone. Vehicle same type, same objective, same origin direction. State of interacting vehicle, speed, and moving direction. Which vehicle could be in a conflict? When and where the conflict will occurs?
Interaction	In conflict situation, one vehicle will go straight, all the other vehicles have to give way. In a normal situation, vehicles try to make group and go together with the same type of vehicles in its observation zone. For lane-based vehicles, use stop and go strategy.
Stochasticity	Reaction time Desired speed. Destination point.
Collectives	Vehicles make decision based on its local environment and its behavior change due to future decision of other agents. At the time step, the decision of the subjective vehicle in conflict with affects the others. The collective is represented by the decision of one vehicle will affect other vehicles and finally affect the entire roundabout.
Observation	Outputs: Individual: positions and speed at each time step, trajectory, travel time, speed, turning angle rate v.s. speed, Whole roundabout: area occupancy, simulated videos, traffic flow, average speed.
Details	
Initialization	Set up the geometry of the roundabout, road surface, boundary, road marker, entering and exiting approach, vehicle generation area, vehicle destination, inside the roundabout, entering / exiting reference direction. Default parameters for generated vehicles, desired speed, speed, direction, reaction time.
Input data	Traffic volume, OD matrix, speed distribution, desired speed, reaction time.
Sub-model	Conflict-solving model Collective model Desired direction model

5.3 Model implementation

5.3.1 Geometry setup

This step is to construct an environment in the simulator that is similar to the ground truth. Layer by layer, the geometries of the roudanbout are assigned into the environment through patch's properties. The primitive *import-pcolors* in Netlogo is utilized to insert the properties. The layer is imported in the order, road surface, boundary, road marker, entering and exiting approach, vehicle generation area, vehicle destination, inside the roundabout, entering / exiting reference direction.

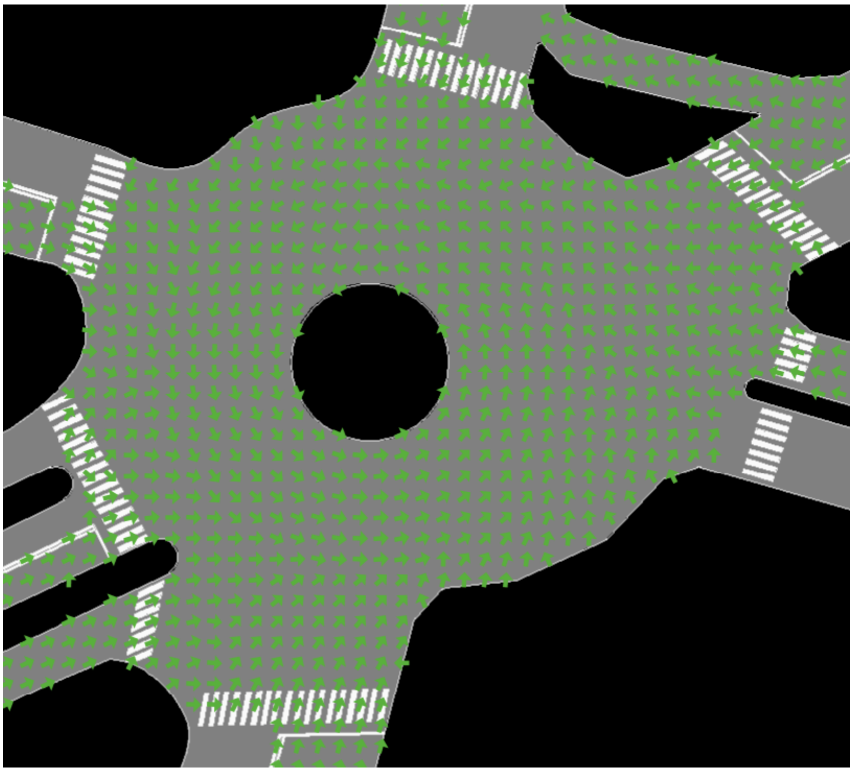


Figure 5.1. Environmental reference direction for entering

Desired direction is given for entering and exiting direction. It is constructed based on the collected trajectory map of TW. When TW merges, circulates, and diverges without any conflict, it will follow this typical trajectory. The trajectory then later is constructed as direction vector at any position in the roundabout. These vector are embedded in the environmental layer in Netlogo, namely environmental reference direction.

For entering, the direction is mainly pointing to the center of the roundabout. As closed to the center, the direction is aligned with the circulating direction. At the entering approach, right after the stop line, the direction is matched with entering approach direction. At the boundary of the central island, the direction is only circulated around. In the middle area, the direction gradually changes from entering direction to circulating direction. On the other hand, the direction at the road curb is pointing to the inside road surface area, also exemplified in Figure 5.1. It shows the suggested direction when a vehicle is going hitting the curb. In the middle, the direction gradually changes from two extremes, the outside curb and central island boundary.

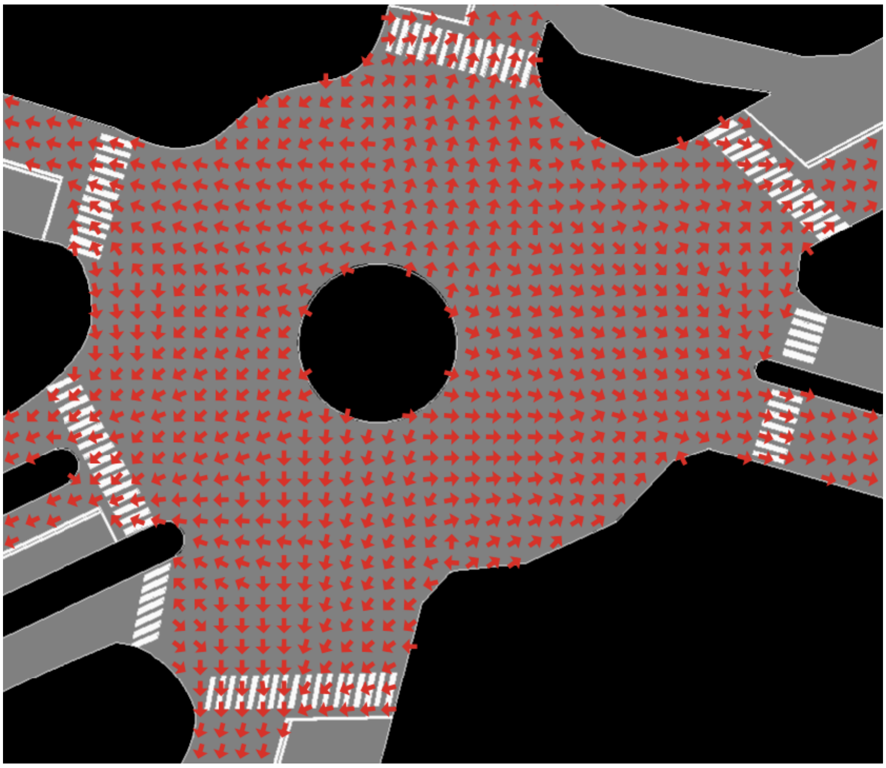


Figure 5.2. Environmental reference direction for exiting

For exiting, at the beginning of the exiting approach, the direction is the same as the exiting direction. In the middle patch, the roundabout area is divided into six areas in accordance with six approaches. In these areas, each direction faces the nearest destination patch of this area. The destination patches are shown in Figure 5.4. The direction at the road curb is pointing to inside road surface area. In the transition area, the direction is combined by boundary, circulating direction, and face toward the nearest destination patch. The area belongs to the exiting approach, the direction face towards the nearest destination patch.

Finally, finishing the geometry setup, the environment of Netlogo is as Figure 5.3.

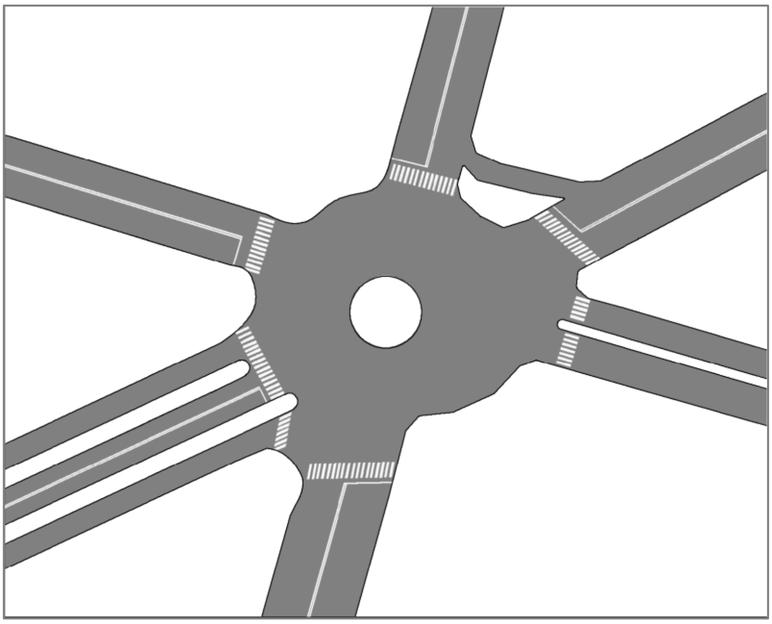


Figure 5.3. Geometry environment in Netlogo

5.3.2 Vehicle generation

Vehicles will be generated similar to real data under Poisson distribution, Ksontini *et al.* (2014). It means the number of generated cars equals the car flow rate in real data. In case of cars, for each duration of *generated frequency of car*, a car is produced and placed in the free area in the car's lane. The segment for placing a car is the fifteen-meters-straight road from the edge of the simulator, as in Figure 5.4. The produced car is lately given the set of parameters as in Table 5.2. As the whole simulation run under the time-step counting, the *generated frequency of car* is calculated by the following equation,

$$generated\ frequency\ of\ car = \frac{simulation\ time}{number\ of\ generated\ car} \tag{5.1}$$

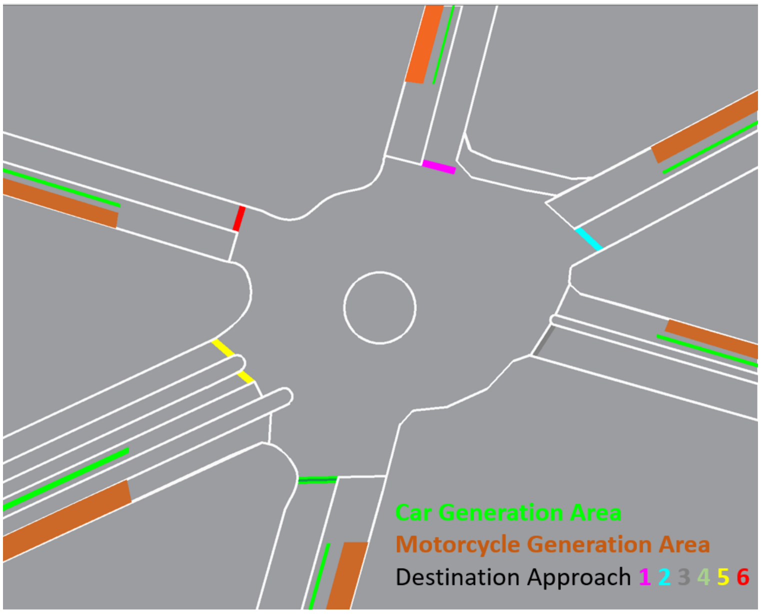


Figure 5.4. Vehicle generation and destination area

Table 5.2. The specification of generated car

Quantity		Real Data	Simulator
Car length		4.5m	23 patches
View angle		60 degrees	60 degrees
Acceleration from standstill	$a_{from\ 0}$	0.84 m/sec^2	0.017 patch/tick^2
Free deceleration	a_{free_dec}	-1.18 m/sec^2	-0.059 patch/tick^2
Break	a_{break}	-8.5 m/sec^2 Kudarauskas (2007)	-0.425 patch/tick^2
Desired velocity	$v_{desired}$	~N(8.585, 0.888^2) m/sec	~N(4.293, 0.444^2) patch/tick
Initial speed	v	~N(5.91, 1.36^2) m/sec	~N(2.96, 0.68^2) patch/tick
Limited velocity inside the roundabout	v_{rd}	3 m/sec	1.5 patch/tick

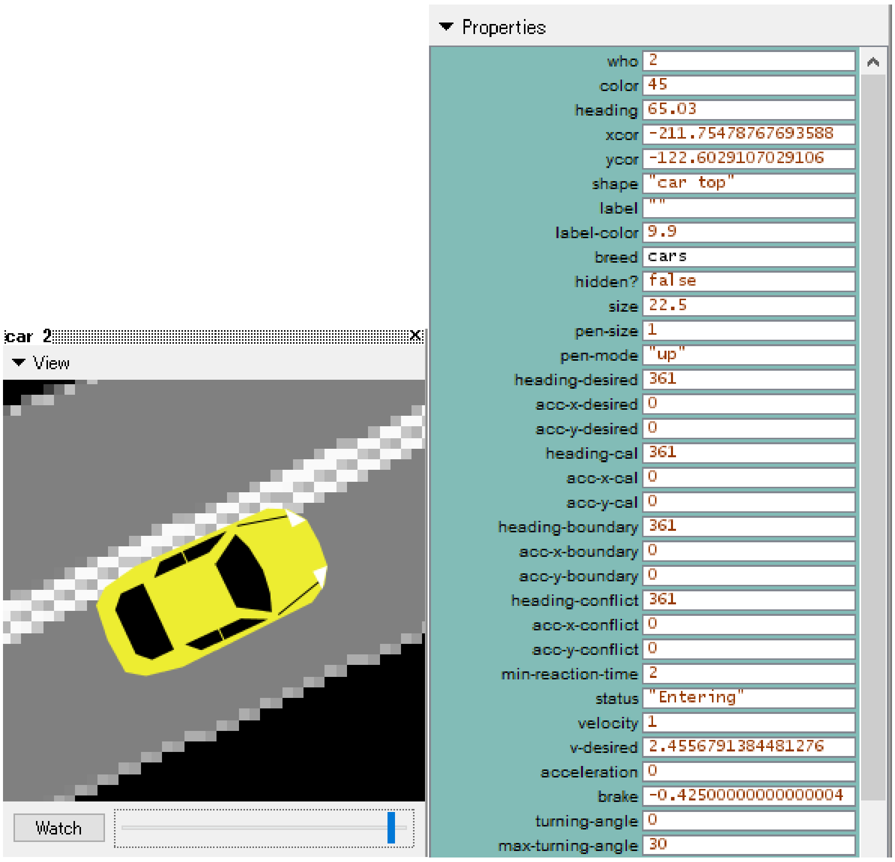


Figure 5.5. Characteristics of generated car

Similarly, TW in each entering approach is generated after each a *generated frequency of TW* at a random position along the first *15 meters* segment inside the TW's lane. Each TW is assigned the list of parameters, as in Table 5.2. The initial velocity follows normal distribution $N(5.91, 1.36^2)$ as the real data. These parameters would be exchanged to the unit in simulation graphic unit, *1 m = 5 patch* and *1 s = 10 tick*, with *patch* and *tick* are the spatial and temporal unit in the simulator. As a result, the number of TWs in approach is calculated by the following expression,

$$generated\ frequency\ of\ motor = \frac{simulation\ time}{number\ of\ generated\ motor} \qquad (5.2)$$

Table 5.3. The specification of generated TW

Quantity		**Real Data**	**Simulator**
TW length		1.9m	10 patches
View angle		60 degrees	60 degrees
Acceleration from standstill	$a_{from\ 0}$	0.4 m/sec^2 Minh *et al.* (2007a)	0.02 patch/tick^2
Free deceleration	a_{free_dec}	-0.924 m/sec^2	-0.046 patch/tick^2
Break	a_{break}	-6.9 m/sec^2 Nguyen (2012)	-0.345 patch/tick^2
Desired velocity	$v_{desired}$	~N(8.59, 0.89^2) m/sec Nguyen (2012)	~N(4.29, 0.45^2) patch/tick
Initial velocity	v	~N(3.61, 1.82) m/sec	~N(1.81, 0.91^2) patch/tick
Limited velocity inside roundabout	v_{rd}	11 m/sec	5.5 patch/tick

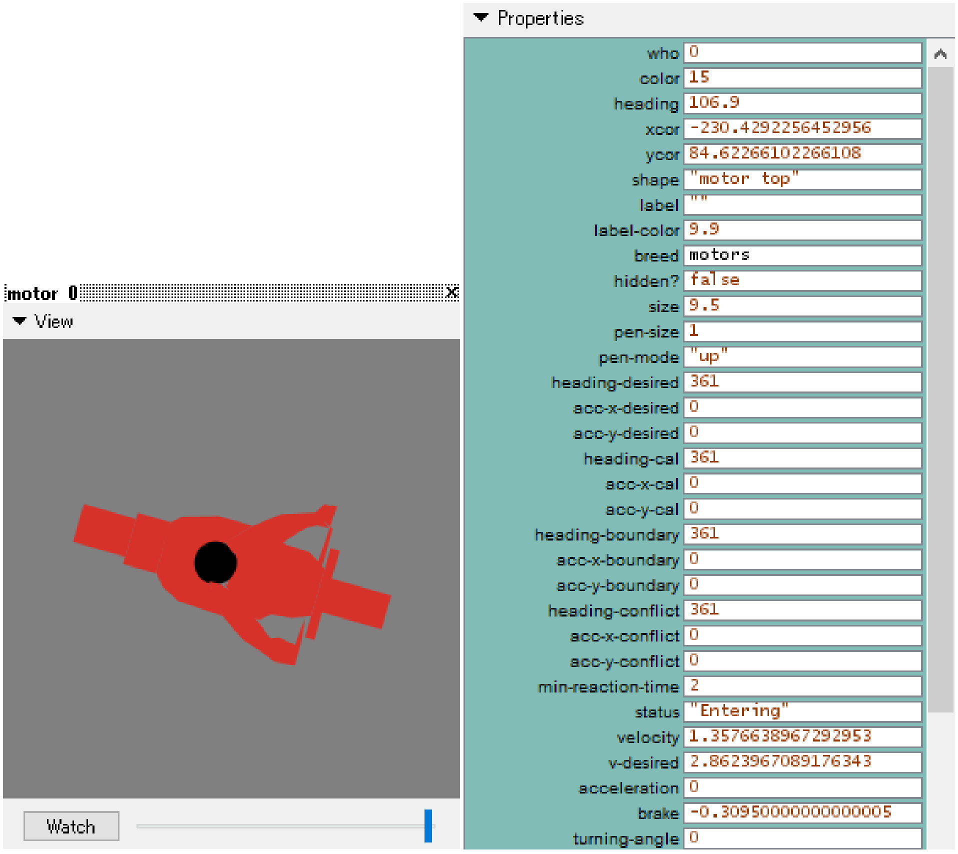


Figure 5.6. Characteristics of generated TW

The vehicles are produced in the midblock in the hope of giving them a stable status before the roundabout. The vehicles are generated at the same time in two opposite directions of a road after the inter-arrival times. The inter-arrival time is generated by normal distribution to fit the traffic volume in the recorded video. The vehicle placing position is chosen randomly along the *10 meters* block based on the available space.

After being generated, each vehicle is assigned several following characteristics, vehicle type, vehicle size, desired velocity, acceleration of break, initial velocity, turning decision inside the roundabout. These characteristics are estimated in the field so as to imitate the real one adequately.

5.3.3 Input

The main inputs of the simulator could be classified in two groups as below,

- Static properties (geometry): roundabout design, vehicle generating/exiting area, movement phases area (more accurately when modified by the field trajectory), roundabout area, entering/exiting/boundary direction vector for each approach.
- Dynamic properties (vehicles): desired speed, speed distribution, traffic volume, OD matrix, reaction time.

The input traffic flow and OD-matrix of the simulator are the same as the real data. The visual result is presented in Figure 5.6. The detailed numerical analyses are presented in the next section.

Table 5.4. Input OD-matrix of the developed simulator

		Exiting Approach					
		1	**2**	**3**	**4**	**5**	**6**
Entering Approach	**1**	-	5.4	21.4	57.1	10.7	5.4
	2	3.3	-	0.0	15.0	53.3	28.3
	3	28.1	1.8	-	3.5	5.3	61.4
	4	60.7	29.5	3.3	-	0.0	6.6
	5	26.7	50.0	18.3	0.0	-	5.0
	6	6.7	16.7	55.0	21.7	0.0	-

Unit: %

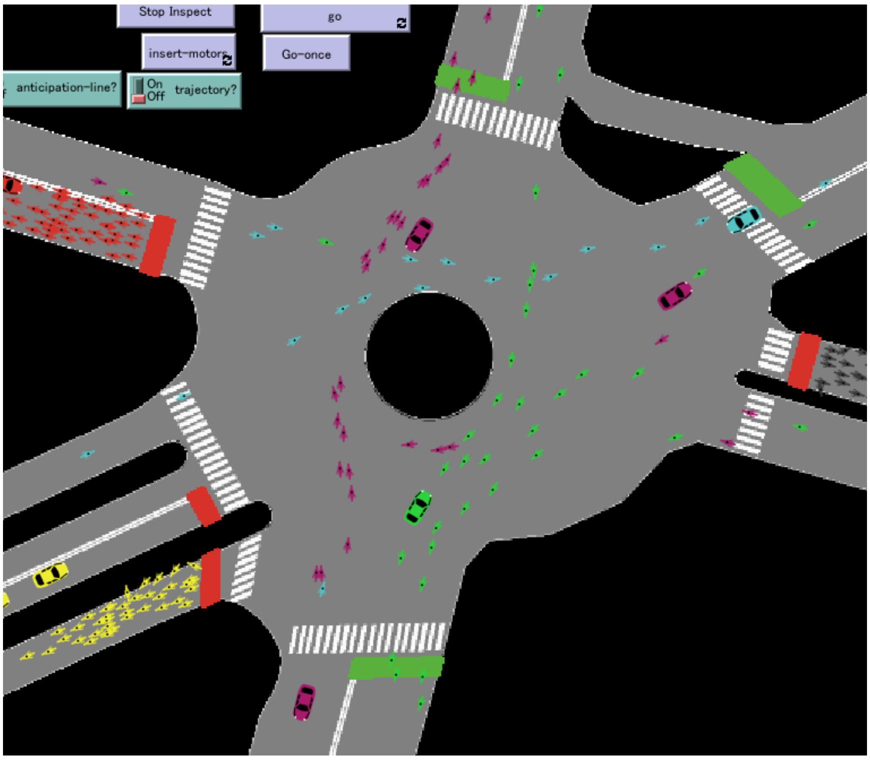


Figure 5.7. Screenshot of the developed simulator

Chapter 6. RESULTS

This chapter proposes innovative microscopic indicators, which are travel time, turning angle rate, delay, conflict rate, following space, and time-to-collision for validation. The results from the developed simulator, PTV VISSIM, and real data are compared to point out the merits and demerits of the proposed model.

6.1 Indicators

In order to validate the novel model, the results from the developed simulator are compared with real data and simulation results from popular commercial microscopic simulation software, PTV VISSIM. The real data is divided into two parts. The first 50% of the data is used for parameter calibration. The remaining 50% of the data is considered to validate the model. Regards PTV VISSIM, the latest version, VISSIM 11, is employed in the study. VISSIM is a pioneer in developing models for non-lane-based vehicles, as mentioned by Budhkar (2017). Several studies have used VISSIM for simulating heterogeneous traffic at roundabout Arroju *et al.* (2015); Dodappaneni *et al.* (2016); Pal and Goyal (2016). Moreover, PTV VISSIM has been updated annually from the latest results of PTV's research team. That consolidates that state-of-the-art models in PTV VISSIM. In this study, the simulated roundabout in PTV VISSIM is constructed and run independently in a parallel study, which shares the data of the ground truth with this study. The calibration for VISSIM is detailed in APPENDIX B. ADDITIONAL INFORMATION.

In terms of traffic characteristics, Wong *et al.* (2016) classified them as macroscopic and microscopic characteristics on the basis of observation level. The macroscopic level focus on the entire flow characteristics like traffic volume, mean speed of the stream, density, temporal occupancy, and area occupancy, to name a few. On the other hand, the microscopic level focus on individual characteristic, which includes headway, individual speed, longitudinal/lateral/oblique spacing, lane choice, lateral position within a lane. Based on this classification, the measurements for validation should also be suitable for the model's objective. The reviewing of indicators for validation is conducted in this section. The indicators for validating agent-based modeling in traffic simulation are presented in Table 6.1. The indicators for validating roundabout simulation are listed in Table 6.2. The indicators for validating heterogeneous traffic simulation are provided in Table 6.3.

Table 6.1. Reviewing indicators for validating agent-based modeling in traffic simulation

Reference	Tackled problem	Software	Measurements
Balmer *et al.* (2004)	Large-scale of ten million travelers by implementing the strategy generation and day-to-day agent-based learning.	MATSim	Traffic volume Travel time

Hidas (2002); Hidas (2005b)	Lane-changing behavior with cooperation of reducing speed and deceleration. Weaving and merging behavior.	ARTEMiS	Time–distance diagram Speed and gap diagram Speed difference and gap Speed–flow relationship of the Merge scenario Stop rate as a function of flow rate Traffic volume Travel time
Palmiano *et al.* (2004)	Heterogeneous traffic with midblock jeepney stops.	JSTOPSIM	Time-space diagram. Delay
Lee (2007)	Heterogeneous traffic with multi-vehicular interaction.	BikeSim	Trajectory (spatial time diagram) Headway distribution. Fundamental diagram: flow-speed-density.
Rieser (2010)	Mode choice and schedule-based transit.	MATSim	Traffic volume, Rout-time diagram. Travel time.
Grether *et al.* (2012)	Multiagent modeling of the interaction between travelers and traffic signals		Traffic volume. Travel time.
Nguyen (2012)	Reproduce the zigzag movements of TW at mib-block under heterogeneous traffics	C language	Speed (RMSE 0.481). Ratio of corrected acceleration (59.8%). Ratio of corrected maneuvering (63%).
Ksontini *et al.* (2014)	On the straight road, two-wheelers do not follow physical lane but utilized the entire road width and small space between two cars. The model reproduces the occupied space behavior by using the concept of affordances and virtual lanes.	ArchiSim tool	Speed profile. Visual observation. Travel time, average speeds and Numbers of stops by vehicle type.

Table 6.2. Reviewing indicators for validation roundabout simulation

Author	**Package**	**Subject**	**Measurement**

Peterson (2008)	VISSIM, RODEL	Single and dual lane roundabouts	Capacity, delay
Ambadipudi (2009)	VISSIM, RODEL, SIDRA	Multi-lane roundabouts	Delay, queue length, v/c
Ambadipudi (2009)	VISSIM, RODEL, SIDRA	Multi-lane roundabouts	Delay, queue length, v/c
Bared and Afshar (2009)	VISSIM, SIDRA, Tanner Wu, new NCHRP models	2-3-lane roundabouts	Capacity
Deshpande and Meeting (2011)	SIDRA, RODEL, VISSIM, SimTraffic, HCM 2010	Single-lane roundabouts	Queue length and delay
Al-Ghandour *et al.* (2011)	VISSIM	Single-lane roundabouts	Delay
Chen and Lee (2011)	VISSIM, RODEL, SIDRA	Multi-lane roundabouts	Queue length and delay
Chen and Lee (2011)	VISSIM, RODEL, SIDRA	Multi-lane roundabouts	Queue length and delay
Gallelli and Vaiana (2012)	VISSIM	Single-lane roundabouts	Delay
Arroju *et al.* (2015)	VISSIM	Single-lane roundabout	Capacity (MAPE 10.14%)
Giuffrè *et al.* (2017)	VISSIM	Double-lane roundabout Turbo roundabout Flower roundabout Target roundabout	Traffic volume (GEH 87.5%)

Table 6.3. Reviewing indicators for validating heterogeneous traffic simulation excepted Table 6.1 and Table 6.2

Paper – Authors	Methodology / Model	Indicators
Thamizh Arasan and Jagadeesh (1995)	Passenger Car Unit (PCU)	Average Stopped delay Degree of saturate.
Rao and Rengaraju (1998)	The concept of vehicle-crossing time has been introduced to process the vehicles during simulation.	Conflict rate (conflicts per vehicle) Intersection volume Chi-Square Test for Tlme-Headways Chi-Square Test for Number of Conflicts

Asaithambi and Ramaswamy (2008)	Simulate the flow of heterogeneous traffic through a signalized intersection. Model is developed in the C++ language using the object-oriented approach.	Waiting time
Rongviriyapanich *et al.* (2010)	MIxTrafSIM was developed by using objected-oriented Java programming.	Clearing time – number of TWs at intersection. Discharge headway. Startup Lost Time – Number of TWs in queue.
Linh *et al.* (2010)	Microscopic model for motorbike dominated traffic based on Cellular Automata modeling approach in MIXSIM. A utility function has been introduced to model the logic of lane changing behaviours.	Speed. Variation of saturation flow. Discharge flow rate TW headway distribution, accumulation. Queue length, queue formation
De Jong (2013)	Apply traffic-behavioral theory underlying Shared Space to modelling mixed traffic. Simulation model is written in Matlab.	Average speed. Time Exposed to critical TTC.
Mohan and Ramadurai (2013)	Extend the traffic pressure to the mixed traffic and apply to area occupancy formation. C++ programing language	Traffic flow (MAPE 5%) Speed and Area occupancy relationship (under-predict congestion)
Huynh *et al.* (2013)	Using social force model to simulate interaction between the left-turn and opposite straight-through vehicles. Using PTV VISWALK software.	Traffic flow
Babu *et al.* (2015)	Using social force model and the intelligent driver model to simulate heterogeneous traffic at mid-block.	Individual Trajectory Simulation (MAPE lateral 1.41% and longitudinal 3.15%) Performance of the model for lane affinity.
Gowri *et al.* (2015)	Microsimulation model describes the weaving and accumulating behaviors near the stop line of TW at signalized intersection. The simulation is developed based on C++ language using Object-Oriented Programming (OOP).	Delay (mean in real data 46 s and simulation 52 s)
Ma *et al.* (2017)	Proposed two-dimensional model to simulate both longitudinal and lateral	Travel time (mean real data 15.0 s and simulation 15.1 s).

	movement of left-turning car at two-phases mixed-flow signalized intersection.	Trajectory (Spatial coverage of turning trajectories 88.8%). Distribution of Post-Encroachment Time, PET (mean in real data 4.13s and simulation 4.31s).

Based on these above indicators, yielding the dissertation's scope, the microscopic indicators are emphasized. Two new indicators are introduced, which are total turning angle and low-speed duration, for model evaluation. As mentioned in simplifications, the two parameters determining vehicle's movement are speed and moving direction. The vehicle's positions by time are updated from the current position based on how far and which moving direction that vehicle moves within a time step. Thus, the two indicators, speed distribution and total turning angle, are suggested to quantitative these two parameters. In addition, due to the focusing on tackling conflict, the low-speed duration and total turning angle of each OD-pair are proposed in order to quantitative conflict-solving model. Regarding vehicles' locations, lateral position, trajectory map, and coverage area are other conventional microscopic indicators for validating the model. They are, therefore, also taken into account in the validation. In summary, the travel time, total turning angle, and low-speed duration are targeted for examine the regular movement model and the conflict-solving model. The lateral position, trajectory map, and coverage area are aimed for the collective behavioral model.

Besides individual observation, the study also analyzes the results under an overall view. As the essential advantage of the microscopic simulation, the interaction and reaction of each individual finally results in the traffic status of entire roundabout. For that reason, the performance of the entire roundabout is essential for validation. Thus, the macroscopic characteristics are also examined, including traffic flow, speed distribution, and area occupancy.

The mean absolute percentage error (MAPE), a goodness-of-fist measure, used by Babu *et al.* (2015); Swamidass (2000), is utilized to examine the accuracy. Swamidass (2000) stated that MAPE is appropriate for monitoring the goodness-of-fit between predicting and actual data. Lewis (1982) postulated the scale of interpretation of MAPE value that the model is validated as <10% - highly accuracy, 11-20% as good, 21-50% as reasonable, >50% inaccurate.

6.2 Travel time

The first microscopic indicator is travel time. It is the duration from the moment vehicles pass through the pedestrian zebra crossing to enter roundabout until it pass again to exit. It is the parameter that strongly affected by velocity, travel path, density, and conflict-solving duration. The key factor that prolongs the travel time are the conflicts with other flows and desired speed. Regarding the non-conflict situation, the TW keeps on running towards the desired direction and velocity. The travel time, in this case, is the smallest one for an OD pair. When facing a conflict, one of the involved TWs has to slow down and change its moving direction. The travel time of the TW, thereby, is higher than the non-conflict scenario. The more number of conflicts TW faces, the longer the travel time is. It is also that the more effective of conflict-solving model, the higher accuracy of the simulated travel time.

The travel time, hereby, focuses solely on TW, a non-lane-based vehicle with complicated movement. The presented values are grouped into pairs of OD. The travel time from the developed simulator, Table 6.4, and from PTV VISSIM, Table 6.7. Figure 6.1 is the graph of the travel time of the OD pairs, which have twenty-five samples. As shown in and Table 6.6, the MAPEs are varying widely from 2.9% to 102.8% according to the OD pair. The mean MAPE is 28.1%, which could be considered as reasonable results. The mean MAD, 4.7 s in Table 6.6, is acceptable compared to the maximum travel time, 27.4 s in approach 1 to 2. Even the proposed model is less accurate than the one in PTV VISSIM that both the MAPE and MAD, Table 6.8 and Table 6.9, the slight differences also show that the model could be considered as good in travel time. MAPE of VISSIM is smaller, 23.0%, but the MAD is higher, 4.9 s.

Table 6.4. Mean travel time of TW from the developed simulator

Developed Simulator		**Exiting Approach**					
		1	**2**	**3**	**4**	**5**	**6**
Entering Approach	**1**	-	27.4	25.0	15.6	11.4	7.4
	2	5.5	-	0.0	20.5	17.4	15.9
	3	10.5	3.6	-	22.4	20.3	18.7
	4	15.9	14.5	10.7	-	0.0	17.8
	5	17.6	18.0	13.8	0.0	-	16.9
	6	21.9	23.4	19.7	11.2	0.0	-

Unit: Second

Table 6.5. MAPE travel time between the developed simulator and the real data

MAPE Developed Simulator		**Exiting Approach**						**Mean**
		1	**2**	**3**	**4**	**5**	**6**	
Entering Approach	**1**	-	47.3	31.8	19.0	42.5	21.4	28.1
	2	52.3	-	-	29.4	44.5	33.0	
	3	12.1	23.6	-	40.4	46.0	2.9	
	4	19.1	18.0	22.5	-	-	102.8	
	5	7.7	14.7	13.8	-	-	-	
	6	14.9	18.4	14.4	9.5	-	-	
Unit: %								

Table 6.6. MAD travel time between the developed simulator and the real data

MAD Developed Simulator		**Exiting Approach**						**Mean**
		1	**2**	**3**	**4**	**5**	**6**	
Entering Approach	**1**	-	13.0	7.9	3.0	4.8	1.6	4.7
	2	2.9	-	-	6.0	7.7	5.3	
	3	1.3	0.9	-	9.0	9.3	0.5	
	4	3.0	2.6	2.4	-	-	18.3	
	5	1.3	2.7	1.9	-	-	-	
	6	3.3	4.3	2.8	1.1	-	-	
Unit: Second								

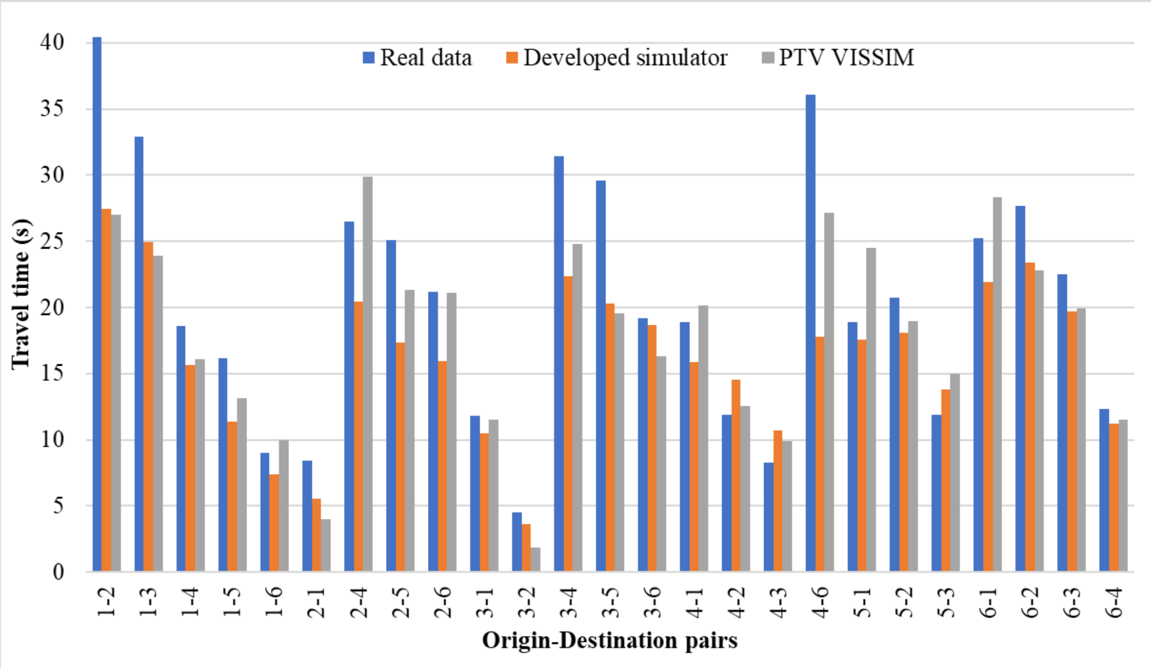


Figure 6.1. Comparison chart of travel time between the developed simulator, real data, PTV VISSIM

Table 6.7. Mean travel time of TW from PTV VISSIM

PTV VISSIM		Exiting Approach					
		1	**2**	**3**	**4**	**5**	**6**
Entering Approach	**1**	-	27.0	23.9	16.1	13.1	10.0
	2	4.0	-	36.5	29.9	21.3	21.1
	3	11.5	1.9	-	24.8	19.5	16.3
	4	20.2	12.5	9.9	-	28.5	27.1
	5	24.5	19.0	15.0	0.0	-	31.3
	6	28.4	22.8	19.9	11.6	2.9	-

Unit: second

Table 6.8. MAPE travel time between PTV VISSIM and the real data

MAPE PTV VISSIM		Exiting Approach						**Mean**
		1	**2**	**3**	**4**	**5**	**6**	
Entering Approach	**1**	-	49.7	37.6	15.6	23.6	-	23.0
	2	110.2	-	-	11.3	17.9	0.3	
	3	2.3	-	-	26.6	51.4	17.7	
	4	6.2	5.1	16.2	-	-	33.1	
	5	22.8	9.1	20.6	-	-	-	

	6	11.1	21.4	12.9	6.5	-	-	
Unit: %								

Table 6.9. MAD travel time between PTV VISSIM and the real data

MAD PTV VISSIM		**Exiting Approach**						**Mean**
		1	**2**	**3**	**4**	**5**	**6**	
Entering Approach	**1**	-	13.4	9.0	2.5	3.1	-	4.9
	2	4.4	-	-	3.4	3.8	0.1	
	3	0.3	-	-	6.6	10.1	2.9	
	4	1.3	0.6	1.6	-	-	9.0	
	5	5.6	1.7	3.1	-	-	-	
	6	3.2	4.9	2.6	0.7	-	-	
Unit: Second								

6.3 Total turning angle

As a crucial parameter that decides TW's movement, the turning angle is a reasonable indicator to quantitative the simulated TW. The total turning angle of each OD pair is, hereby, proposed to validate the developed simulator. It is the cumulative turning angle of a vehicle from the entering position to the exiting position. It firstly depends on the direction of entering and exiting approach. As the larger turning angle from entering direction to exiting direction, the value of the total turning angle is also larger. Moreover, it also depends on the number of conflicts that vehicles face. Similar to the travel time, the more conflicts the vehicle solves, the larger the total turning angle results. For that reason, it is a promising indicator that reflexes the vehicle moving and tackling conflicts. The time resolution of the collected total turning angle from the developed simulator and PTV VISSIM are rescaled into 0.5s, which is identical with the one of the extracted data.

As illustrated in Table 6.10, the MAPE of the total turning angle ranges from 6.9% to 18.0%. The small MAPE values are often achieved in the OD pair that entering and exiting directions are almost straight, for example, pair 1-4, 2-5, 3-6. It is understandable phenomena that vehicles with minimum turning angle to reach the destination will have the smallest MAPE. Overall, all the OD pairs have good values of mean MAPE, 12.5%. The developed simulator, therefore, could be considered as good in association with the total turning angle. MAPE results from PTV VISSIM range from 2.8% to 66.7%, which is much broader than the developed simulator. The mean MAPE, 27.8%, is higher than the developed simulator. Both the developed simulator and VISSIM has a smaller total turning angle value in all OD pairs compared to real data. That because both two simulations could not fully capture the TW's maneuver in terms of frequency as well as the magnitude. The developed simulator gets one step closer regarding reproducing the maneuverability of TW in the ground truth.

Table 6.10. Comparison of total turning angle for each OD pair

OD pair	Real data (degree)	Developed Simulator (1) (degree)	MAPE (1) (%)	PTV VISSIM (2) (degree)	MAPE (2) (%)
1-3	1096.1	995.0	10.2	1128.2	2.8
1-4	498.2	465.9	6.9	870.9	42.8
2-5	669.7	608.4	10.1	663.2	1.0
2-6	633.5	547.5	15.7	853.3	25.8
3-1	331.5	369.1	10.2	782.0	57.6
3-6	444.2	497.4	10.7	266.5	66.7
4-1	747.2	659.2	13.3	608.2	22.8
4-2	506.1	441.6	14.6	364.4	38.9
5-1	710.6	627.3	13.3	1051.3	32.4
5-2	730.6	645.8	13.1	829.7	11.9
6-3	884.9	775.2	14.1	766.7	15.4
6-4	595.8	504.9	18.0	515.4	15.6
		Mean	**12.5**	Mean	**27.8**

6.4 Low-speed duration

Mentioned above as the second indicator that quantitative the effectiveness of the conflict-solving model, the low-speed duration is the period of time that a vehicle moves slower than a determined speed. It describes the mean total duration that a vehicle slows down, speeds up, and maintains low speed to deal with conflicts. The more numbers of conflict, the longer low-speed duration is. Similarly, the more sophisticated of conflicts, the longer duration that vehicle travels at low speed. The limit of low speed here, 2.4 m/s, is assumed that is double pedestrian's speed in Chang and Wang (2011). The assumption is firstly based on the observation that TW should travel faster than pedestrians at least twice. Secondly, the range 0-2.4 m/s occupies 28.55% of the speed distribution.

Table 6.11. Comparison of low-speed duration

Speed Range (m/s)	Real Data (s)	Developed Simulator (s)	PTV VISSIM (s)
0 - 2.4	7.47	7.84	3.88
	MAPE	*4.95%*	*48.06%*

The mean duration that a single TW travel below the low-speed limit is presented in Table 6.11. The developed simulator results 7.84 s, MAPE is only 4.72%. This result is highly accurate compared to real data. Regarding the low-speed duration, the model could be seen as high accuracy, based on Lewis (1982). It is also far superior to VISSIM, MAPE 92.53%. The VISSIM result agrees with the speed analysis that the vehicles travel at higher speed than real data and rarely slow down because of conflict. The discrepancy, hereby, demonstrates the efficacy of the proposed model, especially the conflict-solving model, compared to the current popular model in PTV VISSIM.

6.5 Lateral position

The positions of vehicles while traveling inside the roundabout are strongly dependent on the movement phases, entering and exiting approaches, and interaction of the vehicle with other vehicles inside the roundabout. Owing to the distribution of lateral positions of the flow, the space usage and operational efficiency of roundabout could be investigated. Thus, the distribution of the lateral positions is a useful qualitative indicator for validation. Four crossing sections, A-A, B-B, C-D, and D-D, are colored in Figure 6.2. They are placed in order to observe objectively the three phases of vehicles at approaches 1 and 2. The distributions of lateral positions are portrayed in Figure 6.3.

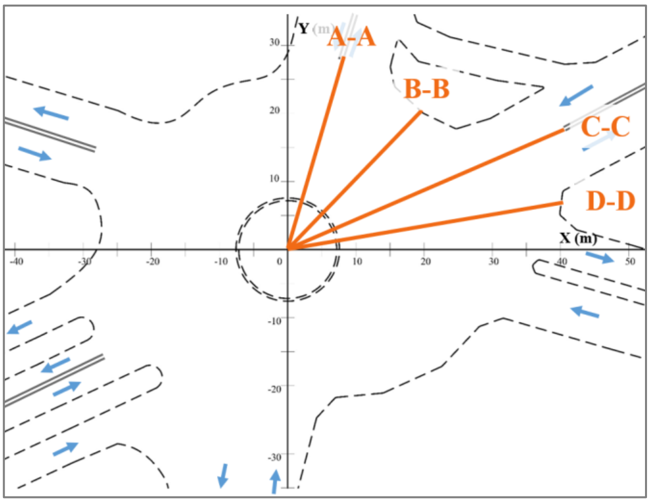


Figure 6.2. Crossing sections of the roundabout in order to observe lateral position

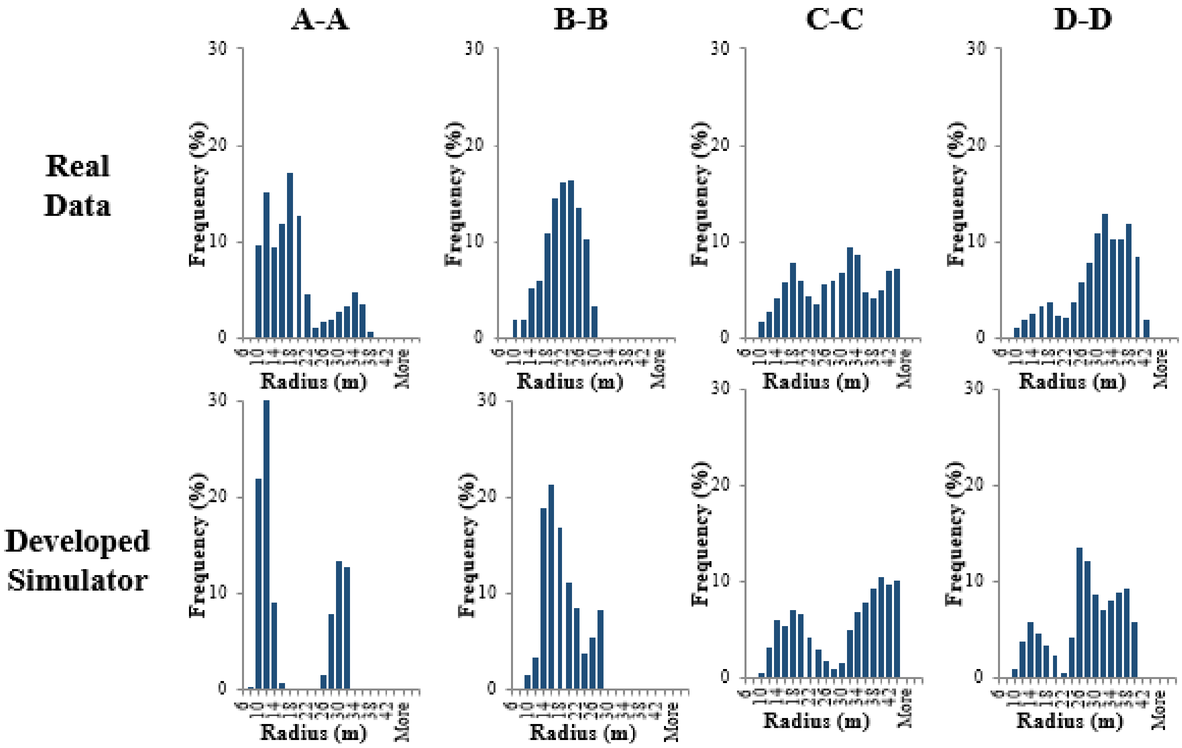


Figure 6.3. Distribution of lateral position at crossing sections

Section A-A shows the circulating and diverging flows of vehicles, who are going to exit to approach 6. At this stage, the vehicles start diverging and go towards approach 6. In Figure 6.3, both real data and the developed simulator exemplify obviously distribution of two flows. The graph of the developed simulator is separated and has a high proportion in a smaller area. Section C-C also shows the alike circulating and diverging flows with a wider variation. While the real data exposed an equal distribution along the entire section, the result from the developed model is intensive in a small area. Especially, vehicles that exit at approach 1 were in the half of the diverging process. It is showed in the chart of the developed simulator.

At section B-B, the entering flow from approach 2 merges with circulating flow. The graph of the real data and the developed simulator exposes a similar trend. However, the separation between merging and circulating flow is much clearer in the developed simulator. The reason is the developed model is less variation in trajectory than the ground truth. Section D-D also exposes close phenomena with section C-C, however, the high proportion is shifted into the right side. To sum up, at crossing sections B-B, C-C, and D-D, the developed model is proven a good representation of the space usage of the roundabout both in the trend and the frequency. Section A-A has a discrepancy due to the variation of the models in trajectory.

6.6 Trajectory map

Besides the numerical analysis, the visual comparison is also essential for qualitative evaluation. The comparison of individual trajectory is once applied in the traffic microsimulation in heterogeneous traffic by Babu *et al.* (2015). In the below part, the trajectory map of 250 TWs from the developed simulator, Figure 6.4, and from PTV VISSIM, Figure 6.5, are portrayed for comparison. Trajectories of 80 cars from PTV VISSIM are also illustrated in Figure 6.6 for reference.

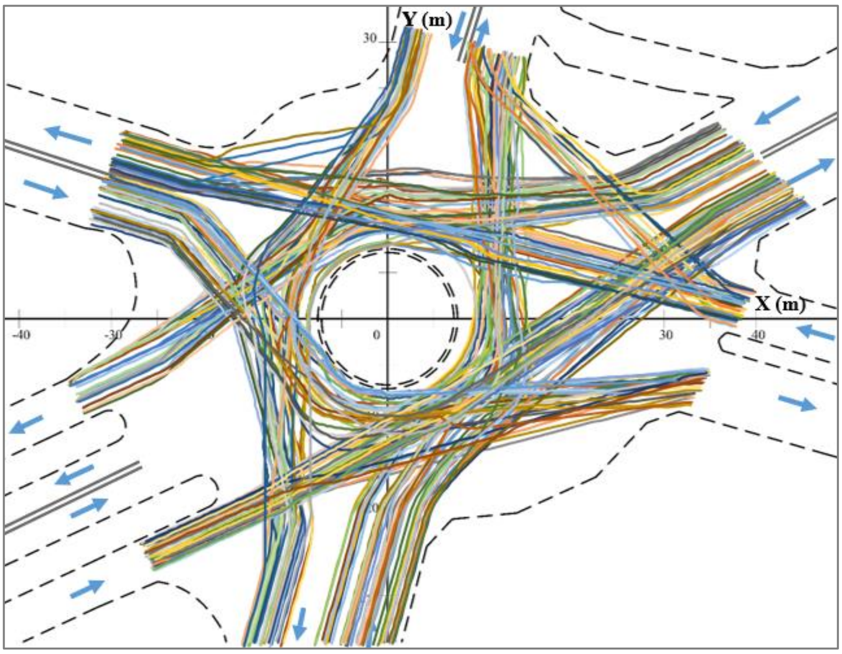


Figure 6.4. Trajectory map of 250 TWs from the developed simulator

As in Figure 6.4, the sinuous trajectories of the developed model exposes the frequent maneuvering of TW. They are concentrated and mainly straight through compared to real data. The less varying trajectories show the limitation of the simulator, especially the conflict-solving model. On the other hand, the trajectories of TWs in PTV VISSIM, Figure 6.5, still have a lane-based shape and similar to trajectories of car in Figure 6.6. The TWs utilize the entire roundabout and move in the circular shape. The diverging area clearly exposes the weakness of lane-changing behavior in TW's model. Lack of maneuvering behavior, which is the uniqueness of TW, could be observed. That one more time confirms the manner of modeling TW in PTV VISSIM, which is splitting lane into narrower stripe and increasing the frequency of lane-changing.

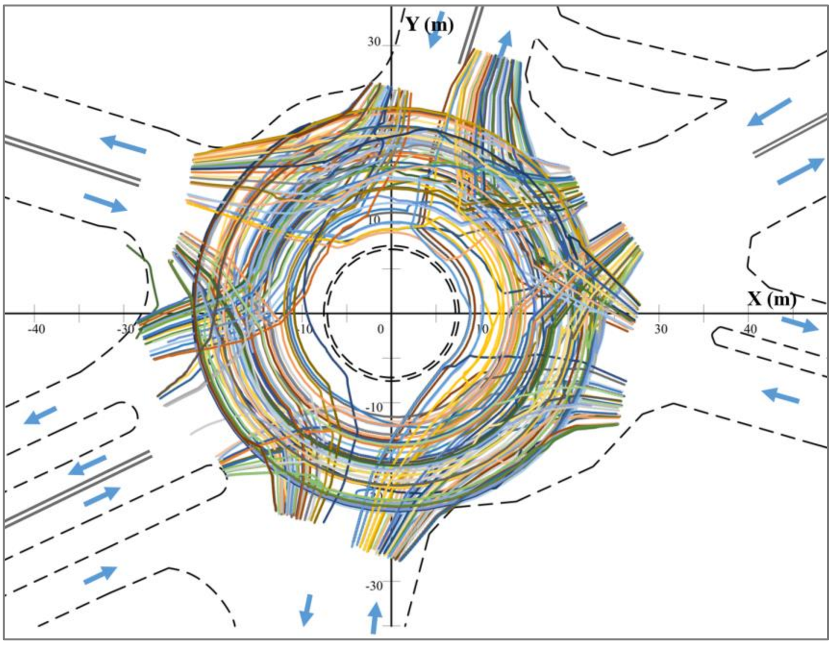


Figure 6.5. Trajectory map of 250 TWs from VISSIM

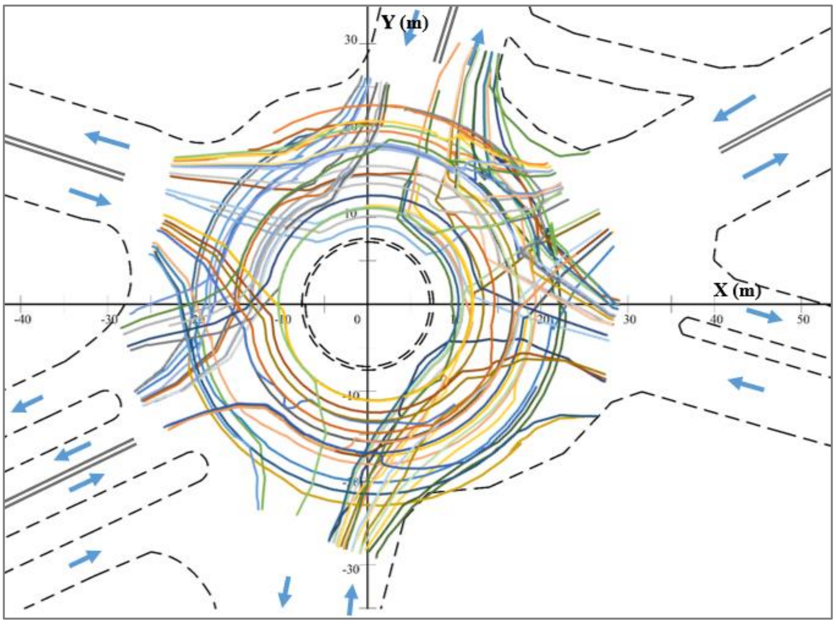


Figure 6.6. Trajectory map of 80 cars from VISSIM

6.7 Coverage area

The coverage area is the quantitative indicator of the trajectory map. It is the proportion of the overlapped area by real data and other simulation results. The calculation is based on the small cell that each cell dimensions are 0.2x0.2 m. The number of overlapped cells will be counted and analyzed. The results, in Figure 6.7, show that the developed simulation has a better coverage area, 68.81%, compare to PTV VISSIM, 60.00%. On the other hand, the corrected proportion of developed simulator lower, 80.32%, than PTV VISSIM, 87.29%. The difference is not so high, less than 6.97%.

By visual observing, it is obvious that the developed simulator is less variated compared to the real data or VISSIM. Only the center area of the roundabout is used. The outer lane space is unused. The PTV VISSIM has a deathly drawback that TWs use entire space like a lane-based vehicle. The model does not expose properly to the nature of vehicles' properties.

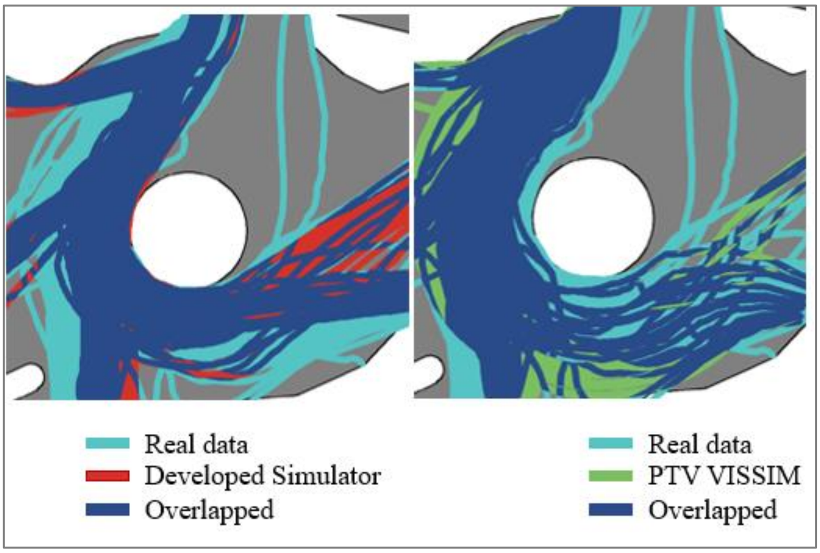


Figure 6.7. Coverage area between real data and developed simulator (right graph), real data and PTV VISSIM (left graph)

6.8 Traffic flow

The first macroscopic indicator for comparison is traffic flow. Non-lane-based and lane-based vehicles are separated for comparison. The developed simulator has mean MAPE 10.1% for all six approaches. Compared with real data, the developed simulator, thereby, could be considered as good regards to throughput flow. Compared with PTV VISSIM, all six approaches in the developed simulator have much better MAPE values, e.g., approach 5 is two times smaller. That exemplifies a superior of the proposed model compared to the popular model in PTV VISSIM.

Table 6.12. Comparison of traffic flow and traffic proportion

Approach	Vehicle type	Video	Simulator		PTV VISSIM	
		Traffic flow (vehicle/h)	Traffic flow (vehicle/h)	MAPE (%)	Traffic flow (vehicle/h)	MAPE (%)
1	TW	2748	2606	5.2	2506	8.8
	Car	324	306	5.6	200	38.1
2	TW	1620	1752	8.1	1788	10.3
	Car	132	113	14.4	143	8.3
3	TW	2748	2494	9.2	2373	13.7
	Car	156	195	24.7	190	21.7
4	TW	3612	3846	6.5	3303	8.5
	Car	288	303	5.2	264	8.2
5	TW	2172	1903	12.4	1515	30.2
	Car	144	132	8.3	121	15.8

6	TW	3108	2773	10.8	2629	15.4
	Car	264	240	9.1	210	20.3
	Mean			10.1		16.6

6.9 Speed distribution

The eighth measurement, speed distribution, is analyzed as in Figure 6.8. The speed is tracked from entering until exiting the roundabout. Compared to the real data, the shape of speed distribution is shifted to the right side. The mean speed value is 3.3 m/s, MAPE 9.09%, could be considered as high accuracy. The shape of the distribution is similar to the normal distribution and the real data. On the other hand, the result in PTV VISSIM in Figure 6.9 is hugely different. In PTV VISSIM, the speed is much faster, mean speed is 5.09 m/s, STD 2.51 m/s, and high speed, over 5 m/s, cover a larger proportion 48.12%. The distribution shape does not follow the normal distribution rule. The reason for this difference is that TWs in PTV VISSIM run faster and mostly cross the other in a conflict situation - overlapped phenomena. Besides, according to the calibration of PTV VISSIM, the slow speed distribution leads to high remaining vehicles, reduces the total traffic volume and prolongs the travel time. Thus after calibration, the input speed in VISSIM is much higher than real data.

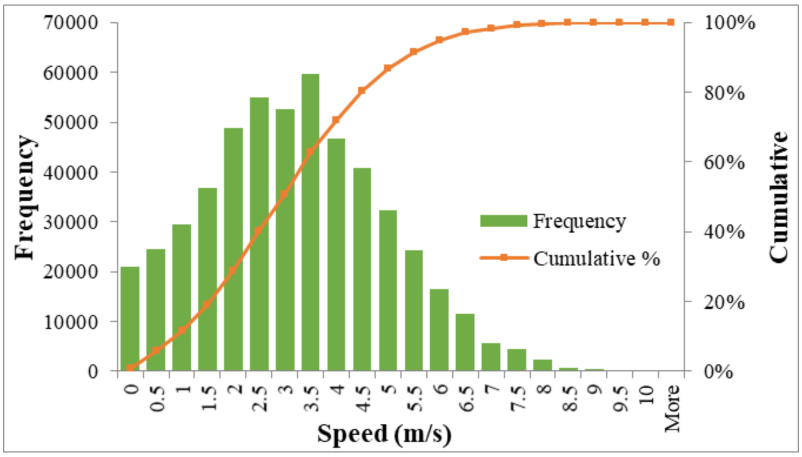


Figure 6.8. Speed distribution from developed simulator

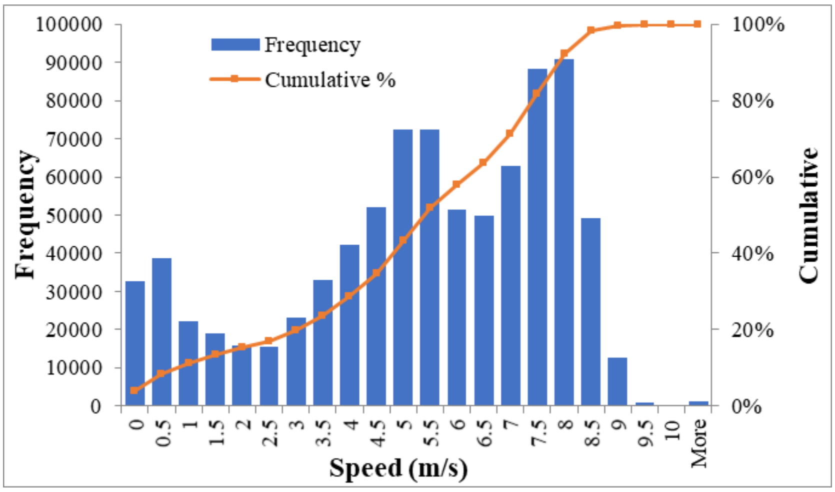


Figure 6.9. Speed distribution from PTV VISSIM

6.10 Area occupancy

As mentioned in section 3.4.3, area occupancy is more suitable measurements for roundabout than density. In the study, it calculated for ten times as presented in Table 6.13. The mean value from the developed simulator is 0.1462, which has MAPE 33.37% compared to real data. The proposed model is, therefore, could be considered as reasonable. The higher value could be understood as there are more vehicles inside roundabout at a moment than real data. It is matched with the lower mean speed in section 6.9 and longer low-speed duration result in section6.10. The developed model is superior to PTV VISSIM, MAPE 58.6%, in area occupancy due to the high speed and unsolved conflict. The vehicles in VISSIM quickly exit the roundabout and usually overlap others in a conflict situation. Thus, the area occupancy of VISSIM is less than the real data.

Table 6.13. Calculated area occupancy from the developed simulator

No.	Motor Area (m^2)	Total Motor Area (m2)	Car Area (m2)	Total Car Area (m2)	Roundabout Area (m2)	Area Occupancy
1	1.32	107791.00	8.05	107791.00	2650.50	0.1356
2	1.32	120400.00	8.05	120400.00	2650.50	0.1514
3	1.32	115517.00	8.05	115517.00	2650.50	0.1453
4	1.32	115679.00	8.05	115679.00	2650.50	0.1455
5	1.32	115059.00	8.05	115059.00	2650.50	0.1447
6	1.32	118035.00	8.05	118035.00	2650.50	0.1484
7	1.32	113843.00	8.05	113843.00	2650.50	0.1432
8	1.32	123738.00	8.05	123738.00	2650.50	0.1556
9	1.32	118129.00	8.05	118129.00	2650.50	0.1486
10	1.32	114181.00	8.05	114181.00	2650.50	0.1436

Mean	0.1462

Table 6.14. Calculated area occupancy from PTV VISSIM

No.	Motor Area (m^2)	Total Motor Area (m2)	Car Area (m2)	Total Car Area (m2)	Roundabout Area (m2)	Area Occupancy
1	1.32	52309.73	8.05	31948.23	2650.50	0.0530
2	1.32	30828.10	8.05	39784.29	2650.50	0.0604
3	1.32	46340.18	8.05	65450.79	2650.50	0.0777
4	1.32	27838.02	8.05	41008.42	2650.50	0.0593
5	1.32	27838.02	8.05	41008.42	2650.50	0.0574
6	1.32	27838.02	8.05	41008.42	2650.50	0.0632
7	1.32	27838.02	8.05	41008.42	2650.50	0.0590
8	1.32	27838.02	8.05	41008.42	2650.50	0.0620
9	1.32	27838.02	8.05	41008.42	2650.50	0.0598
10	1.32	27838.02	8.05	41008.42	2650.50	0.0623
					Mean	0.0614

6.11 Summary

This chapter presented a series of results and indicators for validating the developed simulator. Totally nine indicators are used for both macroscopic and microscopic validation. The total turning angle and low-speed distribution are uniquely proposed in this study for validation. Among nine indicators, two of them are qualitative indicators, lateral position and trajectory map, and the others are quantitative indicators as listed below,

Microscopic indicators:

- Travel time
- Total turning angle
- Low-speed duration
- Lateral position
- Trajectory map
- Coverage area

Macroscopic indicators:

- Traffic flow
- Speed distribution
- Area occupancy

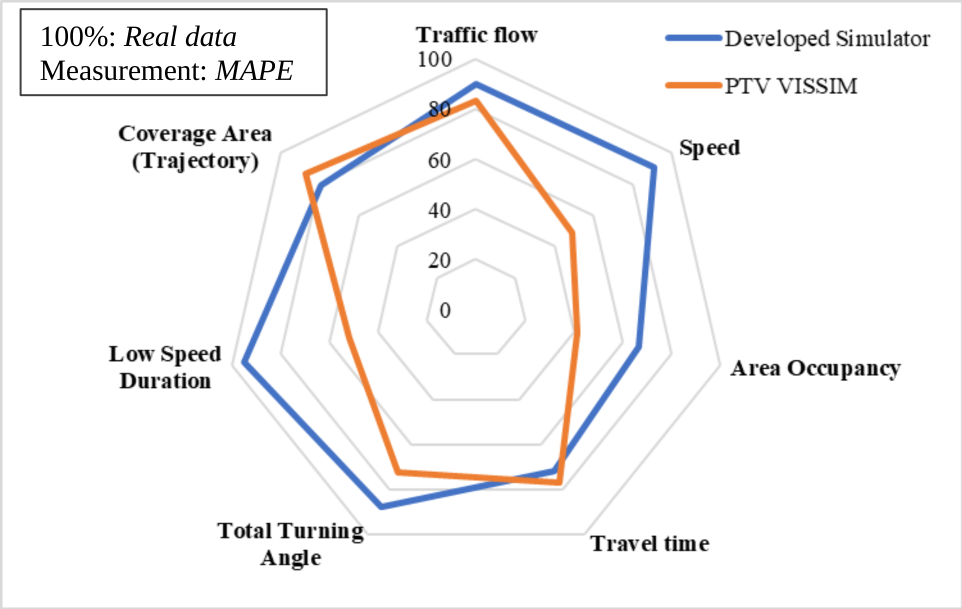


Figure 6.10. Summary of validation under seven indicators using MAPE

The quantitative indicators are collected and portrayed in Figure 6.10. The real data is taken as the base for validation, 100%. The capability of the developed simulator and PTV VISSIM are presented on the accuracy scale under the radar chart format. Related to the macroscopic indicators, the developed simulator shows good results in most of the indicators. Especially, the speed is quite inferior to the PTV VISSIM. Concerning the microscopic side, the results are also good in travel time, turning angle, and low-speed duration. The coverage area, however, is reasonable but is still better than PTV VISSIM. In total, the developed simulator is good in representing both macroscopic and microscopic characteristics of the heterogeneous traffic at the roundabout and is superior to the popular commercial software for heterogeneous traffic, PTV VISSIM.

Chapter 7. CONCLUSION AND FUTURE WORK

The study is now summarized with achievements, contributions, limitations, and recommendations. Concerning research interest, the study proposed the novel motorcycle's interaction model at the individual level. The model potentially applies and expends in the future to improve the accuracy of the future microscopic simulations. It could be a useful tool for policy tests as well as new geometric design tests.

7.1 Summary of the work

The opening section mentioned the strong necessaries of models for heterogeneous traffic and discussed the considerable potential of roundabout in developing countries. Due to the high proportion of TW, two-wheelers, in the near future, the traffic manager in developing countries needs a thriving tool for evaluating the new infrastructure under heterogeneous traffic conditions. The tool that can fully capable of reproducing traffic patterns that emerge in the presence of heterogeneous traffic conditions. However, none of the studies have ever proposed the microscopic model to describe the interaction and making-decision process of non-lane-based vehicles at roundabout. Based on that background, the dissertation addresses this gap by proposing a novel psychological model to simulate the non-lane-based vehicle, TW.

The primary objectives of the study are to analyze the characteristics of TW and to propose a psychological reaction model for reproducing the grouping and conflict-solving behavior. In order to achieve the objectives, the study is established in five stages. The first stage is a literature survey on microscopic modeling heterogeneous traffic, merits as well as demerits of roundabout, and the research gap of modeling TW at roundabout. In the second stage, the survey site, data collection, extraction methods, and data analysis are carried. The third stage focuses on formulate three main models, regular movement model, collective behavior, and conflict-solving models. The detail of the model structure, formulations, and controlling parameters, are presented. In the fourth stage, the efforts of building a microscopic simulator are reported. The model is lately implemented employing the agent-based modeling technique, including geometry setup, vehicle generation, movement phases, input flow. The first half of data, 50%, is using for calibration and the other is using for validation. In the fifth stage, the developed simulator is quantitatively and qualitatively validated based on nine indicators.

Altogether, the results show that the proposed model and developed simulator is good in capturing the grouping and conflict-solving behavior of TWs in the ground truth. Related to macroscopic indicators, the mean MAPE of traffic volume and speed distribution are 10.1% and 9.09%, respectively, could be considered as highly accuracy. The mean MAPE of area occupancy is higher, 33.37% but it is still considered as reasonable. According to the microscopic indicators, the total turning angle and low-speed duration get highly accurate results, which means MAPE are 15.48% and 4.72%, respectively. The travel time is also good, with mean MAPE is 28.1%. The coverage area is up to 68.81% of the real data. Based on the analysis of results, it could be concluded that the proposed model is good in reproducing TW characteristics and the study accomplished its objectives.

The developed simulator is also compared with the popular commercial micro-simulation software, PTV VISSIM. The six over seven quantitative indicators demonstrate the superior of the developed model. The PTV VISSIM has advantage in travel time. However, that comes from the conflict solving capability, showed in speed and low-speed duration, for the accurate traffic flow and travel time.

7.2 Key findings

Key findings of this study are derived from the literature review, data analysis, pilot model development, model implementation, and validation as follows,

- In the literature review part, the study identifies the two constitutions of heterogeneous traffic that are the traffic performance rule and the appearance of small vehicles. If only one of these factors is active, traffic will not exhibit heterogeneous traffic characteristics. That conclusion emphasizes the unique characteristics of heterogeneous traffic compared to homogeneous traffic.
- In data analysis, section 3.5.2, the relationship between T.A.R and speed is formulated. Generally, as faster vehicle moving, lower possible turning angle vehicle can spin. At high speeds, the maneuverability of TW is limited by physic rules, e.g. owing to the inertial restriction. The driver intends to perform large-angle maneuvers at a low speed. The study estimated the relationship between T.A.R and speed at roundabout using a power curve. The estimated curve is highly fit with the data, which R is 0.929.
- Section 3.5.4 exposes that while tackling the conflict, TWs accept a very small critical gap, 1.25 s. This value is smaller as the increase of TW's proportion. This value could be explained due to the advantages of small size, high maneuverability, and high power-to-weight ratio. TWs can utilize the small gap effectively and have more options to deal with conflicts.
- Section 3.5.5 reveals that TW also maintains a clear space around themself. The safety space concept is, therefore, effective at the roundabout. The clearance has an ellipse shape and expands as the increase of velocity.

- The proposed model, which is formed by the collective and conflict-solving model, recorded a good level of reproducing the real scenarios. Six over seven quantitative indicators are validated as good while the other is reasonable, refer Figure 6.10 for more detail.

7.3 Contributions

The study contributes to both the current state of knowledge as well as practice. Related to the academic field, the study has the following contribution,

1. Proposes applying the natural creature group model, which is effective and highly accurate, in traffic simulation.
2. Concept and formulate the models describe microscopic movements of vehicle based on collective behavior and conflict-solving model.
3. Demonstrate the effectiveness of ODD protocol for implementing models in traffic simulation using agent-based modeling technique.
4. Introduce novel microscopic indicators, total turning angle, low-speed duration, for validating the simulation result.

Secondly, the contributions in the practical field are as the following,

1. Develop a traffic simulator as an effective tool to forecast roundabout performance under heterogeneous traffic. The simulator itself is a powerful tool to carry out policy tests or future studies on heterogeneous traffic. It also can be used to optimize the traffic signal cycle at roundabout.
2. Propose a novel manner, psychological decision-making model, to improve the accuracy of the current micro-simulations. Since cars, in heterogeneous traffic, do not always move in the lane. The model could be expanded to simulate not only non-lane-based but also lane-based vehicles under the limited lane discipline.
3. The developed simulator could be upgraded for safety evaluation between Car and TW, Car and Pedestrian, TW and pedestrian, especially in the shared space area.
4. Achieve the first step for ultimate goal, propose a guideline for roundabout design under heterogeneous traffic.
5. Make foundations for future research on vehicle interaction with autonomous vehicles and traffic simulation using the agent-based modeling technique.

7.4 Recommendations for future works

The study contributed the novel model to simulate the interactions of non-lane-based vehicles at the roundabout. For future applications, traffic engineers could follow this trait to develop their own simulation or to improve the accuracy of their simulators. Moreover, the model could be expanded and upgraded for future objectives, for example, evaluate safety at roundabout, optimize the design of roundabout or traffic light cycle. The model is designed flexibly to adapt new traffic rules, which is suitable to examine the traffic under distinctive scenarios. Last but not least, due to the psychological nature of the model, it is useful to simulate the future transportation network where human-driving and semi-autonomous vehicles collaborate.

Even the dissertation achieves its objective with several merits, there are remaining limitations listed as below,

- Concerning data collection, more study cases should be considered to improve the calibrated parameters. A single roundabout has limited the variation of data. A large size roundabout, roundabout without traffic signal, and roundabout with unbalanced approaches should be analyzed in order to consolidate the conclusions.
- Related to modeling, TWs still suddenly maneuver and not actively avoid conflict. The proposed model could improve by proposed the long-range conflict-solving model in the tactical level, not the operational level. The future model should able to generate alternatives route to achieve a destination. It is expected to make the TWs' decision more logical and practical and to increase the variation of TW's trajectories.
- The emergent or aggressive behaviors are not taken into account as a result of the study' scope. The future study, especially safety evaluation, should improve this point in order to increase the accuracy.
- The developed simulator is unsuitable for examining the traffic network with a numbers of roundabout. It is limited for studying a single roundabout only. Future study could implement and integrate the developed model into other simulation software for simulation a network of roads, roundabouts, and intersections.
- Future steps in making guidelines for roundabout should be conducting a wide range of simulations under divergent scenarios for forecasting roundabout performance. The developed simulator should be applied in new geometries and traffic rules.

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APPENDIX A. PUBLICATIONS

1. TRINH, L.T., SANO, K., JAYASINGHE A., TRAN V.T. (2018). Two-player Game-theory-based Analysis of TW Driver's Behavior at a Signalized Intersection. *Asian Transport Studies*, Vol 5, Issue 2, 2018, 272-291

2. TRINH, L.T., SANO, K., HATOYAMA K. (2020). Development of the Conflict-Solving Model to Simulate the Mixed Traffic Behavior. *Transportation Research Board Annual Meeting 2020, Washington DC, United States*.

3. TRINH L.T., SANO K., HATOYAMA K., DE SILVA C. K. (2020). Analysis of Microscopic Characteristics of TW-oriented Mixed Traffic at Roundabout. *Journal of Traffic and Transportation Engineering (English Edition)*.

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6. LE D.D., SANO K., HATOYAMA K., TRINH L.T. (2020). An Overview of Vietnam Water-City Typology By Quantity Of Identification Elements And The Adverse Long-Term Effects By Rising Sea-Level. *Proceeding of 13th International Conference of the Eastern Asia Society for Transportation Studies (EASTS), Colombo, Srilanka, September 2019.*

APPENDIX B. ADDITIONAL INFORMATION

Table 0.1. List of collected videos ar survey site roundabout R2

R2	ID	Collectted time	Length (sec)	Note
1	R2_01	Morning	327	(card 1)
2	R2_02	Off-peak hours	327	
3	R2_03	9:00AM - 11:30AM	327	
4	R2_04	UAV Height 87m,	218	
5	R2_05	Focal F/7.1	327	
6	R2_06		327	
7	R2_07		327	
8	R2_08		220	
9	R2_09		327	
10	R2_10		327	
11	R2_11		327	
12	R2_12		292	
13	R2_13		327	
14	R2_14		327	
15	R2_15		327	
16	R2_16		45	
17	R2_17		327	(card 2)
18	R2_18		327	
19	R2_19		327	
20	R2_20		29	

Table 0.2. Survey of typical car's dimensions in Ho Chi Minh city

No.	Name	L×W×H (mm)	Weight (kg)	W (m)	L (m)
Hatchback Mini					
1	Kia Morning	3.595 x 1.595 x 1.490 mm	960	1.595	3.595
Sedan					
2	Toyota Vios	4410 x 1700 x 1475	1095	1.700	4.410
3	Toyota Altis	4620 x 1775 x 1460	1290	1.775	4.62
4	Mazda 3	4580x1795x1450	1340	1.795	4.58
5	Kia Cerato	4.560 x 1.780 x 1.445 mm	1320	1.78	4.56
6	Honda City	4.440 x 1.694 x 1.477	1124	1.694	4.44
SUV					
7	Toyota Fortuner	4795 x 1855 x 1835	1995	1.855	4.795

8	Mazda CX5	4540x1840x1670	1598	1.84	4.54
MPV					
9	Toyota Inova	4735x1830x1795	1725	1.83	4.735
Pickup					
10	Ford Ranger	5280x1860x1830	2003	1.86	5.28
Average				1.772	4.556

Table 0.3. Survey of TWs' dimensions in Ho Chi Minh city

No.	Name	L×W×H (mm)	Weight (kg)	W (m)	L (m)
TW with Manual gear transmitter					
1	Honda Future	1.931 × 711 × 1.083 mm	105	0.711	1.931
2	Honda Blade	1.920 × 702 × 1.075 mm	99	0.702	1.920
3	Honda Wave RSX	1.919mm × 709mm × 1.080mm	102	0.709	1.919
4	Honda Wave Alpha	1.914mm × 688mm × 1.075mm	97	0.688	1.914
5	Yamaha Sirius	1.940 mm×715 mm×1.075 mm	96	0.715	1.940
6	Yamaha Jupiter	1.935mm × 680mm × 1.065mm	104	0.680	1.935
7	Yamaha Exciter	1,970 mm × 670 mm × 1,080 mm	115	0.670	1.970
TW with Automatic gear transmitter					
8	Honda SH	2.130 mm × 730 mm × 1.195 mm	169	0.730	2.130
9	Honda Lead 125	1.842mm × 680mm × 1.130mm	112	0.680	1.842
10	Honda Airblade 125	1.881 × 687 × 1.111mm	110	0.687	1.881
11	Honda SH Mode	1.930mm × 669mm × 1.105mm	118	0.669	1.930
12	Honda Vision	1.863mm × 686mm × 1.088mm	97	0.686	1.863
13	Yamaha Grand	1.820mm × 685mm × 1.145mm	99	0.685	1.820
Average				0.69	1.92

Table 0.4. Surveyed list of roundabouts in HCMC

No.	Place	Number of legs	Connected Streets
1	Ho con Rua	4	Vo Van Tan + Tran Cao Van + Pham Ngoc Thach
2	Cuoi duong CMT8	6	Nguyen Thi Nghia + Ly Tu Trong + CMT8 + Le Thi Rieng + Nguyen Trai

3	Nga 5 Cong Quynh	5	Cong Quynh + Nguyen Trai + Pham Ngu Lao
4	Nga 6 Cong Hoa	6	Nguyen Van Cu + Tran Phu + Hung Vuong + Ly Thai To + Nguyen Thi Minh Khai + Pham Viet Chanh
5	Vong Xoay An Lac	5	Kinh Duong Vuong + Hau Giang + An Duong Vuong
6	Vong xoay Dan chu	7	Nguyen Thuong Hien + Ba Thang Hai + CMT8 + Nguyen Phuc Nguyen + Ly Chinh Thang + Vo Thi Sau
7	Nga 7 Ly Thai To	6	Le Hong Phoc + Ngo Gia Tu + Ly Thai To + Dien Bien Phu
8	Nga 6 Nguyen Tri Phuong	6	Nguyen Tri Phuong + Ngo Gia Tu + Nguyen Chi Thanh
9	Pham Van Dong khu Linh dong	8	Pham van dong + Kha Van Can + Linh dong
10	Pham Van Dong cong vien Gia Dinh	11	Pham Vang Dong + Nguyễn Kiệm + Nguyễn Thái Son + Hoang Minh Giam
11	Nga 3 An Lac	6	Kinh Duong Vuong + Quoc Lo 1A
12	Bung binh Phu Lam	5	Tan Hoa Dong + Ba Hon + Kinh Duong Vuong + Hong Bang
13	District 9, Hightech center 1	4	Vo Chi Cong + Lien Phuong
14	District 9, Hightech center 1	4	Vo Chi Cong + Cau vuot
15	District 11	4	Lac Long Quan + Ong Ich Khiem + Hoa Binh
16	Hiep Binh Chanh, Thu Duc district	4	Quoc Lo 1A + Quoc Lo 13
17	Ward 3, Go Vap district	6	Nguyen Thai Son + Pham Van Dong + Nguyen Kiem + Hoang Minh Giam + Bach Dang

Table 0.5. Generated vehicle's properties in Netlogo

Variable	Value/ Unit	Definition
`Turtle-own`		
`xcor`	m	X coordinate of front-middle point at the calculating time.
`ycor`	m	Y coordinate of front-middle point at the calculating time.
`velocity`	m/s	Speed of vehicle at the calculation time
`v-desired`	m/s	Desired velocity at free flow.

`Acceleration`	m/s^2 Default: 0 Could be positive (+) or negative (-)	Calculated acceleration and deceleration,
`Brake`	m/s^2	The maximum deceleration of the vehicle. It based on the brake system capability.
`direction`	Degree [0; 360]	Moving direction of vehicle, the unit vector of moving direction, at the calculation time in the global coordinate system. 0: is the North direction. Positive (+) is clockwise
`Pre-direction`	Degree [0; 360]	Moving direction of vehicle, the unit vector of moving direction, at the previous time-step time in the global coordinate system. 0: is the North direction. Positive (+) is clockwise
`Desired-direction`	Degree [0; 360]	The desired direction that the vehicle want to go. This direction is calculated at the tactical level by roundabout-travel model, goal-oriented model, conflict-solving model
`Ori-approach`	Degree [0; 360]	The direction of the entering approach that vehicle goes through.
`Des-approach`	Degree [0; 360]	The direction of the exiting approach that vehicle goes through.
`Des-patch`		The prefer exiting point at destination approach. This patch could be identified by x y coordinates system.
`Turning-angle`	Degree [-90; 90]	The angle from the current moving direction to the next-time-step moving direction. The angle that the vehicle will turn in his local coordinates system. And it is not the steering angle of the handle or of the front wheels. It represented for the magnitude of change in moving direction in the individual frame of reference. Another name is “veering angle”
`turning-angle-rate`	Degree/second TAR = abs(direction - dir-previous) / time-step	The Turning-angle-rate (TAR) depicts how fast the vehicle changing in its moving approach.
`Running-status`	1 : run outside roundabout 2 : stop at traffic signal 3 : roundabout traveling model 4 : goal-oriented model 5 : extreme case too closed boundary 6 : extreme case too closed motor 7 : extreme case too closed car	This variable show the running status of vehicle. It show which model are activate. This variable is useful for debug.
`Inside-rd?`	Yes/No	

Moving-phase	1 : outside roundabout 2 : merging 3 : circulating 4 : diverging	To recognize the movement type of vehicle based on its location, direction. To identify group and to calculate desired direction.
Extreme-case	1 : no extreme case 2 : too closed boundary 3 : too closed motor 4 : too closed car	The variable to activate the extreme case model include social force and safety zone boundary.
Extreme-boundary		Name of considered boundary position.
Extreme-motor-1		The most influential TW.
Extreme-motor-2		The second influential TW.
Extreme-car		The most influential car.

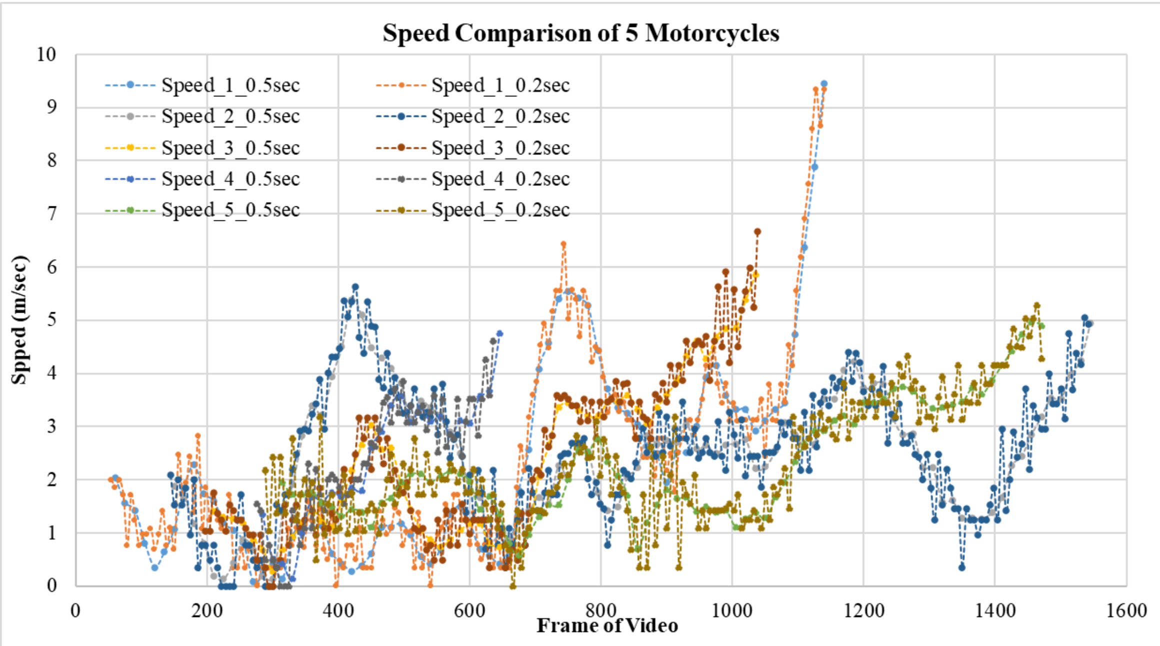

Figure 0.1. Comparison of speed between distinctive timestep of data extraction

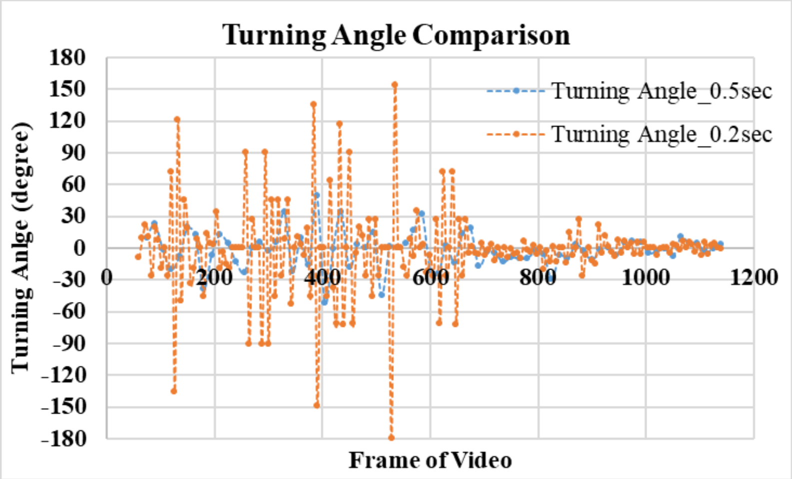

Figure 0.2. Comparison of turning angle between distinctive timestep of data extraction

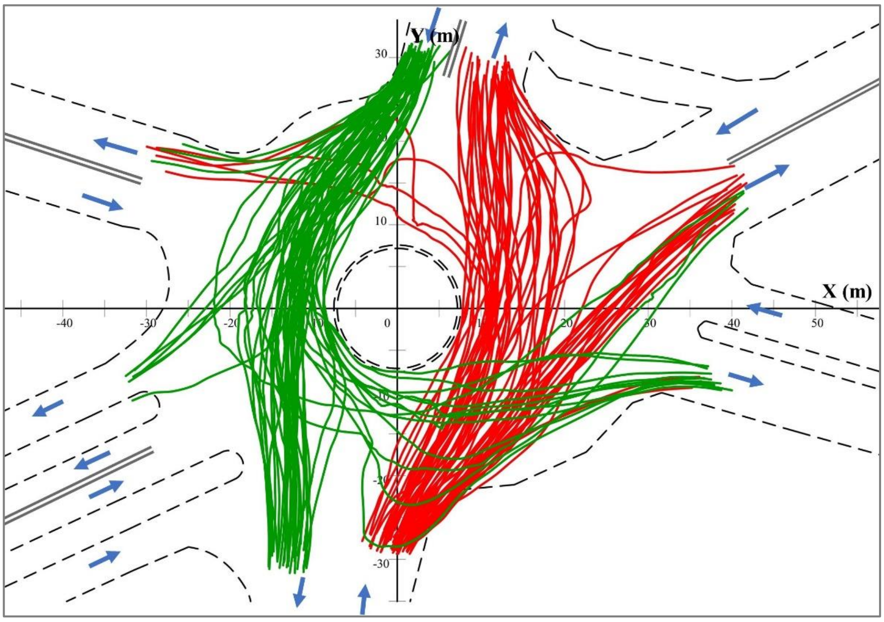

Figure 0.3. Trajectory maps of 100 TWs from entering approaches 1 and 4 from real data

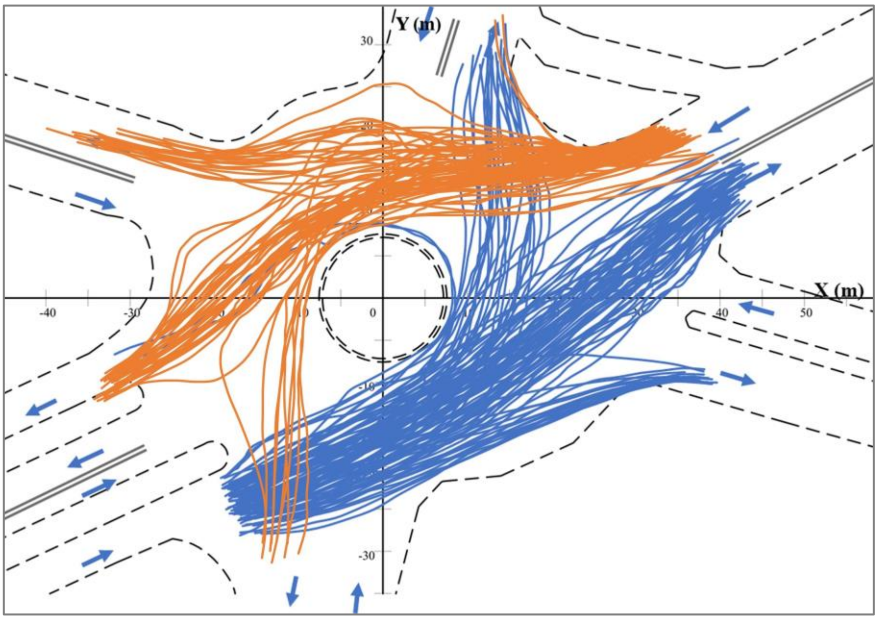

Figure 0.4. Trajectory maps of 200 TWs from entering approaches 2 and 5 from real data

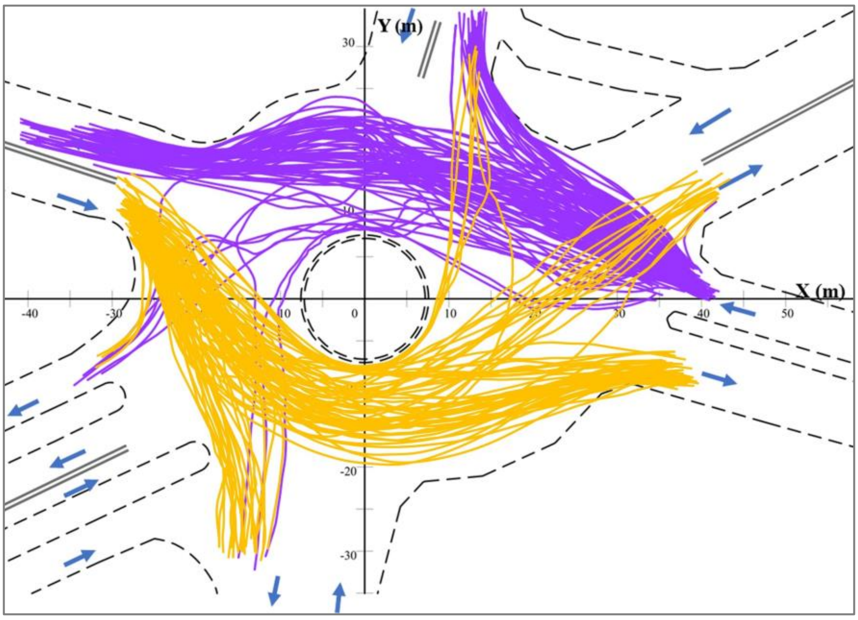

Figure 0.5. Trajectory maps of 200 TWs from entering approaches 3 and 6 from real data

PTV VISSIM calibration

For driving behavior, PTV VISSIM is using the Wiedemann (1974) model. In this study three essential parameters are calibrated, *ax* is average standstill distance, *bx_add* is addictive part of the desired safety distance, *bx_mult* is multiplicative part of the desired safety distance, Phy and Yamamoto (2019).

Table 0.6. PTV VISSIM Calibration with ax = 0.25 m

		bx_mul											
		0.5	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**
bx_add	**0.5**	12.7	12.9	12.3	12.4	12.5	12.5	12.6	13.1	13.1	13.5	13.4	13.8
	1	12.5	12.5	12.4	12.0	12.4	12.6	13.3	13.3	13.8	13.9	14.3	15.3
	1.5	12.0	12.8	12.1	12.1	12.8	12.9	13.3	13.7	14.8	15.0	15.6	16.0
	2	12.1	12.4	12.6	12.9	13.5	13.9	14.2	14.6	15.3	16.1	17.3	17.2
	2.5	12.9	13.0	13.0	13.7	14.0	14.8	15.1	15.9	16.7	17.5	17.6	18.7
	3	12.7	13.7	14.1	14.4	15.2	15.7	16.3	17.3	17.7	18.4	19.2	19.7
	3.5	14.0	14.7	15.2	15.7	16.4	17.1	17.8	18.4	19.7	19.8	20.1	21.2
	4	15.0	15.8	16.2	16.9	17.7	18.3	19.2	20.1	20.4	20.9	21.9	22.5
	4.5	16.4	16.7	17.5	18.4	19.3	19.8	20.6	21.3	21.9	22.4	23.3	23.9
	5	17.5	18.0	19.3	20.0	20.5	21.6	22.1	22.6	23.3	23.7	24.4	25.2
	5.5	19.4	19.7	20.6	21.2	22.4	22.1	22.8	23.8	24.9	25.1	25.9	26.6
	6	12.7	21.6	22.3	22.6	23.3	23.8	24.5	25.0	25.8	26.5	27.2	27.9

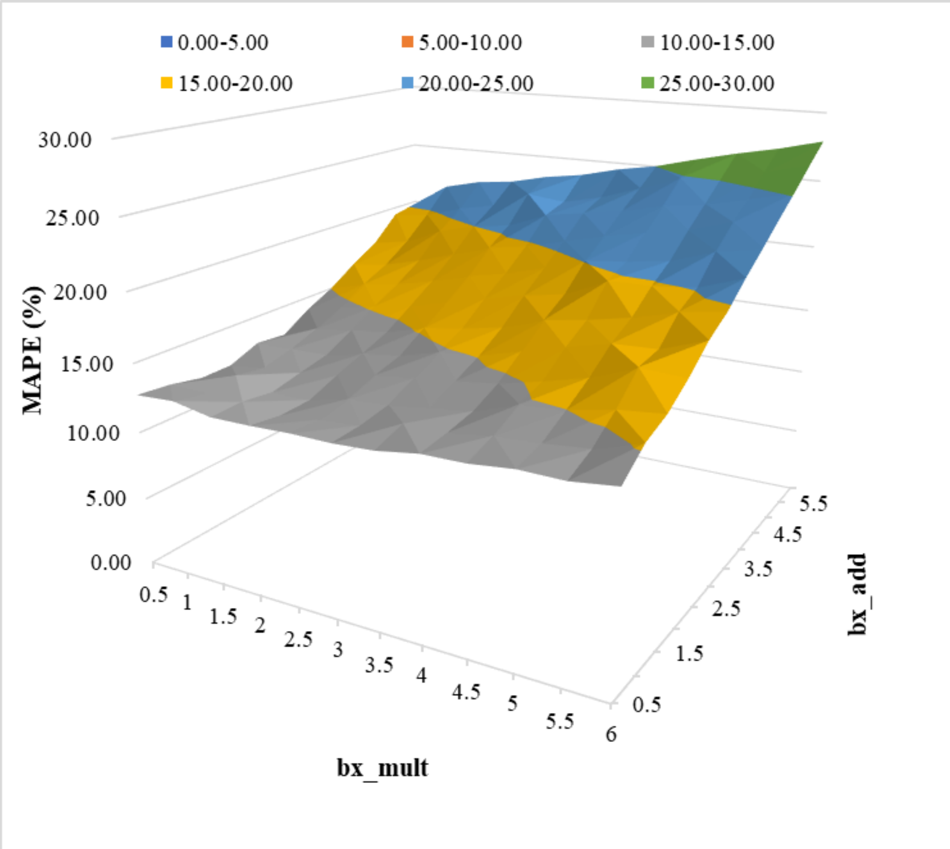

Figure 0.6. PTV VISSIM Calibration with ax = 0.25 m

APPENDIX C. MAIN NETLOGO CODE

Relationship between T.A.R and speed

```
to cal-max-turning-angle-by-speed
  ;; Calculate maximum Turning angle follow TAR relationship with Speed
  let tar (51.895 * (velocity / velocity-scale) ^ (-0.125))
  set max-turning-angle (round tar / time-scale + 1)
  set turning-angle 0

  (ifelse
    ;; There is no Emergency maneuver
    heading-cal = 361 [
      set turning-angle subtract-headings heading-desired heading
      ifelse abs turning-angle <= max-turning-angle [
        set heading precision (heading + turning-angle) 1
      ]
      [
        ;; Turn Left or Right
        ifelse turning-angle >= 0 [ set heading precision (heading + max-turning-
angle) 1 ]
        [ set heading precision (heading - max-turning-angle) 1 ]
        set turning-angle max-turning-angle
      ]
    ]
    ;; There is Emergency maneuver
    [
      if heading-cal > 360 [ set heading-cal heading-cal - 360 ]
      if heading-cal < 0 [ set heading-cal heading-cal + 360 ]
      ;; Add maneuverability in emergency maneuver
      set max-turning-angle max-turning-angle + 3
      set turning-angle subtract-headings heading-cal heading
      ifelse abs turning-angle <= max-turning-angle [
        set heading precision (heading + turning-angle) 1
      ]
      [
        ;; Turnn Left of Right
        ifelse turning-angle >= 0 [
          set heading precision (heading + max-turning-angle) 1
          set turning-angle max-turning-angle
        ]
        [
          set heading precision (heading - max-turning-angle) 1
          set turning-angle -1 * max-turning-angle
        ]
      ]
    ]
  )
end
```

Calculating next movement

```
to calculate-next-move
  draw-anticipation-line-motor
  draw-anticipation-line-car

  ;;This procedure is reduce the calculation for using the same list for all motors
are at intersection
  ask turtles [
    set conf-motor-list (list "null")
    set conf-motor-pxcor-list (list "null")
```

```
    set conf-motor-pycor-list (list "null")
    set conf-car-list (list "null")
    set conf-car-pxcor-list (list "null")
    set conf-car-pycor-list (list "null")
    set closest-conf-patch "null"
  ]
  ;; Motor conflict motor
  let conflict-patch-set1 patches with [(length anticipation-motor-list >= 2) and
(not (member? "null" anticipation-motor-list))]
  ;let conflict-patch-set1-1 conflict-patch-set1
  ask conflict-patch-set1 [
    let iteration length anticipation-motor-list
    let i 1
    while [i <= iteration] [
      let motor-id item (i - 1) anticipation-motor-list
      set motor-TTC-list lput (precision (cal-time-to-conflict-TTC (motor motor-id)
self) 1) motor-TTC-list
      set i i + 1
    ]
    set motor-TTC-list remove "null" motor-TTC-list
  ]

  ;; Car conflict car
  let conflict-patch-set2 patches with [(length anticipation-car-list >= 2) and (not
(member? "null" anticipation-car-list))]
  ;let conflict-patch-set2-1 conflict-patch-set2
  ask conflict-patch-set2 [
    let iteration length anticipation-car-list
    let i 1
    while [i <= iteration] [
      let car-id item (i - 1) anticipation-car-list
      set car-TTC-list lput (precision (cal-time-to-conflict-TTC (turtle car-id)
self) 1) car-TTC-list
      set i i + 1
    ]
    set car-TTC-list remove "null" car-TTC-list
  ]

  ;; Motor and car conflict
  let conflict-patch-set3 patches with [(length anticipation-car-list + length
anticipation-motor-list >= 2) and (not (member? "null" anticipation-car-list)) and
(not (member? "null" anticipation-motor-list))]
  ;let conflict-patch-set3-1 conflict-patch-set3
  ask conflict-patch-set3 [
    ;; Motor time-to-conflict list
    let iteration length anticipation-motor-list
    let i 1
    while [i <= iteration] [
      let motor-id item (i - 1) anticipation-motor-list
      set motor-TTC-list lput (precision (cal-time-to-conflict-TTC (turtle motor-id)
self) 1) motor-TTC-list
      set i i + 1
    ]
    set motor-TTC-list remove "null" motor-TTC-list
    ;; Car time-to-conflict list
    set iteration length anticipation-car-list
    set i 1
    while [i <= iteration] [
      let car-id item (i - 1) anticipation-car-list
      set car-TTC-list lput (precision (cal-time-to-conflict-TTC (turtle car-id)
self) 1) car-TTC-list
      set i i + 1
    ]
    set car-TTC-list remove "null" car-TTC-list
  ]


  ;; -At first step, Solve conflict only inside roundabout
```

```
  ask turtles with [[in-roundabout?] of patch-here = true]  [
    let current-turtle-id [who] of self
    ;; --Answer the question whether turtle is facing the conflict. If yes, Find all
conflict that turtles is facing.
    let conflict-patch-set1-1 conflict-patch-set1 with [member? current-turtle-id
anticipation-motor-list]
    let conflict-patch-set3-1 conflict-patch-set3 with [member? current-turtle-id
anticipation-motor-list]

    ;; Remove conflict from behind of vehicle. Solve only conflict infront
    set  conflict-patch-set1-1  conflict-patch-set1-1  with  [abs(subtract-headings
(heading-agent-to-agent myself self) [heading] of myself) < 20]
    set  conflict-patch-set3-1  conflict-patch-set1-1  with  [abs(subtract-headings
(heading-agent-to-agent myself self) [heading] of myself) < 20]

    ifelse any? conflict-patch-set1-1 [
      ;; --Remove the current turtle id and sort the agentset by distance
      ask patch-here [ set conflict-patch-set1-1 other conflict-patch-set1-1 ]
      let conflict-patch-list1-1 (sort-on [distance myself] conflict-patch-set1-1)
      let pxcor-motor-list (list "null")
      let pycor-motor-list (list "null")

      ;; --Filter patch with the same anticipation-motor-list, remove the same
conflict but listed in several patches
      set  conflict-patch-list1-1  remove-duplicated-contents-list  conflict-patch-
list1-1

      ;; Export to the storage list of conflicting patch
      foreach conflict-patch-list1-1 [ patch-id ->
        ;if not member? ([pxcor] of patch-id) pxcor-motor-list and not member?
([pycor] of patch-id) pycor-motor-list [
          set conf-motor-list (sentence conf-motor-list ([anticipation-motor-list] of
patch-id))
        repeat length ([anticipation-motor-list] of patch-id) [
          set pxcor-motor-list lput ([pxcor] of patch-id) pxcor-motor-list
          set pycor-motor-list lput ([pycor] of patch-id) pycor-motor-list
        ]
        ;]
      ]
      set conf-motor-pxcor-list (remove "null" pxcor-motor-list)                  ;;
this is the list of conflicting patches of one motor
      set conf-motor-pycor-list (remove "null" pycor-motor-list)
      set conf-motor-list (remove "null" conf-motor-list)
      set conf-motor-list remove-duplicates conf-motor-list
      set conf-motor-list remove current-turtle-id conf-motor-list

      ;; --Find the closet conflicting patch
      ;set conflict-patch one-of (patch-set conflict-patch-set1-1 conflict-patch-
set3-1) with-min [distance myself]
      set closest-conf-patch min-one-of (patch-set conflict-patch-set1-1 conflict-
patch-set3-1) [distance myself]
      ifelse is-patch? closest-conf-patch [
        set time-to-conflict (precision (cal-time-to-conflict-TTC self closest-conf-
patch) 1)
      ]
      [ set time-to-conflict 1000 ]                                              ;; No
conflict point
    ]
    [
      set conf-motor-pxcor-list (list "null")
      set conf-motor-pycor-list (list "null")
      set time-to-conflict 1000
    ]

    ifelse any? conflict-patch-set3-1 [
      ;; --Remove the current turtle id and sort the agentset by distance
      ask patch-here [ set conflict-patch-set3-1 other conflict-patch-set3-1 ]
      let conflict-patch-list3-1 (sort-on [distance myself] conflict-patch-set3-1)
```

```
      let pxcor-car-list (list "null")
      let pycor-car-list (list "null")

      ;;  --Filter  patch  with  the  same  anticipation-motor-list,  remove  the  same
conflict but listed in several patches
      set   conflict-patch-list3-1   remove-duplicated-contents-list   conflict-patch-
list3-1

      ;; Export to the storage list of conflicting patch
      foreach conflict-patch-list3-1 [ patch-id ->
        ;if not member? ([pxcor] of patch-id) pxcor-car-list and not member? ([pycor]
of patch-id) pycor-car-list [
          set   conf-car-list   (sentence   conf-car-list   ([anticipation-car-list]   of
patch-id))
        repeat length ([anticipation-car-list] of patch-id) [
          set pxcor-car-list lput ([pxcor] of patch-id) pxcor-car-list
          set pycor-car-list lput ([pycor] of patch-id) pycor-car-list
        ]

        ;]
      ]
      set conf-car-pxcor-list (remove "null" pxcor-car-list)                 ;; this
is the list of conflicting patches of one motor
      set conf-car-pycor-list (remove "null" pycor-car-list)
      set conf-car-list (remove "null" conf-car-list)
      set conf-car-list remove-duplicates conf-car-list
      set conf-car-list remove current-turtle-id conf-car-list



      ;; --Find the closet conflicting patch
      ;set  conflict-patch  one-of  (patch-set  conflict-patch-set1-1  conflict-patch-
set3-1) with-min [distance myself]
      set  closest-conf-patch  min-one-of  (patch-set  conflict-patch-set1-1  conflict-
patch-set3-1)
      [(distance myself / [velocity] of myself) + item 0 (sort-by < (remove "null"
(sentence motor-TTC-list car-TTC-list))) ]
      ifelse is-patch? closest-conf-patch [
        set time-to-conflict (precision (cal-time-to-conflict-TTC self closest-conf-
patch) 1)
      ]
      [ set time-to-conflict 1000 ]                                            ;; No
conflict point
    ]
    [
      set conf-car-pxcor-list (list "null")
      set conf-car-pycor-list (list "null")
      set time-to-conflict 1000
    ]
  ]
end


to-report cal-time-to-conflict-TTC [vehicle conf-patch]
  ;; The time gap from the Front of vehicle to the conflicting patch
  let time-gap 0
  let half-length motor-length / 2
  if is-car? vehicle [ set half-length car-length / 2]
  let dist (sqrt (([xcor] of vehicle - [pxcor] of conf-patch) ^ 2 + ([ycor] of vehicle
- [pycor] of conf-patch) ^ 2 ))
  ifelse dist <= half-length [
    set time-gap 0.1
  ]
  [
    set dist dist - half-length
    ifelse [velocity] of vehicle > 0.1 [
      set time-gap (dist / [velocity] of vehicle)
    ]
```

```
    [ set time-gap 1000 ]                          ;; vehicle almost stop, never crash
  ]
  report time-gap
end
```

Merging phase

```
to merging
  (ifelse
    ori-approach = 1 [
      let ref-patch min-one-of merging1-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging1-ref-line  merging1-
des-temp (dist + 0.3 * dimension-scale))
      ;; In case that dist = 0
      if not is-agent? des-temp [ set des-temp min-one-of merging1-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging1-des-temp [distance patch 0 0]
      ]
      set heading-desired heading-agent-to-agent self des-temp
      ;show (word "ref-patch" ref-patch)
      ;show (word "des-temp" des-temp)
      ;Show (word "dist: " precision (dist + 0.2 * dimension-scale) 1)
      ;show (word "heading: " heading-desired)

      ;ask des-temp [set pcolor orange]
    ]
    ori-approach = 2 [
      let ref-patch min-one-of merging2-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging2-ref-line  merging2-
des-temp (dist + 0.2 * dimension-scale))
      ;; In case that dist = 0
      if not is-agent? des-temp [ set des-temp min-one-of merging2-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging2-des-temp [distance patch 0 0]
      ]
      set heading-desired heading-agent-to-agent self des-temp
      ;ask des-temp [set pcolor orange]
    ]
    ori-approach = 3 [
      let ref-patch min-one-of merging3-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging3-ref-line  merging3-
des-temp (dist + 0.3 * dimension-scale))
      ;; In case that dist = 0
      if not is-agent? des-temp [ set des-temp min-one-of merging3-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging3-des-temp [distance patch 0 0]
      ]
      set heading-desired heading-agent-to-agent self des-temp
      ;ask des-temp [set pcolor orange]
    ]
    ori-approach = 4 [
      let ref-patch min-one-of merging4-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging4-ref-line  merging4-
des-temp (dist + 0.2 * dimension-scale))
      if not is-agent? des-temp [ set des-temp min-one-of merging4-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging4-des-temp [distance patch 0 0]
      ]
```

```
      set heading-desired heading-agent-to-agent self des-temp
      ;ask des-temp [set pcolor orange]
    ]
    ori-approach = 5 [
      let ref-patch min-one-of merging5-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging5-ref-line  merging5-
des-temp (dist + 0.7 * dimension-scale))
      ;; In case that dist = 0
      if not is-agent? des-temp [ set des-temp min-one-of merging5-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging5-des-temp [distance patch 0 0]
      ]
      set heading-desired heading-agent-to-agent self des-temp
      ;ask des-temp [set pcolor orange]
    ]
    ori-approach = 6 [
      let ref-patch min-one-of merging6-ref-line [distance myself]
      let dist distance ref-patch
      set  des-temp  (patch-in-2-patchset-with-distance  merging6-ref-line  merging6-
des-temp (dist + 0.3 * dimension-scale))
      ;; In case that dist = 0
      if not is-agent? des-temp [ set des-temp min-one-of merging6-des-temp [distance
patch 0 0] ]
      if [road-surface?] of des-temp != true [
        set des-temp min-one-of merging6-des-temp [distance patch 0 0]
      ]
      set heading-desired heading-agent-to-agent self des-temp
      ;ask des-temp [set pcolor orange]
    ]
    [
      set heading-desired env-ref-dir-enter
    ]
  )
  set status "Merging"
  if rd-travel-time-start = 0 [ set rd-travel-time-start ticks ]
end
```

Circulating

```
to circulating
  let  temp-circulating-patch  min-one-of  (patches  with  [circulating?  =  true])
[distance myself]
  ifelse [env-ref-dir-enter] of temp-circulating-patch != 361 [
    ;; Compensation for high speed vehicle to make sure that vehicle will run in
circle.
    let angle-a asin (velocity / distancexy 0 0)
    set heading-desired ([env-ref-dir-enter] of temp-circulating-patch - angle-a)

  ]
  [
    set heading-desired [env-ref-dir-exit] of patch-here
  ]
  ;; Gradually change to circulating
  set heading-desired sum-5-headings heading-desired 1 heading 1 0 0 0 0 0 0
  set status "Circulating"
end
```

Diverging

```
to diverging-2
  let temp-des-patch des-patch
  let temp-patchset patches-des-motor1
```

```
  (ifelse
    member? des-patch patches-des-motor1 [ set temp-patchset patches-des-motor1 ]
    member? des-patch patches-des-motor2 [ set temp-patchset patches-des-motor2 ]
    member? des-patch patches-des-motor3 [ set temp-patchset patches-des-motor3 ]
    member? des-patch patches-des-motor4 [ set temp-patchset patches-des-motor4 ]
    member? des-patch patches-des-motor5 [ set temp-patchset patches-des-motor5 ]
    member? des-patch patches-des-motor6 [ set temp-patchset patches-des-motor6 ]

    member? des-patch patches-des-car1 [ set temp-patchset patches-des-car1 ]
    member? des-patch patches-des-car2 [ set temp-patchset patches-des-car2 ]
    member? des-patch patches-des-car3 [ set temp-patchset patches-des-car3 ]
    member? des-patch patches-des-car4 [ set temp-patchset patches-des-car4 ]
    member? des-patch patches-des-car5 [ set temp-patchset patches-des-car5 ]
    member? des-patch patches-des-car6 [ set temp-patchset patches-des-car6 ]
    [ ]
  )
  if is-agentset? temp-patchset [
    set heading-desired heading-agent-to-agent self des-patch
  ]
  set status "Diverging-2"
end
```