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A Concept of Safety Space for Describing Non-lane-based Movements of Motorcycles

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A Concept of Safety Space for Describing Non-lane-based Movements of Motorcycles

by

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ABSTRACT

The motorcycle is the main transport mode for commuters in Vietnam owing to its lower cost and higher mobility compared to the car when running on congested city roads. A better understanding of the characteristics of the motorcycle traffic flow can be very helpful in formulating proposals for traffic management policies.

The basic difference between the car and the motorcycle is in their movement. The former is lane-based, whereas the latter is non-lane-based. Under congested conditions, cars tend to stay in a single lane, while a motorcycle often swerves to the right or left without following a lane; making the interactions in the longitudinal direction between cars the important concern and interactions in both longitudinal and lateral directions the important concern for motorcycles. Thus, this study was conducted to investigate the effects of the zigzag movements of motorcycles on issues of traffic congestion and traffic safety as detailed below:

Firstly, the study researched the characteristics of non-lane-based movements considering the effect of the lead motorcycles' velocity changes on the two behaviors of a subject motorcycle: acceleration and deceleration. A concept of safety space was introduced to describe the changes of these behaviors in response to the safety level of the safety space which boundary is determined by the influence of other motorcycles.

Secondly, models based on the proposed safety space concept was developed and calibrated using data extracted from video clips taken at road segments in Ho Chi Minh City, Vietnam. Non-linear regression analysis was used for calibration. The model was validated by calculating the root-mean-square error of both estimated and actual field value, which consequently showed that the model reproduced good values of motorcycle speed and direction.

Thirdly, the research developed a microscopic simulator to further verify the zigzag movements of motorcycles. The simulation program was written in the C language and run under the Linux operating system. The calculation process combines two different models (1) a free acceleration model for describing the acceleration behavior to achieve free speed when no influential motorcycle is running in front of a subject motorcycle and (2) the proposed non-lane-based model for describing the behaviors of acceleration or deceleration when influential motorcycles exist. The computer simulation was used to reproduce two basic types of non-lane-based movements, namely, oblique following and swerving movement and to verify the difference in the fundamental diagrams between lane-based and non-lane-based movements.

Fourthly, the study aims to investigate the characteristics of the mixed traffic flow that affect traffic safety, also applying the concept of safety space. The research questions are formulated as: (1) how long is the safety distances that the car and the motorcycle keep with their surrounding vehicles, (2) how the safety distances differ when the influential vehicle ahead is a car or a motorcycle. The parameters were also estimated from the mixed traffic flow data collected in Ho Chi Minh City. The safety spaces of the car and the motorcycle were calculated and results were discussed.

Finally, the developed simulator which follows the concept of safety space was applied to assess the motorcycle conflict caused by non-lane-based movements on a road segment. For each time step in the simulation, speed, distance, driver reaction time and motorcycle's physical size were the essential factors considered to calculate the safety levels of the safety spaces for different motorcycle flow densities.

The results from this research are expected to be very useful in understanding the characteristics of driving safety for the motorcycle traffic flow in the developing countries.

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Chapter 1 INTRODUCTION

1.1 BACKGROUND

Although the characteristics of the car traffic flow have been extensively studied, there is little knowledge on the motorcycle traffic flow despite the motorcycle's popularity in developing countries. Figure 1 shows that several big cities in Asia use the motorcycle as the main transportation mode. In Vietnam, motorcycles are mainly used among cars, buses, and non-motorized transportation modes. They make up 50% and 60% of traffic flow in Ha Noi and Ho Chi Minh City, respectively, whereas, the ratio of bus usage are very low, with only 5% ~ 6%.

There are two main reasons why people prefer to use the motorcycle. The first is its high mobility. Its smaller size and shape relative to car and bus enable it to navigate urban roads easier and faster. It also requires only a small parking space, so people are usually able to park their motorcycles in their houses or offices' garages, making it an effective door-to-door transportation mode. The second reason is economy. Motorcycle costs less than a car, thus it is the optimum choice for low- or middle-income families where each working member could own one.

It is difficult to change the habit of using the motorcycle if people have been using it before. Thus, it is predicted that the motorcycle traffic flow will continue to exist for a long. Like in Taiwan, a strong motorcycle market developed because of the vehicle's high mobility and accessibility. And though Taipei has now become a high income city, still a high density of motorcycle use can be seen.

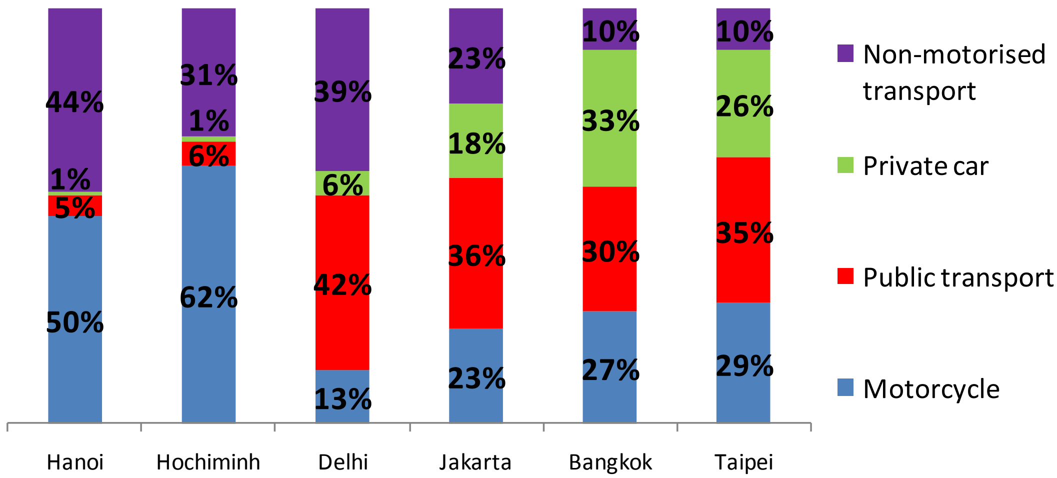


Figure 1.1 Modal split in six Asian cities (Source: Hung, 2006)

In Vietnam in recent years, the number of accidents and fatalities related to motorcycle transportation has increased rapidly. Vietnamese government has been promoting policies to help minimize the number of these incidents. Figure 1.2 shows the number of traffic crash fatalities per 100,000 persons in Vietnam and other countries in 2007. It was found that the number of fatalities in Vietnam is relatively high in the world, with that of Hanoi being higher compared to the average number in Vietnam during an interval of 4 years (2005 – 2008).

Not keeping the safety distance and reckless driving are the main reasons for the accidents in the capital Hanoi (Hung, 2008).

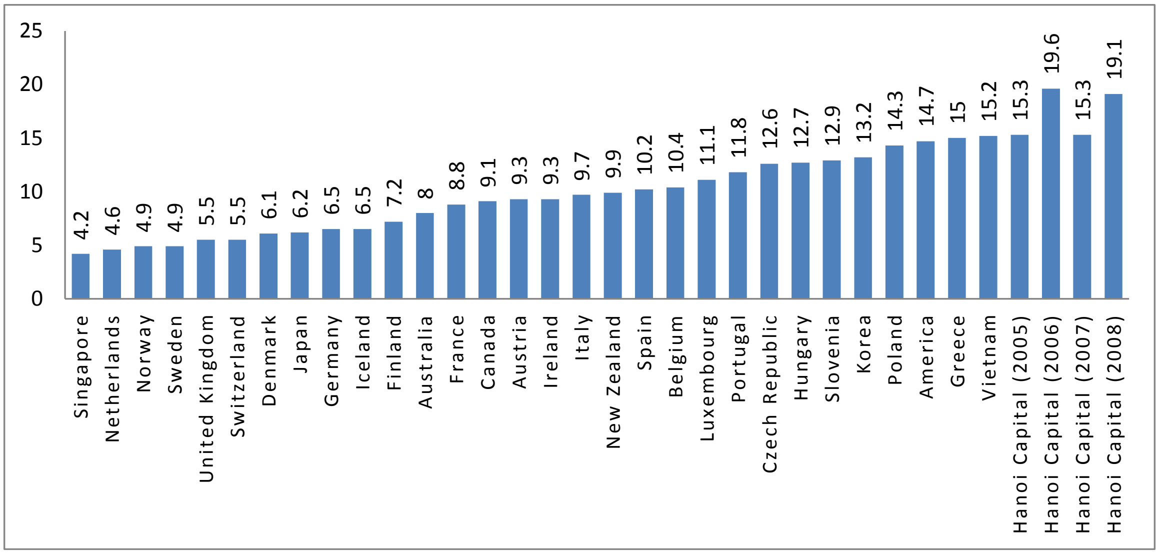


Figure 1.2 The number of traffic fatalities 100.000 persons by country (IRTAD, 2007)

To reduce motorcycle accidents, the first step would be to better understand the properties of the motorcycle movement and how it differs from that of the car. Consequently, policy makers could propose and implement useful traffic management policies based on these understandings.

The basic difference between the car and the motorcycle is in their movement. The former is lane-based, whereas the latter is non-lane-based. Under congested conditions, cars tend to stay in a single lane while a motorcycle often swerves to the right or left without following a lane. While for the car, the interactions of motion between vehicles in the longitudinal direction are the important concerns; for the motorcycle, interactions in both longitudinal and lateral directions need to be taken into consideration. In this research the effects of the non-lane-based movement of the motorcycle on the issues of traffic safety are investigated.

How to describe the non-lane-based movement of the motorcycle is a big challenge in many previous researches. There are many arguments on the acceptable assumptions. Most of the studies divided the non-lane-based movement into the longitudinal movement and the lateral movement, and modeled the separate movements with an assumption on a relationship between them. For the longitudinal movement, the traditional car-following model has been typically used. The lateral movements, however, are modeled with many different assumptions made to consider the relationship between the movements in the longitudinal and lateral directions.

In the model of Cho and Wu (2004), longitudinal positions with respect to influential vehicles affect the lateral position of a subject motorcycle. This is based on the simple assumption that the lateral position of a motorcycle is determined by the average lateral position of surrounding vehicles weighted by their longitudinal positions. Lee et al. (2009) also introduced the “virtual motorcycle lane” concept to identify the leader motorcycle who is leading the subject motorcycle in a virtual motorcycle lane. A motorcycle can change lanes to overtake its leader. The random choice of alternative virtual lanes depends on the utility function, with explanatory factors that include speed and gap acceptance, among others. However, for investigators who assumed that a motorcycle runs in a virtual lane and changes to the next virtual lane randomly, they faced difficulties in determining the width of a virtual lane and in differentiating lane-changing behavior from oblique following behavior just by observing a traffic recording video. Minh et al. (2010) assumed that motorcycles run on the “dynamic lane of motorcycle” and follow another preceding motorcycle on the same dynamic lane. The research calculated the width of the dynamic lane using linear relationship with average speed. Here, average speed of a motorcycle affected its own lateral position.

These approaches above, which modeled the longitudinal movement and the lateral movement separately, led to many arguments on acceptable assumptions. In this study, the introduction of the safety space integrated the longitudinal movement and the lateral movement into one. Safety space is the space that surrounds a single subject motorcycle when it is running along a road. The boundary of the safety space is determined by the influence of other surrounding vehicles that affect the driving behaviors of the subject vehicle. The subject vehicle will control its speed in response to the changes in the safety level of the safety space, to avoid an accident with surrounding vehicles.

1.2 RESEARCH OBJECTIVES

The aim of the study is to develop a concept of safety space that is capable of describing the non-lane-based movements under congested situations, and apply the proposed concept in assessing the motorcycle traffic conflict caused by these movements. To achieve the aim, the study designs five objectives as below:

1) To investigate the characteristics of non-lane-based movements of motorcycles by considering driving behaviors in the congested conditions.

2) To propose a concept of safety space to describing these behaviors, i.e., dynamic movements of motorcycles in traffic made up only of motorcycles.

3) To develop a microscopic traffic simulator based on the concept of safety space to verify the zigzag movements of the motorcycle.

4) To investigate the characteristics of the mixed traffic flow that affect traffic safety.

5) To assess the motorcycle traffic conflict brought by the non-lane-based movements.

1.3 SCOPE AND LIMITATIONS OF THE RESEARCH

The study attempts to investigate the non-lane-based movements of motorcycles on straight road segments under congested situations. Road segments are selected rather than road intersections because driving behaviors here are simpler due to reduction on the effects of road designs such as size of intersection, position of stopping line, signal system and turn-left or turn-right lane. Moreover, congested situations are considered because vehicles zigzag movement is emphasized in these situations. Motorcycles in front change their speed and direction and other motorcycles behind them decelerate or accelerate in response to these changes.

This research focuses solely on heterogeneity in the motorcycle driving behaviors based on the non-lane-based movements under congested situations such as alongside travelling, oblique following and swerving. The other driving behaviors showed under uncongested situations such as free-speed travelling, overtaking and filtering; or at the intersections such as free deceleration, oblique following and left or right turning; or those taking place in different environment conditions such as pair driving, alignment, sight distance, delineation, weather and visibility are not in the scope of this research.

The study explores firstly the characteristics of the homogeneous motorcycle drivers. The future analyses should show differences between homogeneous drivers and heterogeneous drivers. In reality, different drivers react differently to types of stimuli. Hence, heterogeneity in driving styles of different drivers such as different reaction time, aggressive or non-aggressive, knowledge of traffic laws, training and driving skill could make an impact on stability of the analysis results.

For the case study, the research conducted a survey of traffic flow in two road segments in Ho Chi Minh City, Vietnam. Data on motorcycle movement trajectories were extracted from video clips capturing the movements of motorcycles at these 40-m-long road segments. The survey was conducted in the period of December 30–31, 2010, from 6:00 am to 8:00 am and 3:30 pm to 5:30 pm, to record movements of motorcycles during peak hours.

1.4 OUTLINE OF THE THESIS

The thesis comprises of seven chapters, as shown in Figure 1.3. Each chapter is detailed as follows:

Chapter 1 introduces the background, the research objectives and the outline of the thesis.

Chapter 2 provides the literature reviews. Reviewed papers are categorized into two groups, namely, models for describing the driving behaviors of motorcycles, and applications of microscopic simulation models to analyze the issues of traffic accidents.

Chapter 3 proposes the concept of safety space to describe non-lane-based movements of the motorcycles with good potential to analyze traffic safety. The model development based on the proposed concept is presented. The results of the model calibration using survey data and the validation process are presented in the end of the chapter.

Chapter 4 develops a microscopic simulator to verify the zigzag movements of motorcycles based on the proposed model.

Chapter 5 applies the concept of safety space to investigate the characteristics of the mixed traffic flow, i.e., the traffic flow with cars and motorcycles that affect traffic safety. Same as in Chapter 3, but for the mixed traffic flow, this chapter presents the estimation of the model parameters using survey data collected in Ho Chi Minh City. The resulting safety spaces for the car and the motorcycle are also discussed.

Chapter 6 introduces an application of the microscopic simulator to assess the accident potential for non-lane-based movements of the motorcycle at a road segment. The study computes the safety levels of the safety spaces at each time step according to different densities of the motorcycle flow.

Chapter 7 summarizes the new findings in this research and detailed suggestions for the further research.

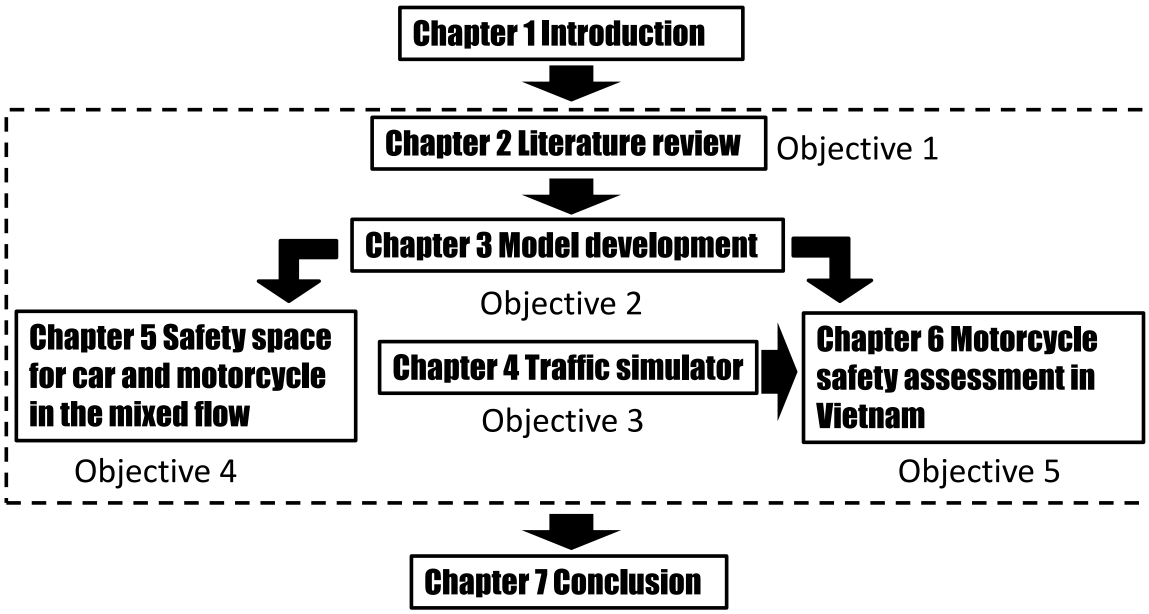


Figure 1.3 Organization of dissertation

Chapter 2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter provides a detailed description of the characteristics of non-lane-based movements. The patterns of driving behaviors related to non-lane-based movements are classified. Review of models describing motorcycle driving behaviors follows. Finally, literatures on the application of these models to analyze traffic safety are presented.

2.2 CHARACTERISTICS OF NON-LANE-BASED MOVEMENTS

Compared with the car, the motorcycle on the road possesses a smaller size and a better ability of turning left or right. Because there is no road designed as motorcycle lane, the motorcycle does not need to follow any lane disciplines. Moreover, as the road laws do not restrict a motorcycle to run on a car lane, a motorcycle can change to any lane that it feels convenient. Even two motorcycles can travel alongside on the same car-lane. Therefore, motions in a longitudinal direction are the main concern for the case of the car, whereas for the motorcycle, both longitudinal and lateral directions should be considered. Investigations on the zigzag movements of motorcycles will contribute to the understanding about the effects of non-lane-based movements on the issues of traffic congestion and traffic safety.

The observed motorcycle driving behaviors related to the non-lane-based movements are categorized by traffic situation and road geometry, as illustrated in Table 2.1. Detailed explanations on these behaviors are given as follows:

Table 2.1 Behaviors of the non-lane-based movements

	Congested situation	**Non-congested situation**
Road segment	Alongside travelling Oblique following Swerving	Free-speed travelling Overtaking Filtering
Road intersection	Free deceleration Oblique following Turning left/right	

Alongside travelling

A motorcycle travels alongside another motorcycle on the same car-lane (Branston, 1977). The standard width of the car-lane, 3.65 m, is designed to fit the average width of the car which is 1.6 m. A motorcycle with an average width of 0.8 m can share the lane easily. Alongside travelling movement is easily observed in congested situations when the density of traffic flow is high.

Oblique following

A motorcycle follows a preceding motorcycle at an oblique position (Robertson, 2003). As a result, motorcycle riders are situated in an angle with a good view of other surrounding vehicles. This helps riders avoid a possible accident and find a chance to overtake lead vehicles.

Swerving

A motorcycle changes its direction quickly to the left or right in response to the sudden braking of a preceding motorcycle (Robertson, 2002). To avoid a rear-end collision with a lead motorcycle, a following motorcycle can decelerate its speed and swerve away from the original position. It is often observed that a motorcycle simultaneously performs these two actions.

Free-speed travelling

A motorcycle travels at a free speed. Free speed refers to the speed at which a motorcycle desires to travel. Under non-congested situation, a rider wishes to run as fast as possible to finish a trip on time.

Overtaking

This behavior happens when a following vehicle decides to pass another vehicle travelling at a lower speed (Minh, 2005). It includes a series of actions: moving laterally, speeding up to pass a lead vehicle, and moving back to the lane. Such behaviors are observed in non-congested situations. Motorcycles often overtake towards an outer lane near a median where vehicles can travel at a higher speed.

Filtering

Filtering refers to the behavior of a motorcycle as it moves through lateral clearances between other vehicles (Oketch, 2000). Filtering behavior often occurs when a higher speed motorcycle overtakes two lower speed motorcycles travelling ahead by moving to the lateral spaces between the two vehicles.

Free deceleration

A motorcycle decelerates its speed freely until it stops at a stop line or at the end of the queue waiting for a green light at the intersection (Minh, 2006). When riders feel free from the influences of the leaders, they will loosen their hand on the acceleration gear and enjoy the free deceleration.

Turning left/right

A motorcycle on the main street changes from the current lane to another lane in order to turn left or right onto the cross-street.

The research focuses on the driving behaviors at a road segment under congested situation; namely alongside travelling, oblique following and swerving. In this study, these behaviors are described by the motorcycle-following model shown in Table 2.2.

Table 2.2 Behaviors of the motorcycle in the scope of this research

	Congested situations	Non-congested situations
Road segment	**Motorcycle-following model** Alongside travelling Oblique following Swerving	Free-speed travelling Overtaking Filtering
Road intersection	Free deceleration Oblique following Turning left/right	

2.3 MODELS OF MOTORCYCLE DRIVING BEHAVIORS

This section discusses the statistical analysis of many basic characteristics of the motorcycle flow, and the models which describe the behaviors of motorcycle, car, mixed flow and pedestrian.

2.3.1 Statistical analysis on motorcycle characteristics

Motorcycle refers to the two-wheeled vehicle equipped with engine. Motorcycles include scooters, mopeds and motorized bicycles. Their average size is 0.7 m ~ 0.8 m wide by 1.6 m ~ 1.9 m long. A motorcycle rider accelerates using the right handle bar, and decelerates by simultaneously loosening the handle bar and applying a leg brake. The maximum deceleration is measured at around -6.19 m/sec^2 in an experiment conducted by Ecker et al. (2001).

Several researchers have investigated the properties of the motorcycle traffic flow. Minh et al. (2005, 2006) investigated some basic characteristics of the motorcycle flow, such as the speed-flow relationship and the distribution of headway. The mean value of a motorcyclist's reaction time has been measured to be ~0.5 s. The headway of motorcycles is found to be 0.5 s to 1.0 s.

Because of its small size and shape, a motorcycle needs less surrounding space to move than does a car. The passenger car unit values for a motorcycle (Lee et al., 2010) were estimated in different speed ranges in congested flow using a simulation model. The results showed that PCU values of motorcycles are 0.4 and 0.5 at flow speeds of 10km/h and 20km/h, respectively. Y et al. (2010) proposed the motorcycle equivalent unit values (MCU values) for the mixed flow with the predominance of motorcycles. MCU value has been found to be related to the mean speed and the effective space of each vehicle type, which is defined as the space needed to maintain the desired speed. The estimation results indicated that MCU values of car, bus and bicycle at a road segment are 3.43, 10.48 and 1.38, respectively.

A motorcycle's speed, like that of a car, decreases when traffic becomes congested. Kov and Yai (2010) reported that the mean speed of the mixed traffic flow decreases tremendously when the number of cars increases. The speed of the car in heavy traffic is less than that of the motorcycle.

2.3.2 Car-following models

Motorcyclists display several kinds of behavior that resemble those of car drivers. Motorcyclists follow their leader and accelerate or decelerate in response to the changes in the speed of the preceding vehicles.

The General Motors model (GM model), which was developed at General Motors research labs by Chandler et al. (1958) and Gazis et al. (1959), assumes that the acceleration of the following car is non-linearly related to three factors: speed of the preceding car, relative speed between the following and the preceding, and the head way between them as shown below:

$$a_n(t) = \alpha v_n^{\beta}(t) \frac{\Delta v_n(t-\tau)}{\Delta x_n^{\gamma}(t-\tau)} \tag{2.1}$$

$a_n(t)$: the acceleration of vehicle *n* at time *t*

$v_n(t)$: the speed of vehicle *n* at time *t*

$\Delta\ v_n(t)$: the speed difference at time *t* between vehicle *n* and vehicle *n*-1

$\Delta\ x_n(t)$: the position difference at time *t* between vehicle *n* and vehicle *n*-1

τ: the car driver reaction time

α, β, γ: parameters

GM model is simple with only three parameters which are also easy to calibrate. Although there are a large number of different calibration results under different traffic conditions (Brackstone and McDonald, 1999), GM model is still applied to microscopic simulation (MITSIM) due to its simplicity. When applying GM model to the motorcycle, it is important to note that the lateral motorcycle movement is described poorly because GM model only focuses on the longitudinal movement (Lan and Chang, 2005).

For the car, collision avoidance model is an alternative approach for the following behavior. The models of Kometani and Sasaki (1959) and Gipps (1981) assume that following vehicles control their speed to ensure that they can stop safely in order to avoid a possible accident if the preceding vehicle suddenly brakes. From the viewpoint of safety driving, Gipps (1981) introduced the constraints of braking in the emergency regime, extra safety reaction time and safety headway margin. The model has also been applied to many micro simulation programs such as MULTSIM (Gipps, 1986), AIMSUN (Barcelo, 2001). However, collision avoidance models have difficulties in applying to the motorcycle. These models were developed on the systems of motion equations for interactions between a preceding vehicle and a following vehicle. Hence, a limitation exists when considering the interaction of more than two vehicles, which is common in the congested conditions.

Psychophysical model or "Action point" model is a different approach for car-following behavior. The earliest versions of the model (Michaels, 1963; Leutzbach and Wiedemann, 1986) developed a concept that drivers can control their speed by perceptual thresholds. These thresholds are limitations related to changes in distance Δx between two vehicles, their relative speed Δv and rate of divergence of the visual angle of the head vehicle ($\sim \Delta v / \Delta x^2$). When one of these thresholds is exceeded, drivers will change their acceleration, typically in the order of 0.2 m/s^2 (Montroll, 1959) until they cannot perceive that these thresholds are not re-exceeded. The model produced the phenomenon of "spiral plots" which were founded by other studies (Gordon, 1971; Brackstone et al., 2002). "Action point" model has been employed in many traffic simulation programs such as PARAMICS (Cameron and Duncan, 1996), VISSIM (Fellendorf and Vortisch, 2001). Calibration of perceptual thresholds has been less successful because of difficulties in estimating parameters related to human factors, such as recognizing or perceiving the changes of distance and relative speed. Nevertheless, the model is based on the understandable assumptions of perceptual thresholds related to distance and relative speed; hence, can still be used to describe the driving behaviors in a proper way. The concept of this model is a very useful reference for developing a model for motorcycles.

2.3.3 Mixed traffic flow models

In the mixed traffic flow, the car and the motorcycle run on the same lane. The basic difference between the car and the motorcycle is related to the lane-based movement of the former and the non-lane-based movement of the latter. A car runs in lanes and seldom changes lanes. However, a motorcycle changes its direction very often especially under congested conditions. How to describe the non-lane-based movement of the motorcycle is a big challenge for the mixed traffic flow models.

Many researches represented the non-lane-based movement by dividing it into the longitudinal movement and the lateral movement. As the longitudinal movement is similar to the car following, the traditional car-following model has been applied to describe this movement. Example applications are those of Cho and Wu (2004) which developed the "spacing model"; Minh et al. (2006) which used the GM model; and Lee et al. (2009) which applied the Gipps model.

However, the lateral movement is more complex to be modeled. The complexity is in making the assumptions of the relationship between the longitudinal movement and the lateral movement. Cho and Wu (2004) assumed that lateral position of a motorcycle was determined by an average lateral position of the surrounding vehicles weighted by the longitudinal positions of these vehicles. In this model, longitudinal positions with respect to influential vehicles have an effect on lateral position of a subject motorcycle. Minh et al. (2010) assumed that motorcycles run on the "dynamic lane of motorcycle" and follow a preceding motorcycle on the same dynamic lane. The dynamic lane is a virtual lane that motorcycle drivers perceive when running. The research calculated the width of the dynamic lane using linear relationship with the average speed. Here, the average speed of a motorcycle is affected by its own lateral position. Lee et al. (2009) introduced the "virtual motorcycle lane" concept to identify a motorcycle leading the subject motorcycle in the virtual motorcycle lane. A motorcycle can change lanes to overtake its leader. The random choice of alternative virtual lanes depends on the utility function, with explanatory factors that include speed and gap acceptance, among others. However, for investigators who assumed that a motorcycle runs in a virtual lane and changes to the next virtual lane randomly, they faced difficulties in determining the width of a virtual lane and in differentiating the lane-changing behavior from oblique following behavior when only observing a traffic recording video.

Cellular automata model provides a calculation technique for simulating two dimensional motorcycle movements based on the simplicity of moving rules developed for the motorcycle such as car-following, lane-changing or overtaking. The model assumes that a vehicle with a certain type of transportation mode is assigned a certain number of cell units to be equal to the real physical size of the vehicle. Ahuja (2001) set the size of a cell unit as 0.6 m, which is exactly equal to the width of the bicycle considered in this study. Lan and Chang (2005) used a cell unit of 1.25 x 1.25 m^2 so as to represent the size of the car and the motorcycle as 6 x 2 cell units and 2 x 1 cell units, respectively. The time step in updating positions of vehicles is often set as one sec so that vehicles move in a longitudinal distance which is equal to their speed. The model is successful to reproduce fundamental diagrams of the mixed traffic flow. It has been used to analyze the characteristics of traffic congestion caused by the effects of various types of vehicles and the lane width on the mixed traffic flow (Lan and Hsu, 2006).

Both aforementioned conventional models and the cellular automata model have the same problem of deciding the width of motorcycle lane or cell. The lane width that directly affects the flow density through lateral movements can be calibrated using field data. However, this model has a low potential to analyze the issues of traffic safety because the updated accelerations in each time step are given by the fixed values.

2.3.4 Pedestrian movement models

Walking movements of the pedestrian can be categorized as non-lane-based movements. The basic behaviors of the pedestrian under congested conditions, like that of the motorcycle, include (1) accelerating to move in the desired direction, (2) decelerating and turning left or right to avoid a possible collision.

The basic behaviors mentioned above can be represented by the decision making process. Pedestrians choose their direction and speed at each time step so as to maximize their utility function. Antonini et al. (2006) developed a discrete choice model and assumed that the utility function can be explained by influential factors such as desired direction and speed of a subject pedestrian, the number of other influential pedestrians, their positions and moving directions. The advantage of the discrete choice model is in providing a sufficient method to calibrate parameters which considers variability of behaviors according to individual pedestrians. The discrete choice model has been employed to describe the lane-changing behavior of the motorcycle (Lee, 2009). However, the behavior is explained using the virtual lanes for the motorcycle based on the lane-based movement of the car.

Asano et al. (2009) applied the multi-player game theory to describe the decision making process of pedestrians. The study assumed that pedestrians choose their direction and speed at each time step so as to minimize their travel times to the destination while avoiding collisions, corresponding to game theory. However, the model does not consider safety factors such as reaction time, and safety distance related to the description of collision avoidance behavior. Hence, such factors should be taken into account when applying the model to the motorcycle.

Helbing et al. (1995, 1998, 2001) introduced the social force approach to describe the non-lane-based movement of the pedestrian. They assumed that pedestrians do not usually make complicated decisions between alternative behaviors, but rather follow optimized behaviors learned from experience. For example, pedestrians walk at their desired speeds. Sometimes, if they feel uncomfortable with their current position, they may change direction to move to wider spaces. The psychological behaviors can be considered as social forces that cause them to move, and these forces can be entered into an equation to describe the changes of motion. This model explained the influence of density on pedestrian movements. A similar influence should be taken into account when considering the non-lane-based movement of the motorcycle.

2.3.5 An application of the social force model to motorcycle traffic

This research attempted to apply the social force model in modeling the non-lane-based movement of the motorcycle (Appendix A). The results of parameter calibration showed that several estimation parameters do not differ from 0 at the significance level of 0.05. The reasons for the failure are listed below:

1) Acceleration force is a function of desired speed. Desired speed is assumed to be constant in the early papers of the author, and to be an increasing function of time delay in the latter papers. Therefore, how to make an acceptable assumption of desired speed is a difficult problem. Moreover, there is a strong relationship between acceleration force and repulsive force because acceleration is the sum of the two forces. Hence, parameters of acceleration force have a strong correlation with parameters of repulsive force.

2) Repulsive force is not related to the speed difference. Speed difference is the most important factor affecting the magnitude of the acceleration. However, repulsive force is assumed to be a derivative of an exponentially decreasing function of speed and distance with respect to the distance between two vehicles. This point should be paid attention to when modifying the equation of repulsive force.

3) It is difficult to explain the concept of vector addition of social forces which represents the real behaviors. When considering the interaction of two or more influential motorcycles on a subject motorcycle, the acceleration of the subject vehicle changes in large range because of taking the vector addition of these forces generated by influential motorcycles. For example, if there are two influential vehicles in front, the repulsive force will increase twice than that of the case of only one vehicle in front. If the two vehicles approach the subject vehicle, one from both sides, the repulsive force will be zero. This led to unpredictable trajectories of motorcycles which differ from the real data.

4) The condition for modeling the collision avoidance behavior is too simple. The model assumed that repulsive force is an exponentially decreasing function of speed and distance. When two vehicles approach closer, the repulsive force becomes larger and pushes these two vehicles farther. Therefore, it is necessary to provide more conditions for accident prevention such as safety distance and maximum deceleration. Such conditions are taken into account in this study.

5) When reviewing papers of social force model, it was found that there are little papers published in journals showing results of parameter calibration or model validation.

In conclusion, social force model is a good approach when the "force" is assumed to explain an "action" happening. Taking the sum of all the forces may not explain well the moving trajectory of the vehicle. The research tries to develop a better approach that can provide a good estimation of the motorcycle trajectories.

2.4 THE APPLICATION OF TRAFFIC SIMULATION MODELS TO TRAFFIC SAFETY

This section provides literation review on models which are used for predicting traffic accident, especially focusing on traffic simulation models. Also, the traffic simulation measures to assess the safety of vehicles are discussed.

2.4.1 Accident prediction models

The safety level of a vehicle or a facility refers to the number of accidents or rate of accidents involved with the vehicle or the facility. An accident here is defined as a crash between two or more vehicles. There are two popular approaches to estimate the safety level of a vehicle: (1) develop safety performance functions that relate the number of accidents, or rate of accidents, to the explanatory variables using regression analysis, (2) develop simulation models to calculate the safety level using measures for traffic safety assessment.

In the former approach, the correlations among variables are found by analyzing the dispersion and approximated by deriving regression formulas. Neuman and Glennon (1983) found the correlations between the road environment of road design, infrastructure and accident causes. Warshawsly and Shinar (2002) found the relationship between reaction time to a brake light and driver's gender, age, level of expectancy for the brake light, and number of times that a task was performed. This approach requires consensus data on traffic accidents which are very difficult to collect. In reality, probability of traffic accident is very low and varies across the times of day, days of week, locations and special events.

The latter approach has a potential to address the aforementioned problems of lack of observation data. The simulation models were developed on the basis of behavioral modeling of vehicles as mentioned in Section 2.3. Although the models cannot estimate the number of accidents, they can be used to reflect the safety or the increased probability of higher-than-average accident rates (Gettman and Head, 2003). Microscopic models simulate position, speed and acceleration of every vehicle in the traffic flow and update it in every second. Hence, simulation models can produce a larger amount of analysis data than observation data, and with time savings. Lastly, these models cover many scenarios such as night time, weekend, and special locations that observers meet difficulties in data collection.

2.4.2 Measures for traffic safety assessment

Conventional researches focused on measures related to the traffic conflict techniques (Perkins and Harris, 1967; Glauz and Migletz, 1980; Parker and Zegeer, 1988). A traffic conflict is defined as an event involving two or more road users, in which the action of one user causes the other user to make an evasive maneuver to avoid a collision (FHWA, 1990). Road users refer to motorists, motorcyclists, cyclists and pedestrians. According to the definition, conflicts are vehicle interactions which can lead to accidents. A conflict occurs when an action of the first user places the other user in an accident unless the other user does not take an evasive action.

Traffic conflicts can be categorized by types of maneuvers. Definitions of various types of conflicts and the corresponding types of accident are summarized in Table 2.3 (FHWA, 1990). Many studies investigated the connection between the number of observed conflict counts and the number of traffic accidents (FHWA, 1985; Kaub, 2000). They concluded that conflict counts and traffic volume tend to track the accident trends fairly well.

Table 2.3 Types of traffic conflicts

Type of conflicts	**Definition (for right-hand driving)**	**Type of collision**
Same direction	The vehicle in front slows down or turns left/right, and the following vehicle brakes or swerves to avoid the collision.	Rear-end
Lane-change	The vehicle in front changes from one lane to another lane, then the following vehicle brakes or swerves to avoid the collision.	Rear-end
Opposing left turn	An incoming vehicle in the opposite direction turns left, then another vehicle in the other direction applies a brake.	Head-on Side-swipe
Cross traffic	A vehicle on the cross-street turns into the path of a second vehicle on the main street which has the right-of-way to proceed, then the second vehicle brakes or swerves to avoid an accident.	Rear-end Side-swipe
Right-turn-on-red	A right-turn-on-red vehicle turns right into the lane of a second vehicle which has the right-of-way, then the second vehicle brakes to avoid a collision.	Rear-end Side-swipe
Pedestrian or bicycle	A pedestrian or bicycle crosses in front of a vehicle which has a right-of-way then the vehicle applies a brake.	
Secondary	When the first vehicle causes the second vehicle to apply a brake, the third vehicle also brakes or swerves away in response to the second.	Rear-end Side-swipe

The primary measures to determine a conflict using microscopic simulation were introduced by Gettman and Head (2003) in the following list.

Time to collision (TTC)

TTC is the time to collision at the area of potential collision between two vehicles if they continue to run with the same speed without placing evasive actions. It can be measured by dividing the distance by the speed between the two road users at the time of evasive action.

Post-encroachment time (PET)

PET is defined as the time difference between the time the first vehicle passes out of the area of potential collision and the time the second vehicle with right-of-way arrives at the area of potential collision (Allen et al., 1978). Therefore, it is the time difference between vehicles passing through the same conflict area.

Maximum of the speeds of two vehicles involved in the conflict event (MaxS)

MaxS is the maximum speed recorded for each vehicle during the time of evasive action. Then, the maximum speed of those vehicles is determined to be MaxS.

Maximum relative speeds of two vehicles involved in the conflict event (Deltas)

DeltaS is the maximum relative speed recorded for each vehicle during the time of evasive action. Then, the maximum relative speed of those vehicles is determined to be DeltaS.

Deceleration rate (DR)

DR is the deceleration rate of the evasive action taken by a vehicle. Deceleration rate is a measure to indicate the severity of the conflict event. The reason is that when the masses of conflict vehicles are known, it is easy to calculate the momentum values which represent the damage of the resulting collisions.

MaxS, DeltaS and DR can estimate the severity of collisions. These values are available from the output of simulation model at every each time. Because of this reason, this study uses DR as an efficient measure to assess traffic safety of the motorcycle at a road segment.

2.5 SUMMARY

This chapter provides a detailed description of the characteristics of motorcycle non-lane-based movements. Because there is no motorcycle-lane on the road, the motorcycle does not need to follow the lane disciplines. The observed driving behaviors related to the non-lane-based movements were categorized by traffic situation and road geometry. This research focuses only on the behaviors at the road segment under congested situations such as alongside travelling, oblique following and swerving. In this study, these behaviors are described by the motorcycle-following model.

What follows is the review of the models describing the driving behaviors. Results from statistical analysis on many basic characteristics of the motorcycle flow were discussed. A motorcycle needs less surrounding space to move than does a car due to its small size and shape. A motorcycle's speed, like that of a car, will decrease when traffic becomes congested. Car following models were reviewed because motorcyclists display several kinds of behaviors that resemble those of car drivers. For example, a motorcyclist follows its leader and accelerates or decelerates in response to the changes in the speed of the leader. In the mixed traffic flow, the car and the motorcycle can run on the same lane. The car follows the lane-based movement and the motorcycle runs on the basis of the non-lane-based movement. Many researches attempt to represent the non-lane-based movement by separating it into the longitudinal movement and the lateral movement. As the longitudinal movement is similar to the car following, the traditional car-following model has been applied to describe this movement. However, the lateral movement is more complex to model. The complexity comes from the way of making assumptions in the relationship between the longitudinal movement and the lateral movement.

In the pedestrian flow, walking movements of the pedestrian can be considered as non-lane-based. However, almost all of the models for describing movements of pedestrians do not consider safety factors such as reaction time, safety distance, and speed difference related to the description of collision avoidance behavior. Therefore, such considerations should be taken into account in the case of the motorcycle.

Finally, literatures on applications of models for traffic safety were presented. There are two approaches to estimate the safety level of a vehicle. The first is to develop safety performance functions that relate the number of accidents or rate accident to the explanatory variables using the regression analysis. The second is to develop microscopic simulation models to calculate the safety level using traffic conflict measures for traffic safety assessment. The first approach requires the consensus data on traffic accidents which are very difficult to collect. The latter approach has a potential to address the aforementioned problems of lacking observation data. Traffic conflict is an observable situation, in which the action of a user causes the other user to make an evasive maneuver to avoid a collision. Many researches concluded that there is a connection between the number of observed conflict counts and the number of traffic accidents. Traffic conflicts were categorized by types of maneuvers; and the primary measures to determine a conflict situation using microscopic simulation were introduced. This study will use Deceleration Rate (DR) to assess the traffic safety level of the motorcycle at a road segment.

Chapter 3 MODEL DEVELOPMENT

3.1 INTRODUCTION

This chapter develops a methodology for describing the non-lane-based movement of the motorcycle. In the second section, a concept of safety space for the motorcycle is introduced. In the third section, the motorcycle-following model is developed based on the concept. Detailed discussions about the limitations of the previous models are summarized in the fourth section. The fifth section introduces the data collection, including the survey locations and data extraction. Then, calibration is performed to estimate values of parameters for the proposed model in the sixth section. The seventh section compares the estimated results to field data so as to validate the model using statistical measures to calculate the value of errors. The eighth section introduces a microscopic simulator to verify the non-lane-based movements of motorcycles.

The framework of methodology for developing the motorcycle-following model is shown in Figure 3.1.

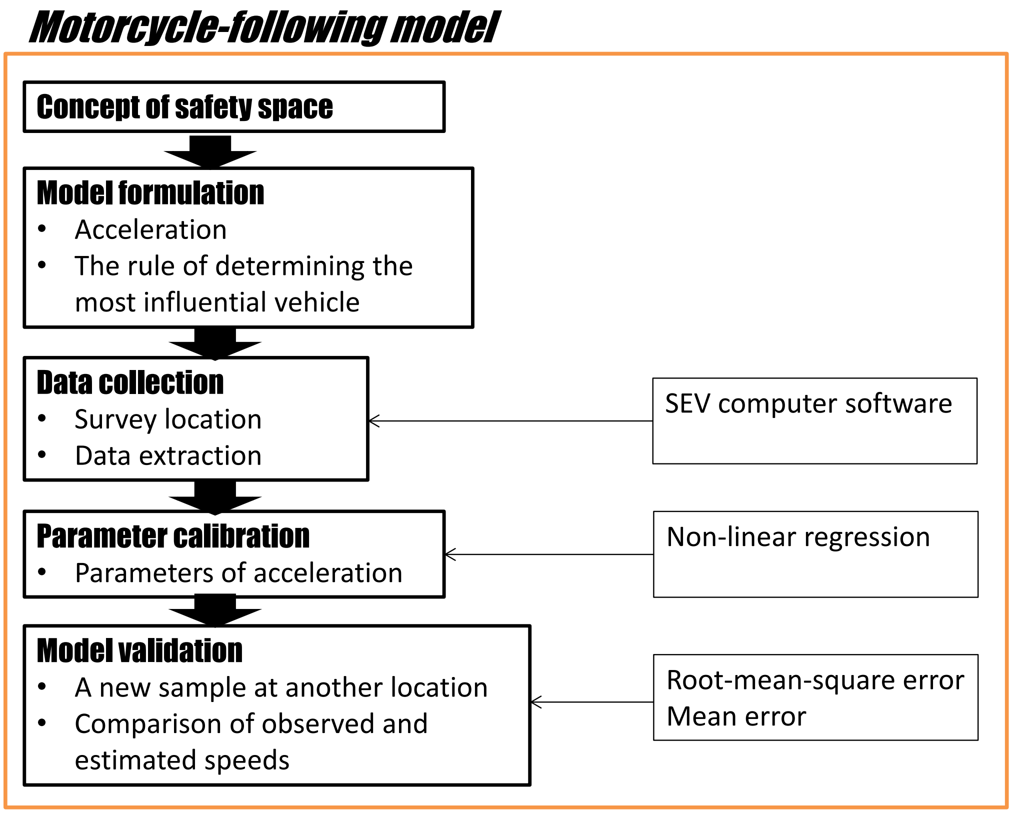


Figure 3.1 Framework of methodology for the motorcycle-following model

3.2 CONCEPT OF THE SAFETY SPACE

Safety space is the space that surrounds a single subject motorcycle when it is running along a road. It has the form of a physical space whose boundary is determined by the influence of other vehicles that affect the driving behaviors of the subject vehicle. A motorist is assumed to perceive this physical space as an approximate half ellipse, as illustrated in Figure 3.2. The boundaries of safety spaces are equipotential lines, meaning that all vehicles on the same line represent the same level of safety, as perceived by the driver of the subject vehicle. When another vehicle moves closer to or farther away from a subject vehicle, the safety space becomes smaller or larger; as a result, the perceived level of safety decreases or increases.

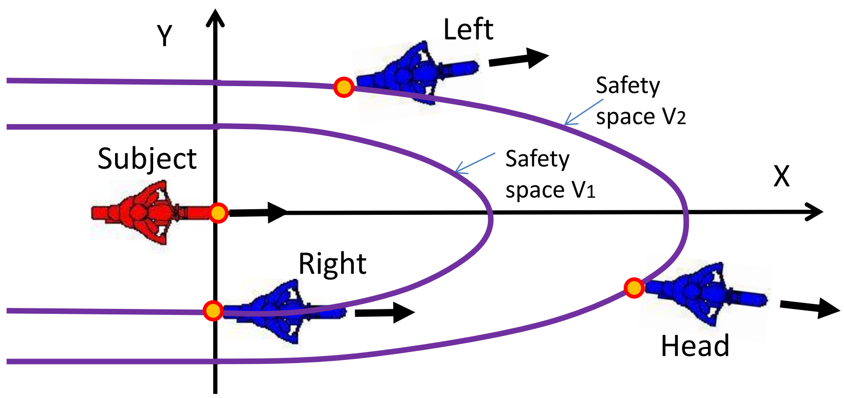


Figure 3.2 Equipotential lines of safety space

Numerous observations of the zigzag movements of the motorcycle have shown that non-lane-based movements can be explained by two behaviors. The first is acceleration in order to achieve a free speed. When a leader motorcycle in front speeds up, the safety space of a subject motorcyclist expands, which then increases speed and moves toward the influential motorcycle so as to enjoy the free speed. The second behavior is deceleration to avoid a collision. When another motorcycle approaches, the safety space becomes smaller and the motorcycle's speed is reduced, while it may also swerve to the right or left. Therefore, there is a very close relationship between changes in a motorcyclist's speed and direction of motion and the changes in the size of the safety space. Furthermore, as the level of safety for a certain safety space is easily expressed by a density equation, it can be used to evaluate how the behavior of a motorcycle changes, depending on a high or low density of traffic flow. Based on these observations, the present study applies the concept of safety space to the motorcycle in order to describe motorcyclists' behaviors. It is assumed that the behavior of a motorcycle driver is not complex, but consists simply of acceleration or deceleration in response to changes in the size of the safety space with a view to achieving a higher safety level.

The safety space for a subject motorcycle is assumed to be determined by the combination of a half ellipsoidal boundary and two parallel lines (see Figure 3.2). The ellipsoidal boundary with its center is placed at the middle point of the front side of the subject motorcycle and crosses the middle point of the back side of the influential motorcycle. The two parallel lines connect to the ellipsoidal boundary and expand to the back of the subject motorcycle. These boundaries make up the whole space surrounding the motorcycle. The ellipsoidal boundary shows the space when the preceding motorcycle runs in front of the subject. Two parallel lines make the clearances on the both side of the subject when two vehicles run side-by-side.

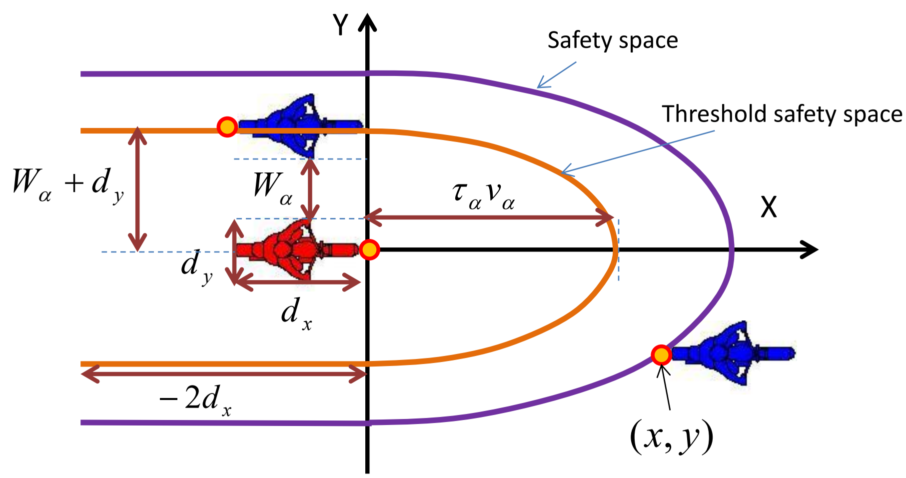


Figure 3.3 Threshold safety space

There are many safety spaces for a given motorcycle. The safety level of a safety space varies according to physical traffic conditions, such as distances between vehicles, their speeds, the sizes of the vehicles and the various reaction times of the drivers. Therefore, the concept of "threshold" safety space is introduced to define the minimal safety level that the motorcyclist considers acceptable for driving and avoiding a possible accident. As shown in Figure 3.3, the threshold safety space of a subject vehicle α is assumed to have an ellipsoidal shape, with the vehicle placed at the center and the direction of its velocity v_α determining the direction of the major axis, and two parallel lines connecting to the ellipsoidal boundary and expand to the back of the subject motorcycle, with the length of two parallel lines being equal to two times of the length of the subject motorcycle. The physical size of a motorcycle on each axis is denoted by d_x, d_y. The length of the semi-major axis is the safety distance on the x-axis, measured from the front side of one motorist to the rear side of another and expressed as $\tau_\alpha v_\alpha$, where τ_α is the relaxation time on the x-axis. *Relaxation time is defined as the time needed to complete a series of actions to avoid a collision: perceive the leading vehicle braking suddenly, swerve left or right, and brake to reduce speed*. The length of the semi-minor axis is the safety distance on the y-axis, given by $W_\alpha+d_y$, where W_α is the lateral distance on the y-axis between two motorcycles. This is also the lateral safety distance when two vehicles are riding side by side. A motorcycle rider is assumed to control the speed and direction of motion so as to keep other motorcycles outside the vehicle's threshold safety space for the collision avoidance.

3.3 MODEL FORMULATION

Suppose that a subject vehicle α travels at speeds v_α at time t. If an influential vehicle β increases or decreases its speed to v_β at time t, then vehicle α will adjust its acceleration a_α, with a lag of reaction time T_α, to be equal to a gradient ∇ of a level of safety V_β for the current position of β with respect to a relative speed vector $\vec{v}_{\alpha\beta} = \vec{v}_\beta - \vec{v}_\alpha$, as follows:

$$a_\alpha(t+T_\alpha) = -\nabla_{\vec{v}_{\alpha\beta}} V_\beta(t) \tag{3.1}$$

The negative sign on the right-hand side of Equation (3.1) means that a_α is negative or positive when β moves in or out of the safety space, respectively. The level of safety V_β for vehicle β can be expressed by an exponential function of the distance between two vehicles. If V_β is assumed to be the equipotential curve of the ellipse and two parallel lines connecting to the ellipsoidal boundary with the length of two parallel lines being equal to two times of the length of the subject motorcycle, then Equation (3.1) can be rewritten as

$$a_\alpha(t+T_\alpha) = \begin{cases} -\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2}+\dfrac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right) & if\ x \geq 0 \\ -\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\dfrac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right) & if\ -2d_x \leq x \leq 0 \end{cases} \tag{3.2}$$

where A and B are parameters. Parameter A represents the magnitude of the safety level, while parameter B represents the effect of stretching out the value of safety level; x, y are the distances between vehicles α and β measured on the x-axis and y-axis, respectively. Equation (3.2) allows the threshold safety space to change its size according to the speed of the subject vehicle: at higher speeds, a larger threshold safety space is needed to maintain the same level of safety.

The direction of the acceleration vector $\vec{a}_\alpha$, which shows the direction of motion, is related to the gradient direction of the safety space as

$$\frac{\vec{a}_\alpha}{\|\vec{a}_\alpha\|} = \begin{cases} \dfrac{\nabla V_\beta}{\|\nabla V_\beta\|} & \text{if } a_\alpha \le 0 \\ \dfrac{-\nabla V_\beta}{\|\nabla V_\beta\|} & \text{if } a_\alpha > 0 \end{cases} \tag{3.3}$$

where $\|\vec{a}_\alpha\|$ and $\|\nabla V_\beta\|$ denote the magnitude of the acceleration vector and the gradient vector, respectively (Figure 3.4). Equation (3.3) shows a simple assumption. When β moves closer to α, α will decelerate ($a_\alpha \le 0$) and keep farther away from β in the gradient direction to avoid a collision. When β moves farther away from α, α will accelerate ($a_\alpha > 0$) to follow β in the reverse gradient direction.

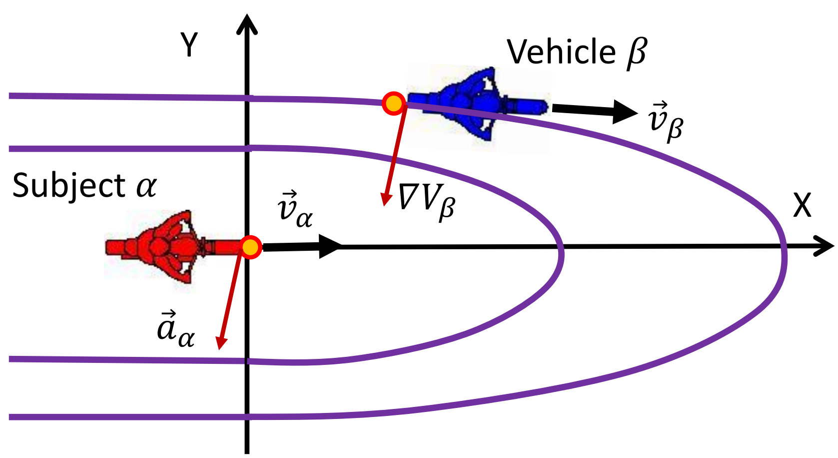


Figure 3.4 Direction of the acceleration vector

Under heavy traffic conditions, a motorcycle driver may not be able to respond to all the influential motorcycles. Hence, it is important to specify which motorcycle is the most influential. Suppose there are N influential motorcycles affecting the driving behavior of a subject motorcycle α and its acceleration for the influential vehicle i is denoted by $\vec{a}_{\alpha i}$. Then it can be assumed that the influential vehicle i is chosen to be the most influential if the subject vehicle responds to it with the maximum magnitude of the acceleration, as follows:

$$\max_{i} \left\{ \|\vec{a}_{\alpha 1}\|, \|\vec{a}_{\alpha 2}\|, \ldots, \|\vec{a}_{\alpha i}\|, \ldots, \|\vec{a}_{\alpha N}\| \right\} \tag{3.4}$$

This assumption is reasonable because a subject vehicle cannot respond to many influential vehicles at the same time. It will focus on decreasing speed to avoid a collision with the most influential vehicle, while paying lesser attention to other vehicles. It also increases speed to follow the most influential vehicle in order to achieve the highest acceleration. Obviously, a subject motorcycle responds to many different "most influential vehicles" during the course of a journey. This explains the right/left swerving behaviors of motorcycle under heavy traffic conditions.

3.4 MODEL DISCUSSIONS

The proposed concept can deal with the limitations of the previous models as follows:

1) The model embodies reasonable assumptions which directly relate acceleration to the distance and relative speed between vehicles based on the concept of safety space. This connects the proposed motorcycle-following model to the conventional car-following model. Hence, the model is able to describe the driving behaviors of motorcyclists in a proper way.

2) There are many arguments regarding acceptable assumptions on the non-lane-based movement. Most of the studies divided the non-lane-based movement into the longitudinal movement and the lateral movement, and modeled the separate movements with an assumption on a relationship between them. However, these approaches made the models complex. In this study, the introduction of the safety space integrated the

longitudinal movement and the lateral movement into one. Here, the direction of the acceleration vector is assumed to be perpendicular to the boundary of the safety space. The assumption ensures that a motorcycle tends to move on the boundary of the safety space and keeps the safety space from another vehicle.

3) The motorcycle has more freedom of the lateral movements than the car. The more freedom it gets, the more safety it pays attention to. However, many models do not consider safety factors such as reaction time and safety distance related to the description of collision avoidance behavior. Hence, such factors should be taken into account when applying the model to the motorcycle. The proposed model provided a threshold safety space for accident prevention calculated by reaction time, relaxation time, and speed, size of a vehicle.

4) A big limitation exists in almost all conventional models when considering interactions of more than two vehicles in the very congested conditions. The present model assumes that a subject rider responds to the most influential rider. In general, a subject motorcycle decelerates to avoid a collision with the most influential vehicle, while paying lesser attention to other vehicles. When a rider wants to accelerate, it also follows the most influential vehicle to get the highest value of acceleration. Hence, these assumptions are understandable for congested situations. In the non-congested conditions, maybe the behaviors of free-speed travelling, overtaking and filtering are not described appropriately using these assumptions.

5) The biggest advantage of the motorcycle-following model related to the ability of application is its simplicity, with only three parameters, and ease in calibration using non-linear regression analysis. Although there could be different calibration results under different traffic conditions, the model can be applied to microscopic simulation under many different situations due to its simplicity.

6) This model has a high potential to analyze the issues of traffic safety because the acceleration in each time step is updated continuously in the simulation progress. This study uses Deceleration Rate (DR) to assess the safety level of motorcycles.

3.5 DATA COLLECTION

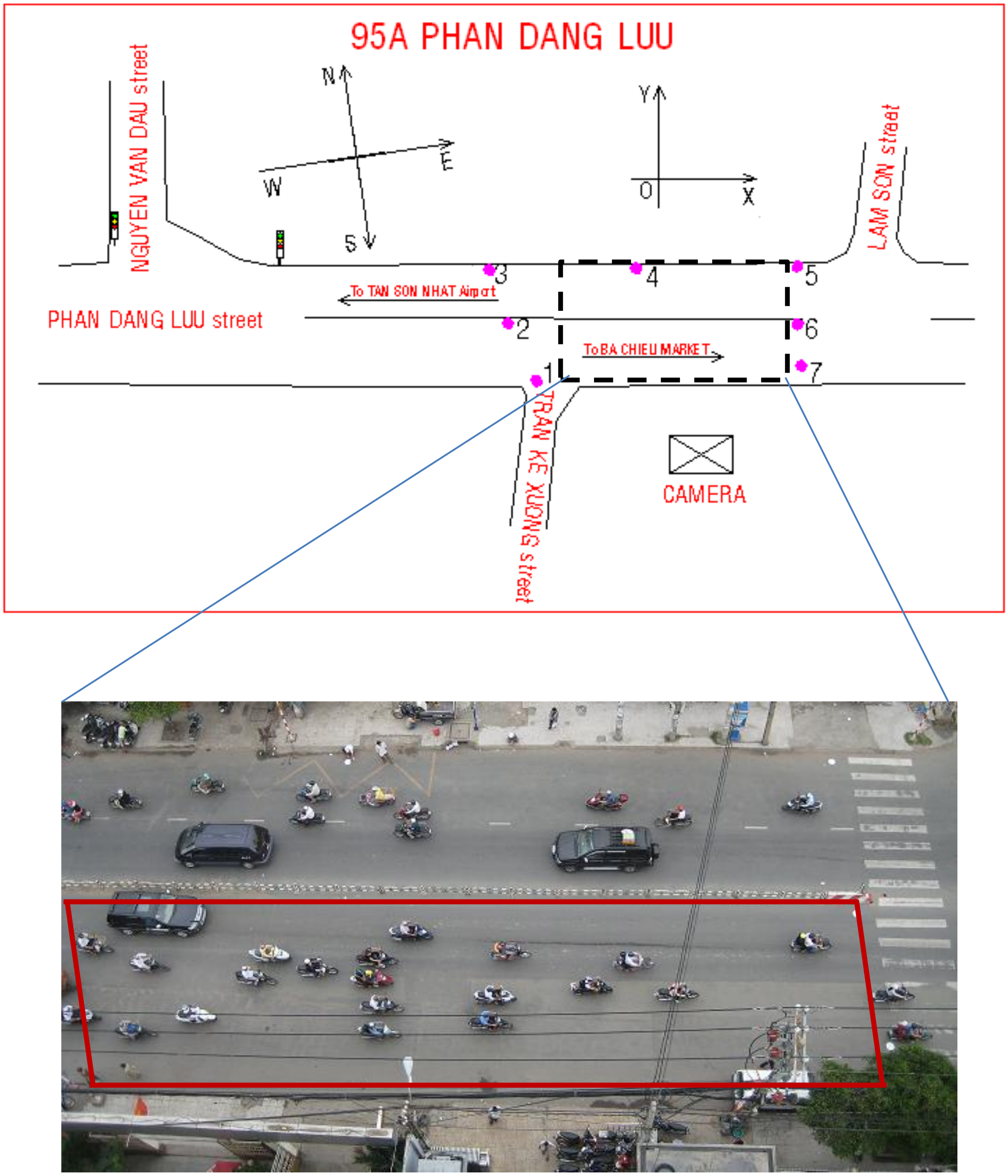
To calibrate the proposed model, data of the trajectories of vehicles over time are necessary. Therefore, time-series trajectory data of each vehicle were recorded using a video camera. One observation extracted from a video contains the information on the position of a target motorcycle and other influential motorcycles at a given time. The next observation for the same target vehicle was made after 0.5 s to capture changes in speed and direction of these vehicles. Because the chapter covers only situations of the congested motorcycle-only traffic, observations with non-congested situations and in which cars and bicycles were present were excluded from the video clips.

3.5.1 Survey location

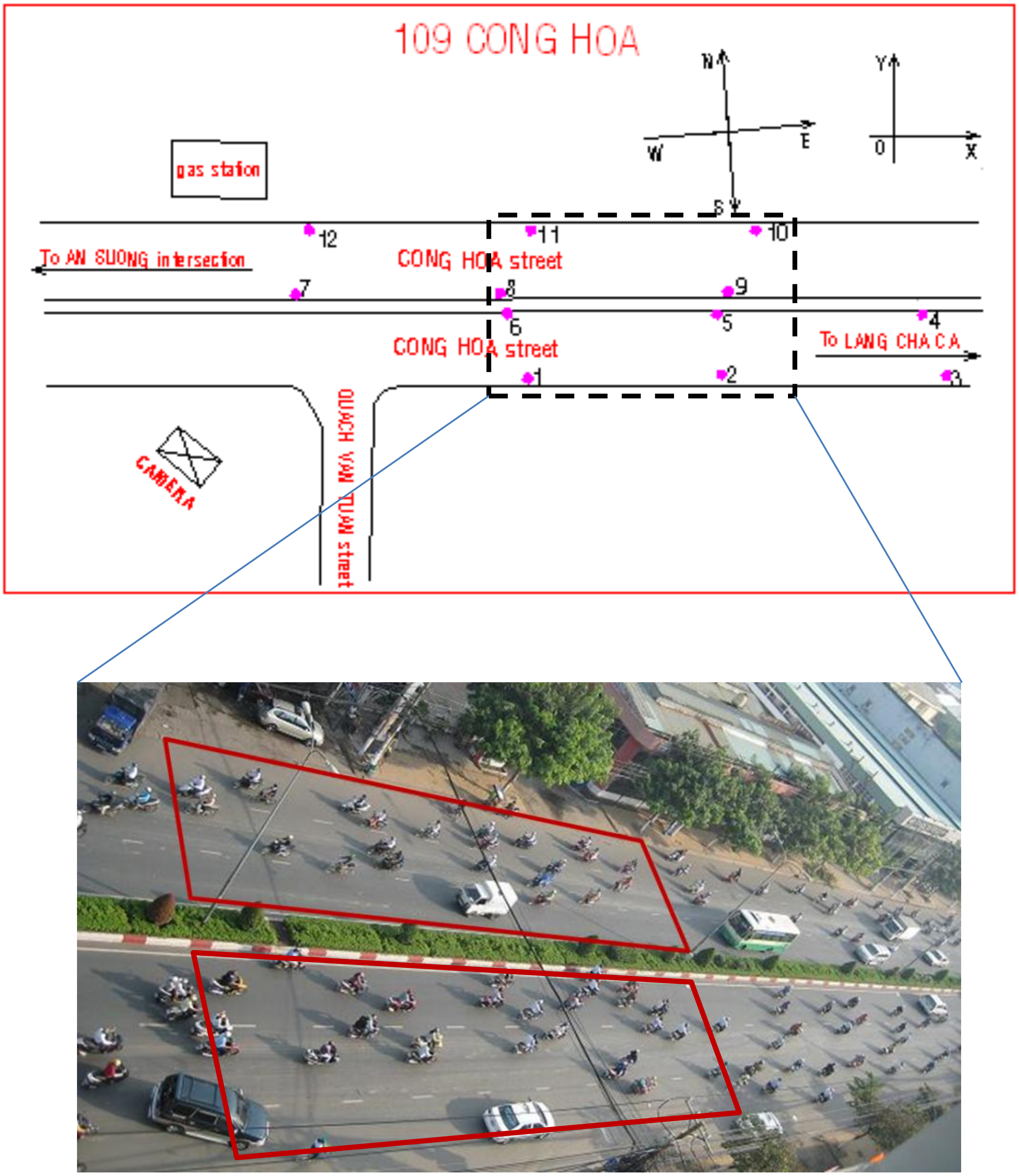
Ho Chi Minh City has a high population of motorcycles, thus a good location to conduct the survey. Two road segments on Phan Dang Luu Street and Cong Hoa Street were selected for data collection. The first road segment is near an intersection and is 8.4 m wide. This segment has only one lane in the observed direction with motorcycles running at an average speed of 20 km/h. The second road segment has 3 lanes in each direction, each lane being 3.65 m wide. The segment is about 100 m from the nearest intersection. Motorcycles run at an average speed of 30 km/h and are allowed to use any lane that is available.

A video recorder was set up on a high building near the study location. Vehicle movements on a 40-m-long road segment in the study direction (Figure 3.5) were captured on video camera at 30 frames/s. The survey was conducted in the period of

December 30–31, 2010, from 6:00 am to 8:00 am and 3:30 pm to 5:30 pm, to record movements of motorcycles during peak hours. Each site was surveyed on two different days and 4 h worth of video clips were obtained from each site.



(a) Phan Dang Luu Street (Width=8.4 m, Length=40 m)



(b) Cong Hoa Street (Width=10.95 m, Length=40 m)

Figure 3.5 Two survey locations in Ho Chi Minh City.

In this study, a SONY PD170 camera with LCD monitor was employed to observe the traffic flow. The original resolution of video was resized so as to display the video clips on any normal monitor. As a result, image video files with a resolution of 1280 x 720 pixels were made to track the trajectories of vehicles. The resolutions of the video image related to the real sizes of two survey locations are listed in Table 3.1. Under ideal situations, the error of tracking data is assumed to range in one pixel resolution. Previous researches (Ahmed, 1999; Hidas, 2005; Lee et al., 2008) used the acceptable pixel resolution which ranges from around 50 mm to 1300 mm. Therefore, the method of tracking data in this study can provide data sets with high accuracy.

Table 3.1 Resolution of the video image at two locations

Pixel resolution	**Phan Dang Luu Street**	**Cong Hoa Street**
Longitudinal (mm/pixel)	37.8	100.5
Lateral (mm/pixel)	42.3	34.3

3.5.2 Data extraction

Speed Estimation from Video Data (SEV) computer software was used to convert video screen coordinates into roadway coordinates. This software was developed by Minh et al. (2006). Input was in the video file format and the output was in Excel file format containing the trajectory data of traffic. A trajectory data set (X-axis and Y-axis coordinates) for one vehicle was extracted by clicking on the positions of that vehicle in the monitor at 0.5-s intervals, this being the average reaction time of a motorcyclist according to Minh et al. (2006).

In this research, the SEV is used to track the trajectory of a subject vehicle and surrounding vehicles. Clicking the mouse on the positions of their head is identified as one observation. The next observation of the same subject vehicle is collected after 0.5 sec. The study collected 7 to 10 observations for each subject vehicle.

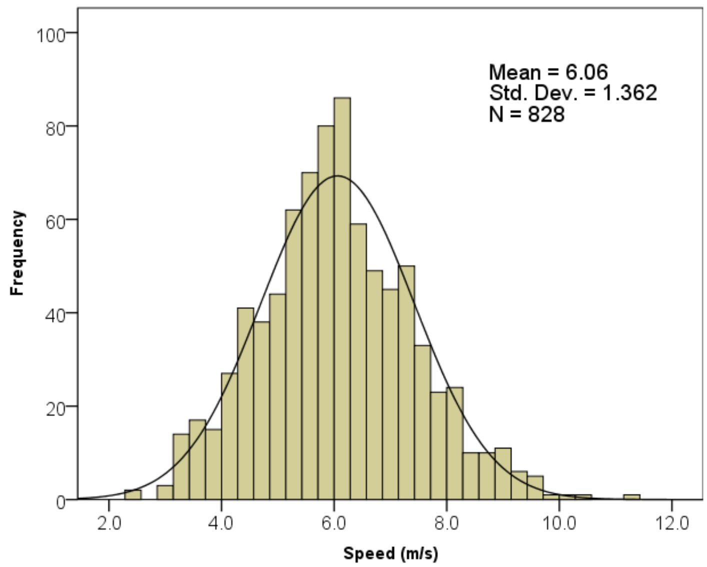
As a result, 828 observations of 144 motorcycles in Phan Dang Luu Street and 579 observations of 152 motorcycles in Cong Hoa Street were used to estimate the parameters of the proposed model. Although more motorcycles could have been considered, it is unlikely that a larger sample would have made a difference to the results, based on the many observations conducted.

3.5.3 Data description

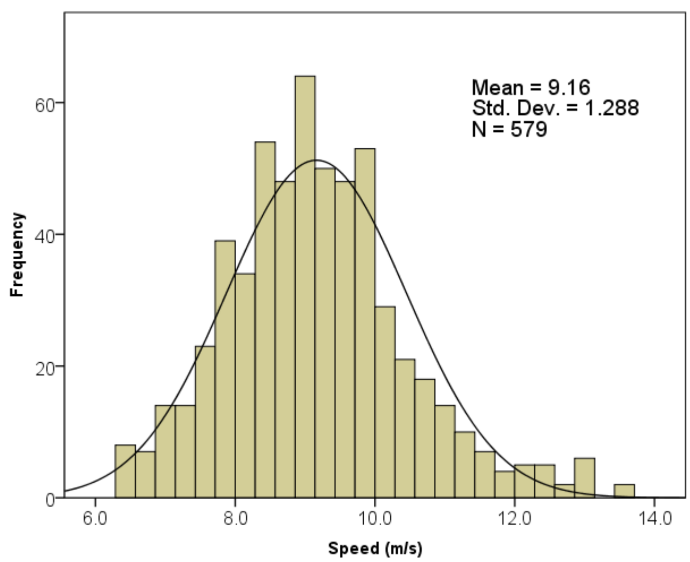
The study presents the properties of safety space using two survey data sets. The speed of motorcycles, the longitudinal distance and the lateral distance between subject motorcycles and most influential motorcycles, and the relationships between them are demonstrated.

Figure 3.6 shows the histograms of the speed at two road segments on Phan Dang Luu Street and Cong Hoa Street. The two road segments have different road conditions, making the average speed of each segment different from each other. The road segment on Phan Dang Luu Street is near an intersection and has only one lane in the observed direction; thus, the average speed is around 20km/h. The road segment on Cong Hoa Street has 3 lanes in each direction and is about 100 m farther from the intersection. Hence, the average speed on this road segment is around 30 km/h higher than Phan Dang Luu.

Figure 3.7 showed the scatter plots of the longitudinal distance against the lateral distance and how these scatter plots change according to the speed. One point in the figure will represent a relative position of the most influential motorcycle with respect to the subject motorcycle in one observation. Therefore, the number of points is equal to the sample size.

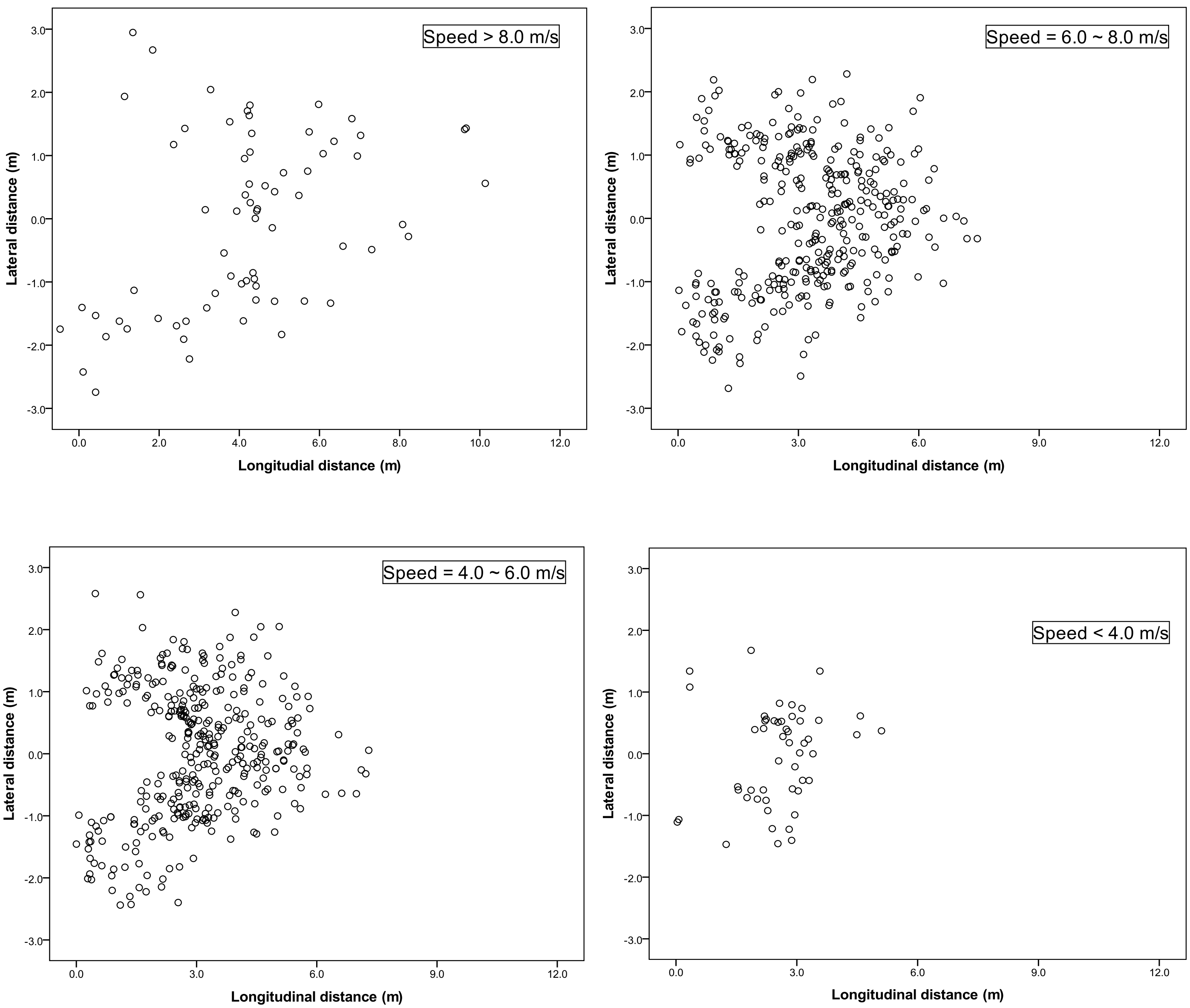


(a) Phan Dang Luu Street

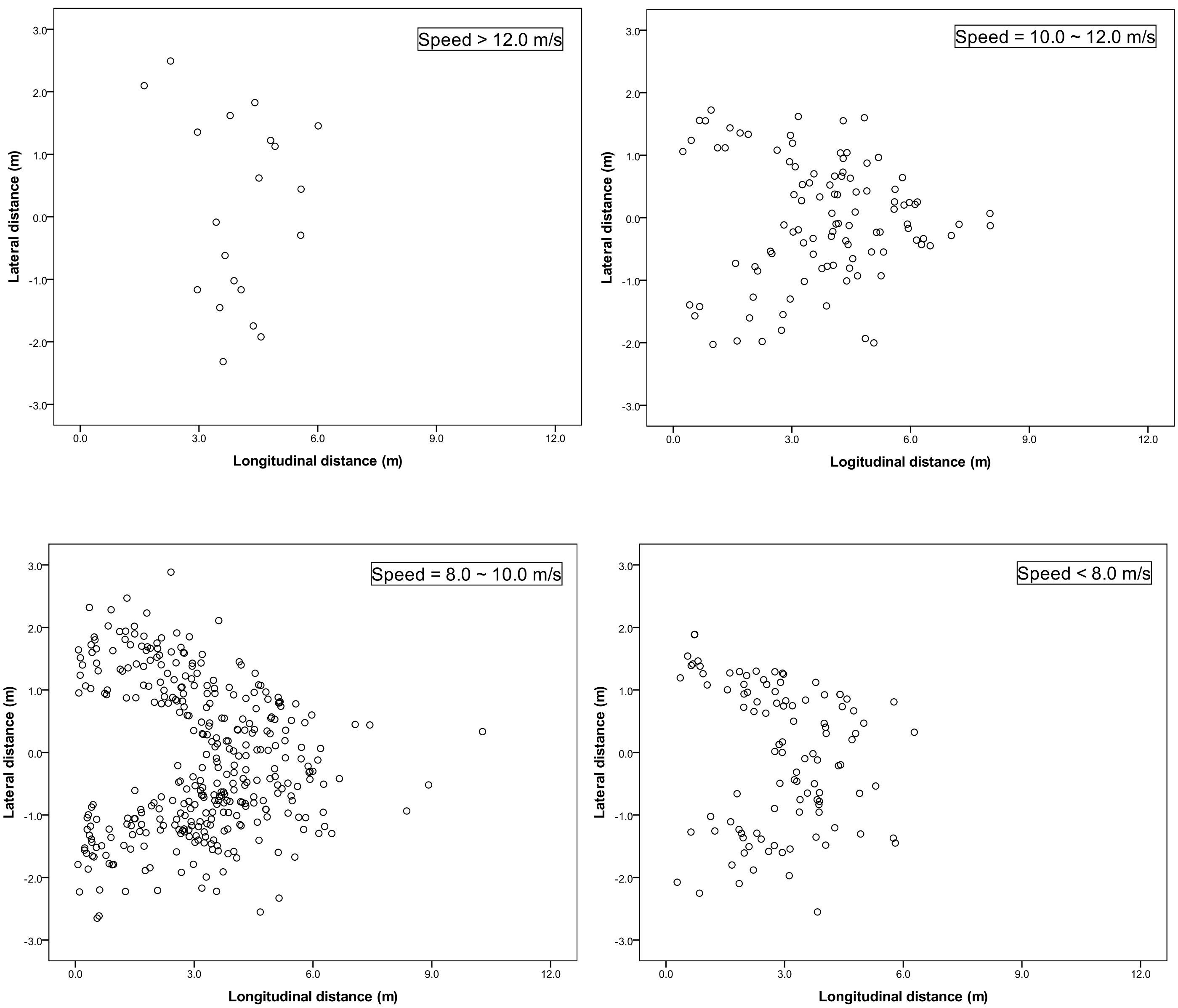


(b) Cong Hoa Street

Figure 3.6 Histogram of the speed at two locations



(a) Phan Dang Luu Street



(b) Cong Hoa Street

Figure 3.7 Scatter plots of longitudinal distance against lateral distance

The subject motorcycle is placed on the origin of the two-dimensional coordinate system. From the results of the scatter plots, many assumptions on the safety space are verified as followings:

1) The scatter points demonstrate safety spaces surrounding the origin of the coordinate system in which the subject motorcycle is placed. It can be concluded that the motorcycle driver always keeps the safety space when running to avoid a possible accident.

2) The data shows that safety spaces have the shape of an approximate half-ellipse. Therefore, there is the relationship between longitudinal distance and lateral distance and this relationship can be expressed by the equation of the half ellipse.

3) It was found that the safety space varies according to the speed. As the speed of a subject motorcycle becomes higher or lower, the safety space is larger or smaller. The longitudinal distance is likely proportional to the speed. However, the lateral distance seems to be constant with the speed. These results provided evidences for the hypothesis on the length of the semi-major axis and semi-minor axis of the ellipsoid safety space (see Section 3.2 and Figure 3.3).

4) By comparing the safety space between 2 different locations at the same speed intervals: 6 ~ 8 m/s and 8 ~ 10 m/s, it shows that the safety space is likely not to depend on the road conditions such as number of lanes, and distance from the intersection (near or far). This finding is consistent with the assumption made in calculating the safety space.

5) The scatter patterns illustrate that the safety space varies across individuals with different relaxation times. However, the difference in relaxation times among individuals is not considered in this research. The future research should pay attention to this limitation.

3.6 PARAMETER CALIBRATION

The proposed non-lane-based model based on the concept of safety space was calibrated by the regression analysis method. This model is formulated in Equation (3.5). Suppose that the error ε is normally distributed and observation data are independent.

$$a_\alpha(t+T_\alpha)=\begin{cases}-\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2}+\dfrac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right)+\varepsilon & \text{if } x\geq 0\\ -\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\dfrac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right)+\varepsilon & \text{if } -2d_x\leq x\leq 0\end{cases} \tag{3.5}$$

To simplify the calculation of the nonlinear function, a few parameters are assumed to be constant (see Table 3.2). The reaction time T of a motorcycle is taken to be equal to the mean value of the reaction time distribution, i.e., 0.5 s (Minh et al., 2006). The lateral distance of the threshold safety space was measured to be 1.8 m from field data for two vehicles riding side by side. The physical size of a motorcycle is taken as the average size in reality.

Table 3.2 Given parameters for the motorcycle-only flow

Parameter	Value
Reaction time T	0.5 s
Lateral distance W	1.8 m
Vehicle size d_x, d_y	length = 1.9 m, width = 0.8 m

SPSS software was used to derive the other parameters by solving the nonlinear regression problem (see Table 3.3). All the parameters were calibrated at the statistical significance level of 1%. The signs of the parameters A, B, and τ are positive because the magnitude of the safety space level must have a positive value. The relaxation time τ at the two different locations observed was almost the same: 0.5 s. As relaxation time is assumed to be the time required for the steering movement to change direction in combination with the braking movement to change speed, in order to avoid a possible collision, it should not differ between the two locations. This stable estimation result of relaxation time strongly supports the reliability of the proposed concept of safety space. Furthermore, interestingly, the estimated relaxation time is exactly equal to the reaction time of 0.5 s. This means that drivers maintain their threshold safety space with a lateral distance of 1.8 m and a longitudinal distance of the product of speed and reaction time. The differences in the values of parameters A and B between the two locations show that drivers on Cong Hoa Street have a higher rate of acceleration than those on Phan Dang Luu Street. Cong Hoa Street has three lanes and an average speed of 30 km/h, higher than the 20 km/h in Phan Dang Luu Street. A higher average speed implies a greater rate of acceleration.

Table 3.3 Derived parameters for the motorcycle-only flow

Parameter	**Location**					
	Phan Dang Luu Street			**Cong Hoa Street**		
	Estimate	Std. Error	t-value	Estimate	Std. Error	t-value
A	4.031	0.874	4.61	6.954	1.385	5.02
B	0.470	0.122	3.85	0.510	0.138	3.70
τ (s)	0.501	0.054	9.28	0.496	0.058	8.55

3.7 MODEL VALIDATION

The estimated results were compared to field data to validate the model. The study used statistical measures to calculate the value of errors. Root-mean-square (RMS) error, the measure of differences between estimated values and the field values, is as follows:

$$RMS\ \ error\ =\sqrt{\frac{1}{N}\sum_{i=1,N}\left(V_i^E-V_i^F\right)^2} \tag{3.6}$$

where

V_i^E = estimated value of speed at the i^{th} observation

V_i^F = field value of speed at the i^{th} observation

N = number of observations

To measure the relative error, RMS percent error is derived as

$$RMS\ \ percent\ \ error\ =\sqrt{\frac{1}{N}\sum_{i=1,N}\left(\frac{V_i^E-V_i^F}{V_i^F}\right)^2} \tag{3.7}$$

The mean error and mean percent error are other quantitative measures expressed as follows:

$$Mean\ \ error\ =\frac{1}{N}\sum_{i=1,N}\left(V_i^E-V_i^F\right) \tag{3.8}$$

$$Mean\ \ percent\ \ error\ =\frac{1}{N}\sum_{i=1,N}\left(\frac{V_i^E-V_i^F}{V_i^F}\right) \tag{3.9}$$

Positive and negative error values imply that the estimated value is over-predicted and under-predicted, respectively.

These errors were calculated for the speed of motorcycles (see Table 3.4). RMS error and RMS percent error of the speed are very small. Speed in Phan Dang Luu Street is over-predicted because the mean error is positive. The mean speed error in Cong Hoa Street is also positive. These indicators show that the proposed model well replicates the actual speed. To validate the zigzag movements of motorcycles, the observed swerving maneuvers to the left or right from the current position were compared with the estimated swerving maneuvers based on all the observations. The results in Table 3.4 show that 60.5% and 62.2% of the observed maneuvers in the two locations, respectively, could be reproduced by the proposed model.

A new sample of trajectory data on the same Cong Hoa Street, but in the other direction, was extracted to confirm the validation of the proposed model. Parameters A and B vary according to road conditions such as number of lanes, distances from intersections, and limited speed, so the new data from the same street should exclude those effects. A total of 994 observations for 120 motorcycles were taken from video clips. The study used the estimated parameters of Cong Hoa Street to predict the speed of motorcycles. The statistical analysis of the model showed stable predictions for the 2 different samples.

Table 3.4 Statistical measures for the speed and the ratio of swerving maneuvers for the motorcycle-only flow

Statistical Measurement	Value		
	Phan Dang Luu Street	**Cong Hoa Street**	**Cong Hoa Street** (in another direction)
RMS error (m/s)	0.486	0.581	0.636
RMS percent error	0.090	0.065	0.069
Mean error (m/s)	0.002	0.030	0.035
Mean percent error	0.006	0.006	0.006
Ratio of swerving modeled correctly (%)	60.5	62.2	63.2

3.8 SUMMARY

The chapter presented the concept of safety space developed for describing the non-lane-based movement of the motorcycle. Safety space was introduced to describe the changes of acceleration or deceleration behaviors in response to the changes of safety level of the safety space whose boundary is determined by the influence of other motorcycles. For example, if an influential vehicle moves closer to or farther away from a subject vehicle, the safety space becomes smaller or larger; as a result, the perceived level of safety decreases or increases and a subject vehicle decelerate or accelerate its speed.

The chapter also described the process of data collection for calibrating the motorcycle-following model. The survey was conducted on December 30 – 31, 2010 in Ho Chi Minh City, from 6:00 am to 8:00 am and 3:30 pm to 5:30 pm to observe traffic in the peak hours. Two road segments were selected for survey locations. Vehicle movements on 40 m long road segment in one direction were captured in videotape at the pace of 30 frames per second. Observation data on the positions of vehicles (X-axis and Y-axis coordinate) were extracted by using SEV software. The discrete observations for a target motorcycle and other influencing motorcycles were recorded after 0.5 sec. There are 4 to 8 observations for one motorcycle. In summation, 826 observations of 144 motorcycles at the Cong Hoa Street and 579 observations of 152 motorcycles at the Phan Dang Luu Street were used for calibration.

In the calibration result, all the parameters were calibrated at the significance level of 1%. The average relaxation time τ at two different locations was approximately equal to 0.5s. This stable estimation result of relaxation time strongly supported the reliability of the proposed concept.

In the model validation, the observed speed was predicted by the proposed model with a small RMS error and RMS percent error of speed. The proposed model could correctly describe around 61% of swerving behaviors to the left or right. Another sample of trajectory data on the same Cong Hoa Street, but in the other direction, was extracted to confirm the validation of the model. Statistical measures for the speed showed stable predictions for the two different samples.

Chapter 4 THE TRAFFIC SIMULATOR

4.1 INTRODUCTION

In this chapter, a simulator is developed to simulate non-lane-based movements of motorcycles in the motorcycle traffic flow. The non-lane-based movements are reproduced and the differences from the lane-based movements are verified.

The chapter starts with introductions of traffic simulation technique. Next, an open source software package was chosen to develop a simulator based on the research purposes. A detailed description on the simulator is presented including the main features, input models and calculation process. The chapter ends with the verification of this simulator.

4.2 TRAFFIC SIMULATION TECHNIQUE

Traffic engineering and transportation planning use simulation models in investigating traffic flow characteristics. These models are grouped into three types based on the scale level of detail in description of traffic vehicles: microscopic, mesoscopic and macroscopic.

Microscopic models track positions of each vehicle every second. The simulation uses random number to generate vehicles from a deterministic rule, and then vehicles select their speed based on the proposed moving rule described by differential equations or other numerical methods. Macroscopic models assume traffic flows as fluid streams. Traffic density, traffic volume and speed over time are simulated based on rules of fluid streams. Hence, the former models tackle traffic on the micro-scale level of each vehicle whereas the latter models pay attention to the macro-scale level of flow.

Mesoscopic models describe the traffic flow on the middle level of detail. These models assume that the road is divided into many cells of given size that can either be empty or occupied by other vehicles. Vehicles will go in one cell and move to another cell based on the proposed rules of moving when going along a road.

Since this research focuses on issues of traffic accident caused by motorcycle non-lane-based movements, it is appropriate to use the microscopic simulation models to describe motorcycle driving behaviors at the level of individual vehicles and to simulate how their movements affect the accident potential.

4.2.1 Agent-based microscopic simulation models

Microscopic simulation models are used to investigate the movements of individual vehicles in the traffic flow. Existing models proposed acceptable assumptions of driving behaviors expressed by differential equations or other numerical methods. Speed and direction of vehicles for moving ahead are decided based on the proposed driving behaviors. Hence, microscopic models are capable to track positions of each vehicle every second.

The agent-based modeling technique is popularly used for microscopic simulation models of each vehicle's driving behaviors. The term "agent" refers to an artificial life agent (Franklin and Graesser, 1997). Agents act to meet the desired purpose by themselves. They respond to other agents and the environment based on deterministic rules. The agents have their characteristics, memory and even ability of learning from experiences. Therefore, after an agent is assigned these rules of driving behaviors, it is capable to act like human in the traffic flow. This agent-based modeling technique is a powerful tool to analyze characteristics of traffic flow by considering interactions and behaviors of individual vehicles (Lee, 2008). Table 4.1 shows a list of agent-based models based on developing history, tackled problems and corresponding software packages.

Table 4.1 Agent-based models for the microscopic traffic simulation

Reference	Tackled problem	Software
Nagel and Schreckenberg (1992)	Flow – density diagram and shock wave.	TRANSIMS
Bazzan et al. (1999)	Not-completely rational decision making: the consideration of mental states like emotions, preferences, intentions.	ITSUMO
El Hadouaj et al. (2000)	Lane-changing behavior with consideration of forecasting duration of interaction.	ARCHISIM
Nagel and Raney (2003)	Large-scale of ten million travelers by implementing the strategy generation and day-to-day agent-based learning.	MATSim
Hidas (2002, 2005)	Lane-changing behavior with cooperation of reducing speed and deceleration.	ARTEMiS
Palmiano et al. (2004)	Heterogeneous traffic with midblock jeepney stops.	JSTOPSIM
Marchal and Nagel (2007)	Location choice of secondary activities with exchanges of information through social network connected by agents.	MATSim
Lee et al. (2008)	Heterogeneous traffic with multi-vehicular interaction.	BikeSim
Rieser (2010)	Mode choice and schedule-based transit.	MATSim

4.2.2 Tools for building traffic simulator

There are a large number of software packages which are available online for building traffic simulator. Each traffic simulator has its features, different purposes of usage and the accuracy of output results. Hence, this study will review traffic simulation packages so as to choose the most suitable one for the research purpose. Some requirements for software packages are presented below:

1) *Open source*

There are available open source simulation packages. Users can use these software free of charge. They can study and modify the source code for the research purpose without any restrictions. However, only a few software products allow users to modify or add a part of the source through providing tools to interact with main source.

2) *Operating system*

Many free software packages work under Linux operating system, and may not be convenient if users run their computer on Microsoft Windows. Some errors could occur when converting pictures and simulation movie clips from Linux to Windows. However, Linux and Mac OS X become more popular now and would be a good choice for operating system.

3) *Programming language*

The popular programming languages are Java, Visual Basic and C.

4) *Graphic presentation*

This is an important factor for the users to see visual results of traffic simulation. When running the simulation, the monitor shows movements of vehicles on the road and what traffic phenomenon could happen in real time. Therefore, graphic presentation is a good way to examine the verification of the simulator.

A number of open source software packages that meet the requirements of building a traffic simulator for this research are introduced in Table 4.2. This research chose the open source software originally developed by Helbing et al. (2000) to build the simulator for the motorcycle traffic. The main reason of the choice is that this research attempts to compare performances between the social force model developed by Helbing and the proposed concept of safety space (see Appendix A).

Table 4.2 Open source software packages

Software package or name of author	**Features**
SUMO	A microscopic traffic simulation deals with large-scale network, route choice, vehicular communication.
Treiber (2009)	The software consists of two models: acceleration and lane-changing.
MATSim	A transport simulation toolkit provides a large scale network, demand-modeling and traffic flow simulation.
MITSIM	A microscopic simulation handles car-following model, lane-changing, traffic signal responding logic and route choice decision based on real time route guidance information.
Helbing et al. (2000)	A simulation for pedestrian movements.
SWARM	Software toolkit offers a platform for agent-based modeling.
REPAST	A toolkit provides a simulation platform for agent-based modeling.

4.3 THE SIMULATOR

The research developed a microscopic simulator to analyze the characteristics of the non-lane-based traffic flow. The simulator used open source which was first introduced for pedestrian simulation by Helbing et al. (1998). The research adopted open source pedestrian simulation because of its modification flexibility and similar features of design for non-lane-based movement modeling. The simulation program was written in the C language and run under the Linux operating system. In the first section, the overall design of the simulator is presented. Then, components on each step of design process are explained in the next section.

4.3.1 Overall design

The overall design consists of the input data and a loop-over process of acceleration calculation and simulation outputs at every simulation time step, illustrated in Figure 4.1.

The simulator can input data of network information, such as the length and width of a road segment, origin-destination points, time-series of traffic rate on a road segment, the estimated values of parameters of the threshold safety space, and the free speed of motorcycles. Then, vehicles are generated at the original points.

The calculation process combines two different models (1) a free acceleration model for describing the behavior of increasing speed to achieve free speed when no influential motorcycles are running in front of a subject motorcycle and (2) the proposed non-lane-based model for describing the behaviors of acceleration or deceleration when influential motorcycles appear. After calculating acceleration, the system updates speeds and determines the next movements of vehicles.

When vehicles arrive at destination points, they are removed from the road segment. The output of the program can show x, y coordinate value, speed, and acceleration of all the vehicles on a road over time in the form of text data and can calculate traffic volume and density of the traffic flow.

The simulator updates calculation progress and output at 0.01 sec time intervals and repeats them until meeting restraint conditions such as maximum simulation time, maximum number of iterations or maximum number of vehicles.

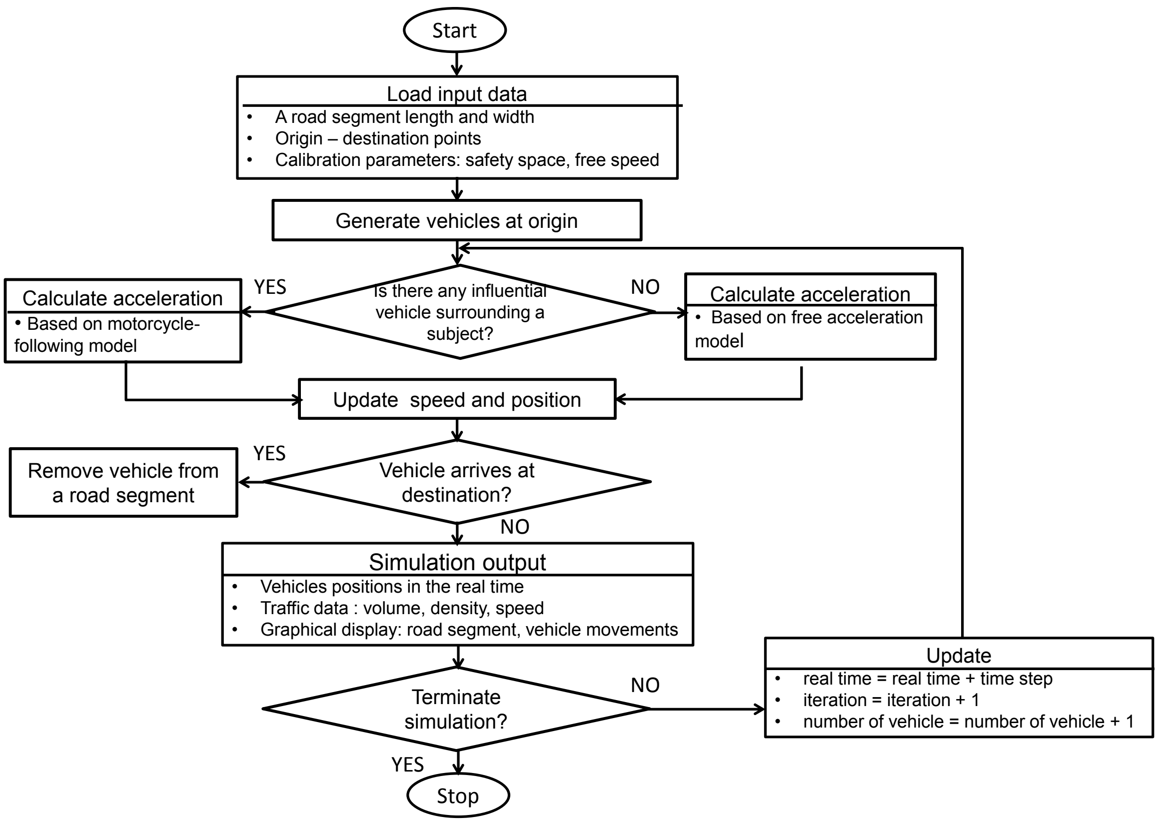


Figure 4.1 Flow chart of the traffic simulation model

4.3.2 Components

This section presents the main components of the simulator in details.

The network and Original – Destination points

The simulator represents the network at the road segment level, based on the research purpose. Here a straight road segment of 200 m length and 5.4 m width with uniform geometric characteristics such as the width of section and number of lanes is considered. All the vehicles are inserted at origin points, ran on the road segment and removed at destination points. When vehicles run at a free acceleration, they speed up in the direction of the road. When vehicles meet obstacles, they will decrease speed and swerve left or right. However, they cannot go out of the road segment from both sides because pushing forces along road side will be activated when vehicles approach.

The road segment is divided into square blocks with the width R= 0.5 m for each. One block contains one vehicle inside it when the center of vehicle goes in the area of the block. Hence the width of the block is set to be small enough to contain only one vehicle at any point of time. When a vehicle moves out of the block i, the ID number of the vehicle will be deleted from the block i and inserted to the new one i+1. When a vehicle wants to scan the surroundings to detect the influential vehicles, each block in the scanning area will inform whether a vehicle stays in or out of the block.

Original points and destinations points are set at two ends of the road segments. One original – destination pair is placed on the same lane, especially when considering car-following model simulation, as shown in Figure 4.2.

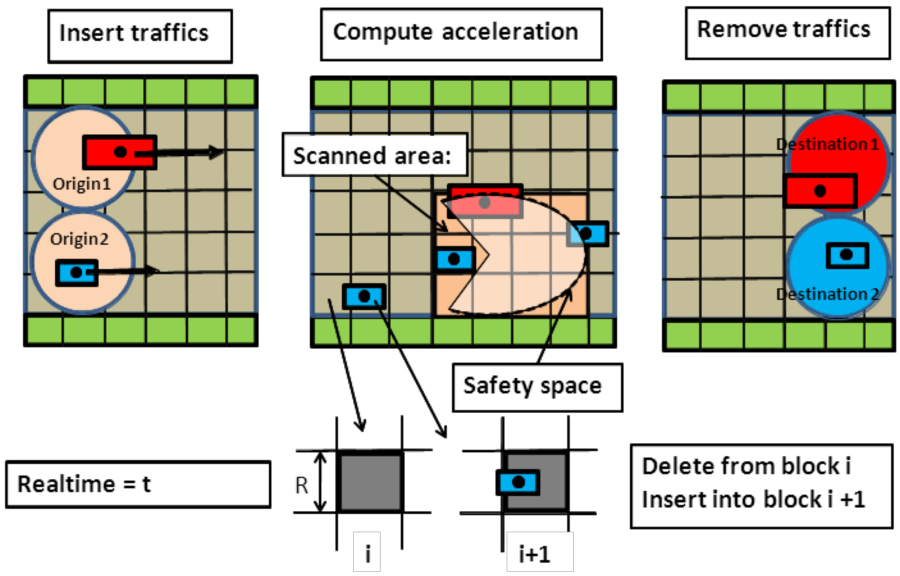


Figure 4.2 Screenshot of the simulator

Vehicle generation

The vehicles are generated randomly inside original points. The randomness makes the initial relative positions between vehicles more realistic and produces the scattered plots of the traffic output data. In addition, vehicles are also generated increasingly over the simulation time in the beginning duration, 800 sec, so as to achieve the maximum traffic rate. Then, traffic rate is drawn from a normal distribution in which the mean decreases with the simulation time (see Equation 4.1). When the queue of waiting vehicles move backward and approach original points, vehicle generation is stopped. This mechanism could simulate the traffic changing from a free flow to a congested flow (Lee et al., 2008).

$$Traffic\,rate\,(veh/sec) = \begin{cases} \dfrac{Time}{1000} & if\ Time \le 800\text{sec} \\ Normal\left(\dfrac{800}{Time}, 0.25^2\right) & if\ Time > 800\text{sec} \end{cases} \qquad (4.1)$$

Signal control

A signal is set at the end of the road segment. It is activated from the 801th sec of the simulation time. The signal cycle of 60 sec has three displays: red, yellow (2 sec) and green. The length of the red light increases by 1 sec after every 120 sec of the simulation progress. Hence, the simulation needs 2 hours to capture all the changes of red light that affects the changes of traffic density.

Simulation time

The time to run a simulation is set to be 8000 sec.

Simulation output

The output results from the simulator are grouped into two types of data as follows:

1) Disaggregate data: includes coordinates in the x-axis and the y-axis, speed and acceleration of each vehicle on a road segment in real time. The simulator provides not only these data, but also graphical display of a road segment and movements of all vehicles on the segment.

2) Aggregate data: includes mean speed, traffic volume and density of the traffic flow on a road segment in real time. In order to achieve aggregate data, the traffic flow on a 100-m-long target segment right behind the traffic signal is collected. The number of traffic going through the downstream of the target segment is measured as the traffic volume. The difference between the number of traffic at the upstream and the downstream is measured as the density. The average speed of four test vehicles which run over 100 m on the target segment is calculated as the mean speed. When the traffic is a free flow, aggregate data is collected at every 30 sec of the simulation time. However, when it is a congested flow, collection time varies from 30 sec to 8 minutes depending on the time needed for a test vehicle to finish running on the target segment.

Model specifications

The models in the simulator determine the acceleration rate for each vehicle under a certain situation. In this simulator, two different models are combined: a *free acceleration model* and the proposed *motorcycle-following model*. The rules for choosing which model to use are as follows:

1) The road segment is divided into many blocks. For each subject vehicle, the simulator scans the blocks which are occupied by the pre-determined safety space so as to examine whether any influential vehicle exists inside the safety space or not. The boundary of the pre-determined safety space is assumed to be far enough for a subject motorcycle to perceive that it is not affected by influential motorcycles, i.e., it feels free to accelerate its speed. For the simplicity of calculation, the boundary is supposed to be a rectangle with the length and the width denoted by L_{free} and W_{free} as shown in Equation (4.2).

$$\text{Pre-determined safety space} = \text{Length } L_{free} \text{ (m)} \times \text{Width } W_{free} \text{ (m)} \qquad (4.2)$$

2) When no influential motorcycles are inside the pre-determined safety space of a subject motorcycle, the free acceleration model is selected to calculate traffic acceleration rate as follows:

$$\begin{aligned} a^x_{\alpha,free} &= \frac{v_{max} - v^x_\alpha}{T_{free}} \\ a^y_{\alpha,free} &= 0 \end{aligned} \qquad (4.3)$$

where $a^{x}_{\alpha,free}$, $a^{y}_{\alpha,free}$ are the free acceleration of a driver α in the x-axis and the y-axis of a road, respectively and v^{x}_{α} is the current speed on the x-axis. v_{max} is the maximum speed which the driver α wishes to run and its direction is parallel to the x-axis of a road. T_{free} is the time needed for changing from the current speed to the maximum speed.

3) Otherwise, when influential motorcycles appear in the pre-determined safety space of vehicle α, motorcycle-following model is chosen to calculate the traffic acceleration rate. If there is only one influential vehicle β, then acceleration rate is determined as below:

$$a_{\alpha,following} = \begin{cases} -\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\frac{x^2}{(\tau_\alpha v_\alpha)^2}+\frac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right) & if\ x \geq 0 \\ -\nabla_{\vec{v}_{\alpha\beta}}\left(A\exp\left(-\left(\frac{y^2}{(W_\alpha+d_y)^2}\right)\Big/B\right)\right) & if\ -2d_x \leq x \leq 0 \end{cases} \tag{4.4}$$

where $\vec{v}_{\alpha\beta} = \vec{v}_{\beta} - \vec{v}_{\alpha}$ denotes relative speed vector; parameter *A* represents the magnitude of the safety level; parameter *B* represents the effect of stretching out the safety level value; v_α is the current speed ; τ_α is the relaxation time on the x-axis of the safety space; W_α is the lateral distance between two motorcycles on the y-axis of the safety space; *x* and *y* indicate the current relative position of the influential vehicle with a subject vehicle on the x-axis and the y-axis; d_x and d_y denote the physical size of a motorcycle on each axis. The direction of the acceleration vector $\vec{a}_{\alpha,following}$ which shows the direction of motion and it is related to the gradient direction of the safety space as given by Equation (3.3).

If there are more than one influential vehicle and the acceleration of subject vehicle α corresponding to the influential vehicle i is denoted by $\vec{a}_{\alpha i}$, then acceleration rate is determined as below:

$$\max_i \left\{ \|\vec{a}_{\alpha 1}\|, \|\vec{a}_{\alpha 2}\|, \ldots, \|\vec{a}_{\alpha i}\|, \ldots, \|\vec{a}_{\alpha N}\| \right\} \tag{4.5}$$

$\|\vec{a}_{\alpha i}\|$ is given as the magnitude of the acceleration of vehicle α in response to the influential vehicle i.

Emergency regime

This regime is applied in the situation when a vehicle takes an emergency brake to avoid a collision with a preceding vehicle. The conventional regime proposed for the car (Yang and Koutsopoulos, 1996) assumed that if a following vehicle α has a headway smaller than a pre-determined threshold distance $L_{emergency}$, then its acceleration is given as follows:

$$a_{\alpha,emergency} = \begin{cases} \min\left\{ a_{\alpha-1} - \dfrac{(v_\alpha - v_{\alpha-1})^2}{2x}, a_\alpha^- \right\} & if \;\; v_\alpha > v_{\alpha-1} \\ \min\left\{ a_{\alpha-1}, a_\alpha^- \right\} & if \; v_\alpha \le v_{\alpha-1} \end{cases} \tag{4.6}$$

where $a_{\alpha-1}$ denotes the acceleration of the preceding car $\alpha - 1$, a_α^- is the normal deceleration rate, i.e., the acceleration when applying a break; v_α, $v_{\alpha-1}$ are speeds of the following car and the preceding car, respectively; x is the distance between two consecutive cars. Equation (4.6) was applied for the one-dimensional movement of the car. In this research, the equation is accepted to extend to two-dimensional motorcycle movement as follows:

Case 1: when a subject motorcycle follows a preceding motorcycle ($L_{emergency} \geq x \geq 0, d_y \geq y \geq -d_y$)

If a motorcycle α follows another motorcycle $\alpha - 1$ with the longitudinal distance x smaller than a pre-determined longitudinal threshold distance $L_{emergency}$, then a subject motorcycle applies an emergency brake to avoid an accident. The braking acceleration $a^{x}_{\alpha,emergency}$ of the motorcycle α on the x-axis is similar to the acceleration of the car. For simplicity, a subject motorcycle is supposed to not have enough time for swerving, i.e., acceleration $a^{y}_{\alpha,emergency}$ on the y-axis is zero, as expressed in Equation (4.7).

$$
\begin{aligned}
a^{x}_{\alpha,emergency} &= \begin{cases} \min\left\{ a^{x}_{\alpha-1} - \dfrac{\left(v^{x}_{\alpha} - v^{x}_{\alpha-1}\right)^2}{2x}, a^{-,x}_{\alpha} \right\} & if \;\; v^{x}_{\alpha} > v^{x}_{\alpha-1} \\ \min\left\{ a^{x}_{\alpha-1}, a^{-,x}_{\alpha} \right\} & if \;\; v^{x}_{\alpha} \leq v^{x}_{\alpha-1} \end{cases} \\
a^{y}_{\alpha,emergency} &= 0
\end{aligned}
\tag{4.7}
$$

where $a^{-,x}_{\alpha}$ is the normal deceleration rate on the x-axis. It is assumed that the speed v^{y}_{α} on the y-axis is not changing during the braking process but suddenly becomes zero when its speed v^{x}_{α} on the x-axis is zero. The assumption is acceptable because the speed on the y-axis is very smaller than the speed on the x-axis; therefore, the movement on the y-axis has an insignificant effect on the rear-end collision between two motorcycles.

Case 2: when two motorcycles run alongside ($-2d_x \leq x < 0, W_{emergency} \geq |y| \geq 0$)

If a subject motorcycle α running beside another motorcycle $\alpha - 1$ has the lateral distance y smaller than a pre-determined lateral threshold distance $W_{emergency}$, the motorcycle is supposed to swerve farther away from an influential motorcycle to avoid an accident. It means that it only changes the acceleration $a^{y}_{\alpha,emergency}$ on the y-axis while keeping the same speed on the x-axis, i.e., $a^{x}_{\alpha,emergency} = 0$ as given in Equation (4.8).

$$a^{x}_{\alpha,emergency} = 0$$
$$a^{y}_{\alpha,emergency} = \begin{cases} \min\left\{ a^{y}_{\alpha-1} - \dfrac{\left(v^{y}_{\alpha} - v^{y}_{\alpha-1}\right)^2}{2y}, a^{-,y}_{\alpha} \right\} & if \ \ y(v^{y}_{\alpha-1} - v^{y}_{\alpha}) \le 0, y \ge 0 \\ \max\left\{ a^{y}_{\alpha-1} + \dfrac{\left(v^{y}_{\alpha} - v^{y}_{\alpha-1}\right)^2}{2y}, a^{-,y}_{\alpha} \right\} & if \ \ y(v^{y}_{\alpha-1} - v^{y}_{\alpha}) \le 0, y \le 0 \\ \min\left\{ a^{y}_{\alpha-1}, a^{-,y}_{\alpha} \right\} & if \ \ y(v^{y}_{\alpha-1} - v^{y}_{\alpha}) > 0, y > 0 \\ \max\left\{ a^{y}_{\alpha-1}, a^{-,y}_{\alpha} \right\} & if \ \ y(v^{y}_{\alpha-1} - v^{y}_{\alpha}) > 0, y < 0 \end{cases} \tag{4.8}$$

where $a^{-,y}_{\alpha}$ is the normal deceleration rate on the y-axis. The equation is an extended version of Equation (4.7) considering the case in which a motorcycle could perform the backward running. The condition of $y(v^{y}_{\alpha-1} - v^{y}_{\alpha}) \le 0$ or $y\left(v^{y}_{\alpha-1} - v^{y}_{\alpha}\right) > 0$ means that two vehicles approach each other or move father away, respectively. The condition of $y \ge 0$ or $y < 0$ shows that the influential motorcycle is on the right or left side of the subject motorcycle. When an influential motorcycle approaches a subject vehicle on the right side, then the acceleration a^{y}_{α} becomes negative and the subject motorcycle will use the minimum value among emergency braking acceleration $a^{y}_{\alpha-1} - \left(v^{y}_{\alpha} - v^{y}_{\alpha-1}\right)^2/2y$ to escape a possible accident or keep the acceleration of the preceding motorcycle $a^{y}_{\alpha-1}$ or the normal acceleration $a^{-,y}_{\alpha}$ on the y-axis. On the contrary, when the acceleration a^{y}_{α} becomes positive, it will use the minimum value.

Stopping regime before traffic signal

A motorcycle is assumed to respond to signal control when the distance to the traffic signal is less than the stopping distance L_{signal} on the x-axis given by:

$$L_{signal} = \max\left\{ -\frac{\left(v_{\alpha}^{x}\right)^2}{2a_{\alpha}^{-,x}}, L_{signal}^{\min} \right\} \tag{4.9}$$

where $-(v_{\alpha}^{x})^2/2a_{\alpha}^{-,x}$ is the distance for a motorcycle running with speed v_{α}^{x} to decrease the speed at the deceleration $a_{\alpha}^{-,x}$ on the x-axis to a stop based on the motion equation. L_{signal}^{min} is a lower boundary of the distance.

When a motorcycle detects a traffic signal from a stopping distance L_{signal}, it would decide to keep running or decrease the speed for a stop right before the signal. While the signal is green or yellow, a driver would pass the signal if the moving time to the signal is shorter than the remaining yellow time. Otherwise, a drive starts applying a brake with the deceleration as follows:

$$\begin{aligned} a_{\alpha,signal}^{x} &= \frac{-v_{\alpha}^{2}}{2x} \\ a_{\alpha,signal}^{y} &= \frac{-v_{\alpha}^{y}}{(x/v_{\alpha}^{x})} \end{aligned} \tag{4.10}$$

where x is the distance from the current position of a motorcycle α with speed v_{α} to the stop line and $a_{\alpha,signal}^{x}$, $a_{\alpha,signal}^{y}$ are the decelerations on the x-axis and the y-axis required for a motorcycle α to stop safely before a traffic signal.

The deceleration in the stopping regime before traffic signal could be applied for the lead motorcycles approaching the signal lights. For the following motorcycles, they not only have to stop before the stop line, but also decelerate to avoid a collision with the leaders. Therefore, their deceleration will take the minimum value among a normal following deceleration $a_{\alpha,following}$ in Equation (4.4), a deceleration rate in the emergency regime, $a_{\alpha,emergency}$ in Equation (4.7), (4.8) and a deceleration in the stopping regime before traffic signal $a_{\alpha,signal}$ in Equation (4.10) as follows:

$$\begin{aligned} a_{\alpha}^{x} &= \min\left\{a_{\alpha,emergency}^{x}, a_{\alpha,signal}^{x}, a_{\alpha,following}^{x}\right\} \\ a_{\alpha}^{y} &= \min\left\{a_{\alpha,emergency}^{y}, a_{\alpha,signal}^{y}, a_{\alpha,following}^{y}\right\} \end{aligned} \tag{4.11}$$

When a traffic signal becomes green, the first leading vehicles accelerate freely from the stop line according to Equation (4.3) and the queuing vehicles will follow the leaders to increase their speed according to Equation (4.4).

4.4 VERIFICATION

This section presents the verification of the simulator. This simulator represents the non-lane-based movements including oblique following and swerving movement. Then, the differences between these lane-based movement and non-lane-based movement are verified using the simulation results of the fundamental diagrams.

4.4.1 Reproduction of non-lane-based movements

A simulation was performed to test the original movements of motorcycles. The oblique following behavior and swerving movement in a congested traffic situation were reproduced. The simulation conditions included a 200-m-long and 5.4-m-wide road segment. Traffic flow which is drawn from a normal distribution as given by Equation (4.1) changes from 0 to 9000 vehicles per hour. The free speed was set to be 28.8 km/h. The estimated parameters of the model for the case of Phan Dang Luu Street and the other parameters were used for simulation as shown in Table 4.3.

Figure 4.3 shows the time-space diagram of the trajectories extracted from simulation progress at congested traffic flow rate of around 3200 veh/h. The traffic signal is installed at a 180-m position on the 200-m-long road segment. The data on the traffic flow behind the traffic signal is collected in a period time of 100 sec when the length of the red light time is 15 sec.

Table 4.3 Parameters for simulations

Road size (length, width, in m)	(200.0, 5.4)
Traffic flow (veh/h)	From 0 to 9000
Free speed v_{max} (km/h)	28.8
A	6.954
B	0.510
Relaxation time τ (s)	0.5
Reaction time T (s)	0.5
Lateral distance W (m)	1.8
Vehicle size (meter length d_x, meter width d_y)	(1.9, 0.8)
Safety space for free acceleration (meter length L_{free}, meter width W_{free})	($2v_\alpha$+3.8, 2.6)
Time needed for changing from the current speed to the maximum speed T_{free} (s)	1.5
Threshold distances in the emergency regime (meter length $L_{emergency}$, meter width $W_{emergency}$)	($0.5v_\alpha$+3.8, 1.0)
Lower boundary of stopping distance before traffic signal L_{signal}^{min} (m)	20

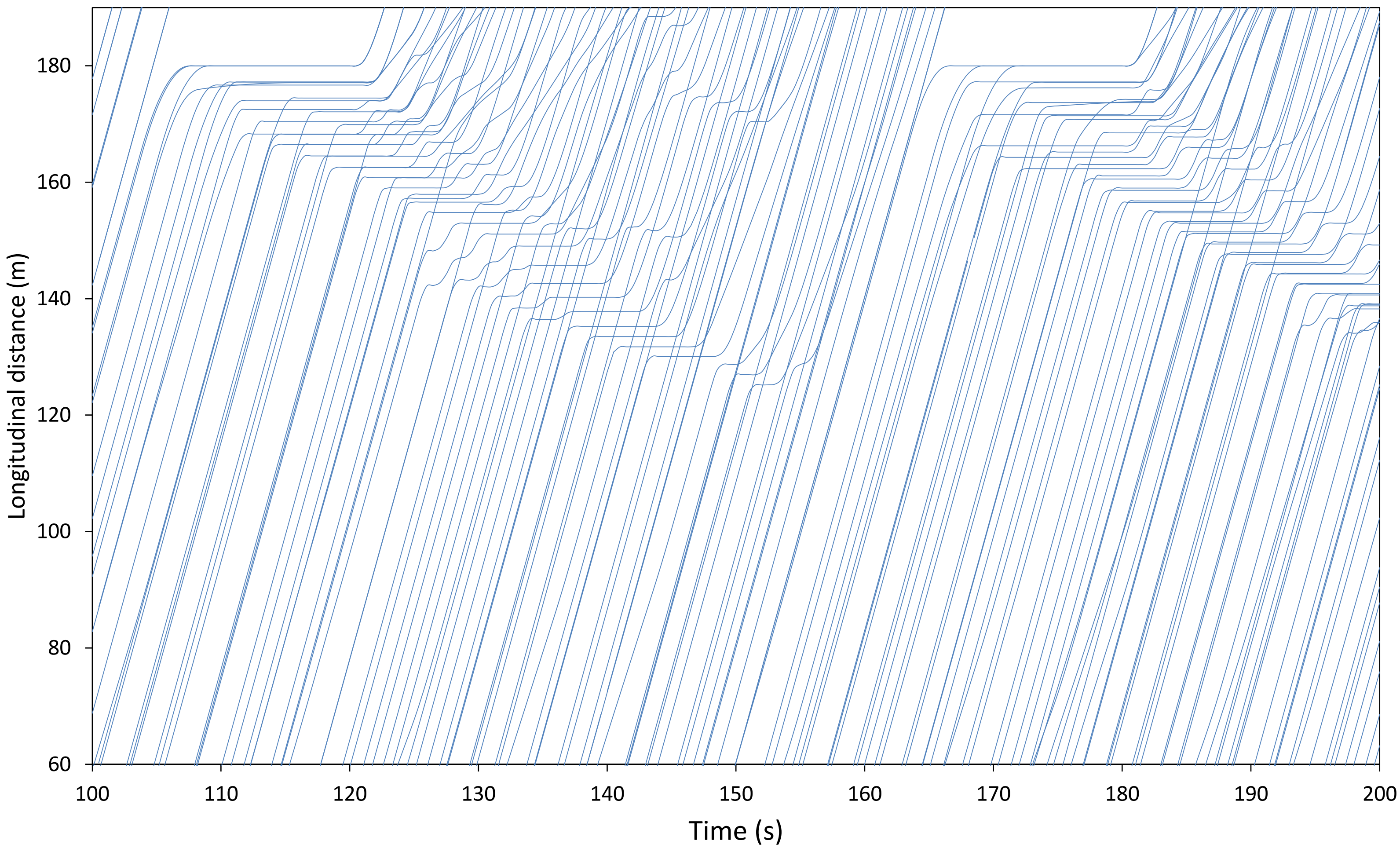


Figure 4.3 Time-space diagram of the trajectories

From the trajectories in Figure 4.3, oblique following and swerving movement are confirmed.

Oblique Following

The simulation reproduced oblique following, which is a very typical motorcycle non-lane-based movement in congested traffic. A motorcycle rider prefers to follow another vehicle at an oblique angle so as to achieve a larger safety space relative to the influential vehicle in front.

The oblique following behavior of a motorcycle is shown in the time-space trajectories as illustrated in Figure 4.4. Each point in the figure represents a position of the most influential motorcycle or the subject motorcycle in every 0.5 sec. Many motorcycles are observed to keep very small headways in the long time while following another along the road segment before approaching the traffic signal.

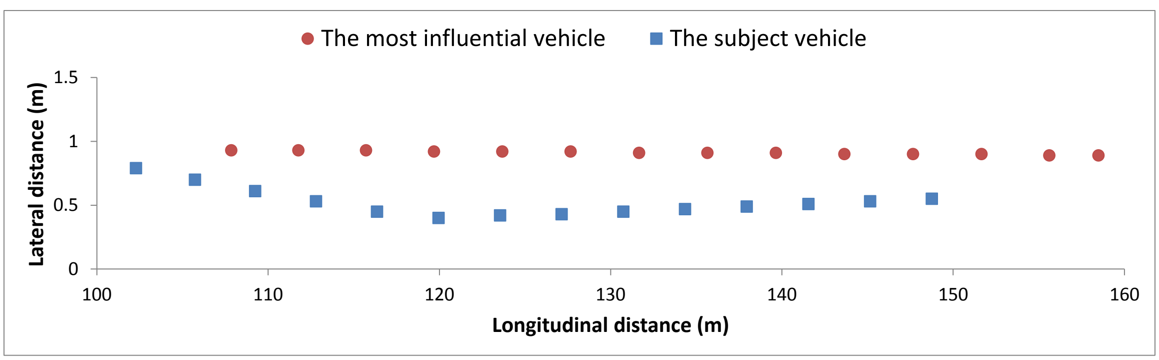


Figure 4.4 Time-space trajectories of the oblique following

Swerving Movement

The swerving movement of a motorcycle was also observed by simulation. This behavior shows the sudden swerving in response to changes in the lead vehicle's speed. The simulation results showed that motorcycles swerve in response to avoid collision as shown in Figure 4.5.

Swerving behaviors can be observed when motorcycles approach the signal. The first motorcycles detecting the red light will decelerate their speed to a stop. Then many following motorcycles also decrease their speed to avoid colliding with the leaders, revealing shock waves in the motorcycle traffic flow. Some other following motorcycles are observed to swerve left or right and consequently overtake their leader in order to move ahead. The trajectories of the swerving motorcycles are chaotic, and cross that of the leading motorcycles as illustrated in Figure 4.3.

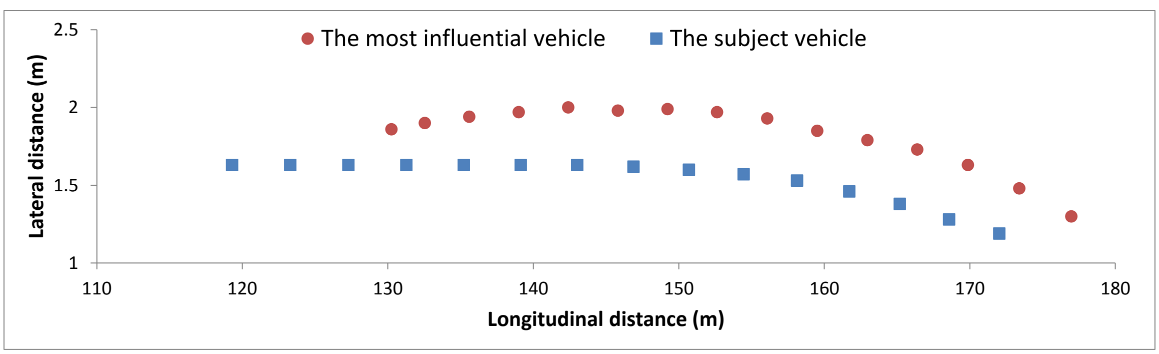


Figure 4.5 Time-space trajectories of the swerving movement

4.4.2 Differences from lane-based movements

Very few studies have compared the lane-based movement with the non-lane-based movement because it is difficult to find a general equation that can cover both. Interestingly, the concept of safety space could also be applied to describe the lane-based movement, such as the car-following model. The difference between these two movements is verified using the simulation results of fundamental diagrams.

Consistency with the Car-Following Equation

It can be demonstrated that the car-following model is just a special case of the non-lane-based model expressed by Equation (4.12) and (4.13).

$$\|\vec{a}_\alpha\| = \begin{cases} A\exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2} + \dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/B\right)\dfrac{1}{\|\vec{v}_{\alpha\beta}\|}\left(\dfrac{xv_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{yv_y}{(W_\alpha + d_y)^2}\right) & \text{if } x \geq 0 \\ A\exp\left(-\left(\dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/B\right)\dfrac{1}{\|\vec{v}_{\alpha\beta}\|}\dfrac{yv_y}{(W_\alpha + d_y)^2} & \text{if } -2d_x \leq x \leq 0 \end{cases} \tag{4.12}$$

$$\frac{\vec{a}_\alpha}{\|\vec{a}_\alpha\|} = \begin{cases} \dfrac{\nabla V_\beta}{\|\nabla V_\beta\|} & \text{if } a_\alpha \leq 0 \\ \dfrac{-\nabla V_\beta}{\|\nabla V_\beta\|} & \text{if } a_\alpha > 0 \end{cases} \tag{4.13}$$

Assuming that in the car-following model, cars follow their leaders without changing their lane, Equation (4.12) can be reduced to a one-dimensional movement as follows:

$$a_\alpha(t + T_\alpha) = A\exp\left(-\left(\frac{x^2}{(\tau_\alpha v_\alpha)^2}\right)\Big/B\right)\frac{x}{(\tau_\alpha v_\alpha)^2}\frac{v_{\alpha\beta}}{\|\vec{v}_{\alpha\beta}\|} \tag{4.14}$$

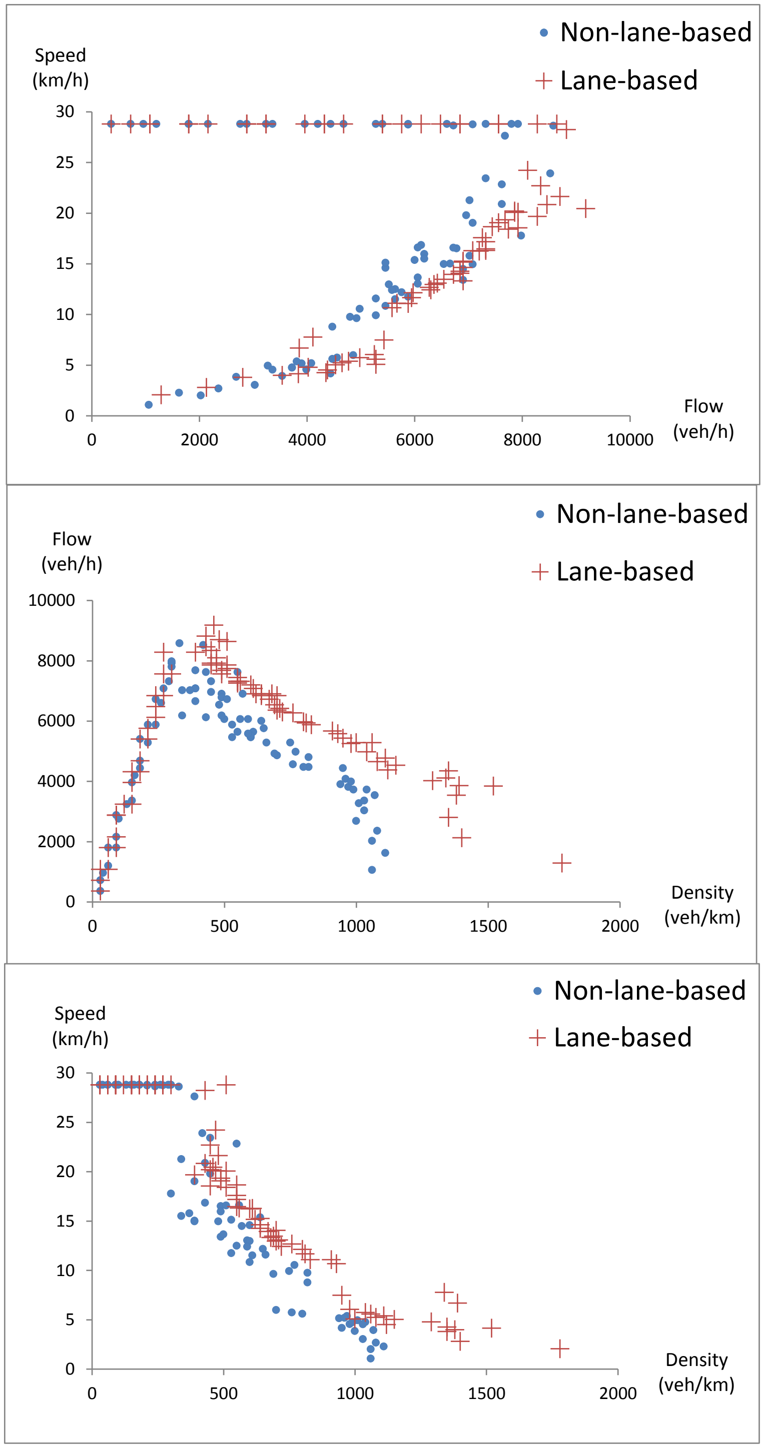
Here, the appearance of the relative speed $v_{\alpha\beta} = v_\beta - v_\alpha$ in Equation (4.14) shows the basic equation for the car-following model. Equation (4.14) becomes a nonlinear car-following model representing the effect of the distance between the leader and the follower.

Comparison of the Fundamental Diagrams

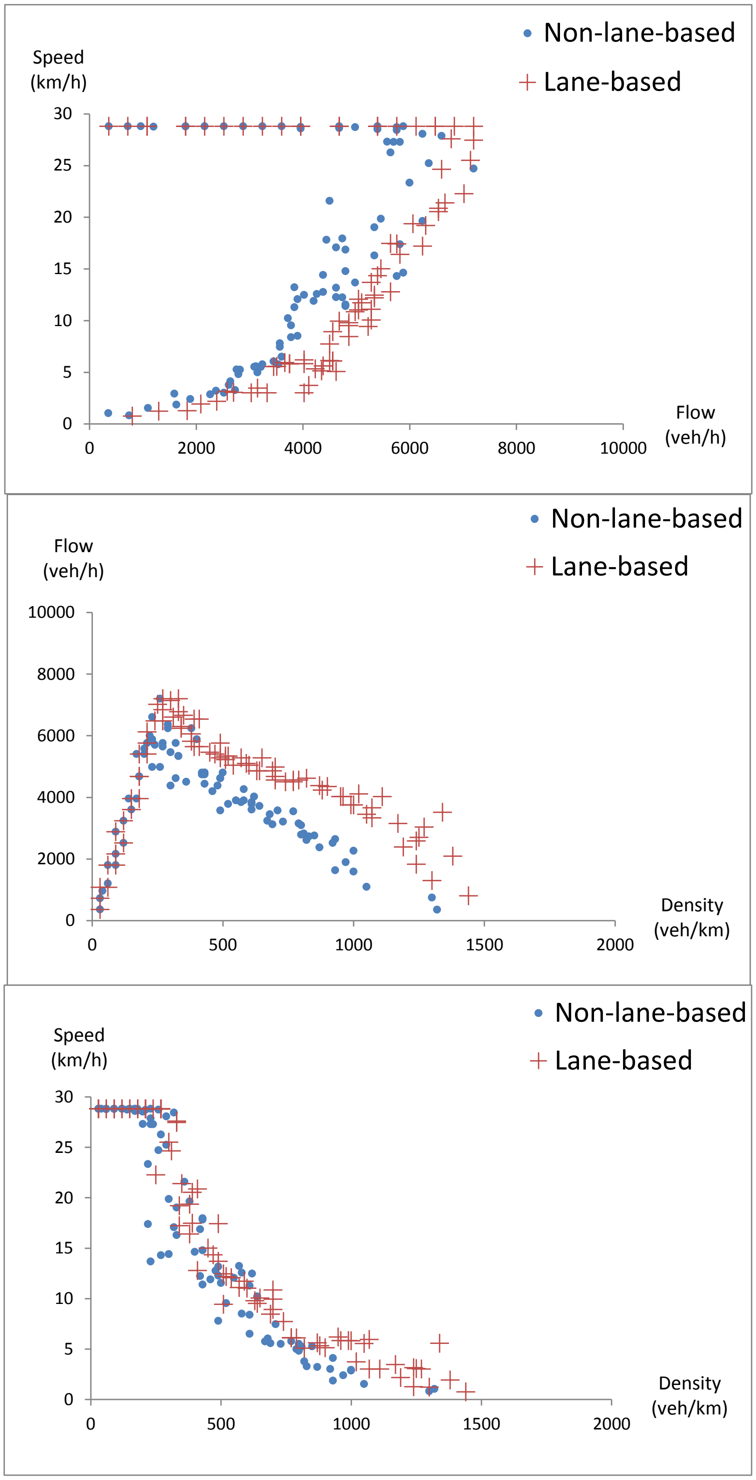
Equations (4.12), (4.13) and (4.14) for non-lane-based and lane-based movements of motorcycles, respectively, were applied using the parameters estimated for Phan Dang Luu Street to predict the fundamental diagrams of traffic flow. For lane-based movements, the original road segment of 5.4 m in width was divided into three virtual lanes, each 1.8 m wide. It is assumed that motorcycles run on these virtual lanes. A sensitivity analysis was conducted with three values for reaction time, namely, 0.3 sec, 0.5 sec and 0.7 sec to confirm the stability of the simulation results.

The results are shown in Figure 4.6. Because the free speed and reaction time are the same for all motorcycles, the dispersion of the output data is small. Motorcycles run at the free speed of around 28.8 km/h in the non-congested situation and then slow down to 1.0 km/h in response to congestion.

For all the cases of different reaction times, two basic differences were found between these movements. Firstly, lane-based traffic flow shows a better performance, i.e., higher speed, traffic flow, and density. This is logical since lane-based movement excludes the influences of movements in the lateral direction, such as swerving left or right. Secondly, non-lane-based behaviors lead to a greater decrease in traffic volume under the congested conditions. This is clear because non-lane-based motorcycles need a larger width for the safety space than lane-based motorcycles in a fixed lane width. Therefore, lane-based movement shows a better efficiency of operation. Furthermore, as the traffic flow improves, the required reaction time reduces. This means that riders with shorter reaction time will contribute less to traffic congestion than riders with longer reaction time.


Non-lane-based
Lane-based
Speed (km/h)
30
25
20
15
10
5
0
0
2000
4000
6000
8000
10000
Flow (veh/h)
Non-lane-based
Lane-based
Flow (veh/h)
10000
8000
6000
4000
2000
0
0
500
1000
1500
2000
Density (veh/km)
Non-lane-based
Lane-based
Speed (km/h)
30
25
20
15
10
5
0
0
500
1000
1500
2000
Density (veh/km)

(a)


Non-lane-based
Lane-based
Speed
(km/h)
30
25
20
15
10
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4000
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Flow
(veh/h)
Non-lane-based
Lane-based
Flow
(veh/h)
10000
8000
6000
4000
2000
0
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500
1000
1500
2000
Density
(veh/km)
Non-lane-based
Lane-based
Speed
(km/h)
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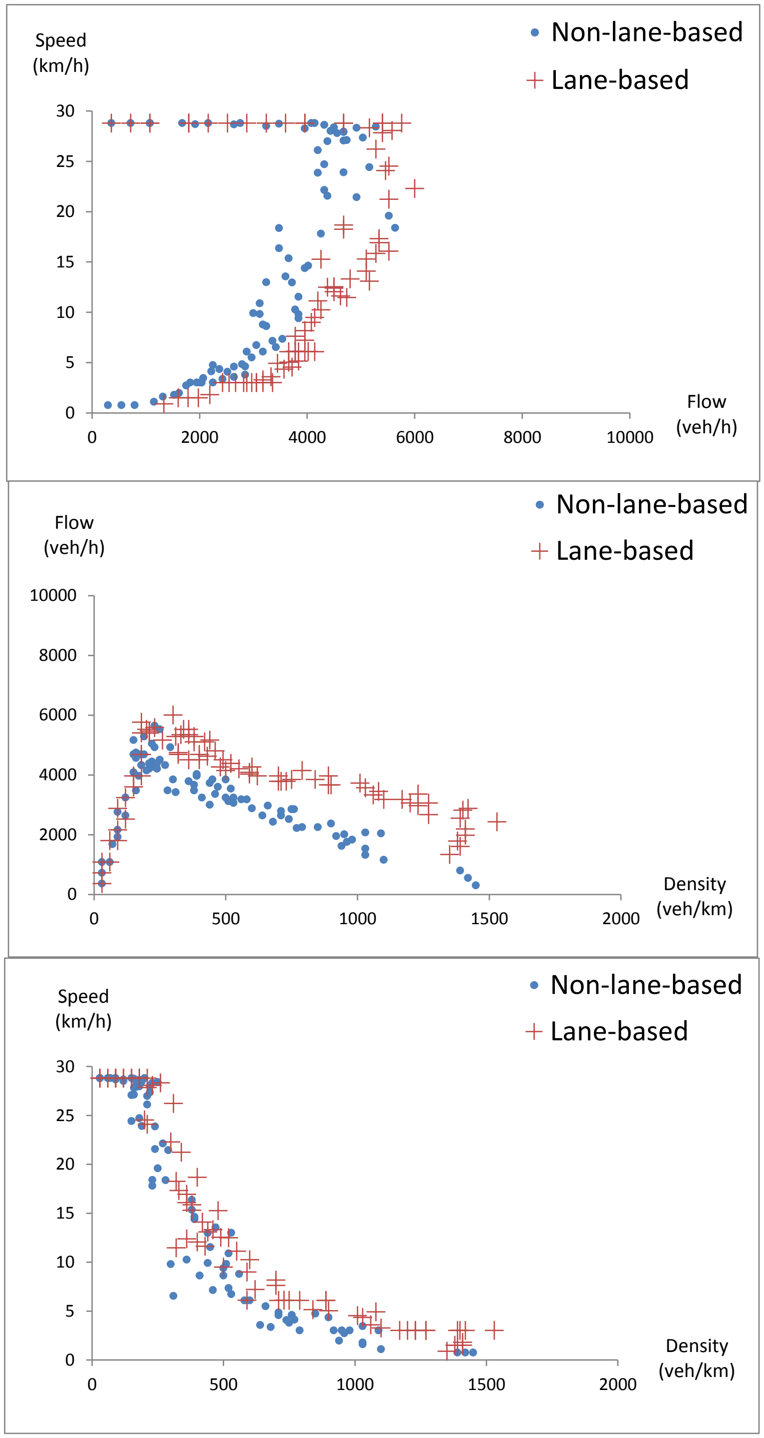
2000
Density
(veh/km)

(b)



(c)

Figure 4.6 Fundamental diagrams: (a) reaction time = 0.3 s, (b) reaction time = 0.5 s, and (c) reaction time = 0.7 s.

4.5 SUMMARY

The chapter introduced the agent-based technique for traffic simulation. An open source software package was selected to develop a simulator based on the research purposes. The computer simulation reproduced two basic types of non-lane-based movements: oblique following and swerving. A comparison of the fundamental diagrams between the non-lane-based movement and the lane-based movement was carried out.

The findings indicated that the lane-based traffic flow shows a better performance, i.e., higher speed, traffic flow, and density than the non-lane-based. In addition, non-lane-based behavior decreases traffic volume to a greater degree than lane-based behavior does under congested traffic condition. At last, riders with shorter reaction time contribute less to traffic congestion than riders with longer reaction time.

Chapter 5 SAFETY SPACE FOR CAR AND MOTORCYCLE IN THE MIXED TRAFFIC FLOW

5.1 INTRODUCTION

This chapter focuses on the characteristics of the mixed traffic flow; a flow which is very common in Asian developing countries. In the mixed traffic flow, cars run on lane based on the lane-based movement and motorcycles could run on the same lane and move to the lane of cars based on the non-lane-based movement. When cars and motorcycles share the same lane, interactions between cars and motorcycles happen. For example, when the density becomes high, high-speed motorcycles prefer to move to the outer lane often used by cars to enjoy larger clearances on this lane. Then cars have to slow down so as to keep a safe distance to avoid accident with the motorcycles. These interactions between cars and motorcycles that affect speed-flow relationship of the mixed flow were verified in many literatures. Kov and Yai (2010) indicated that mean speed of the traffic flow decreases tremendously when the number of cars increases. Other researchers estimated PCU (Passenger Car Unit) values for motorcycle (Lee et al., 2010) or MEU (Motorcycle Equivalent Unit) value (Y et al., 2010) with considerations on the differences of sizes between cars and motorcycles.

The study aims to investigate the characteristics of the mixed traffic flow that affect traffic safety. When running behind another vehicle, drivers must keep a distance far enough to avoid an accident. If a driver underestimates the safety distance, a collision may happen. The distance is likely dependent on the type of the vehicle. Therefore, the research problems are stated as: (1) how long the car and the motorcycle keep their safety distances with surrounding vehicles, (2) how the safety distances differ when the vehicle ahead is a car or a motorcycle.

This chapter introduces an application of the concept of safety space to describe the movements of cars and motorcycles in the mixed traffic flow. Then, by using survey data of the mixed traffic flow collected on the same location as the one in Chapter 3, parameter estimation is conducted. From the estimated parameters, safety spaces of car and motorcycle are calculated, and these results are discussed. The chapter ends with a short summary.

5.2 A MODEL FOR THE MIXED TRAFFIC FLOW

The interactions between car and motorcycle in the mixed flow are observed when one vehicle (car or motorcycle) controls its speed to respond to the change in speed of an influential vehicle (car or motorcycle) ahead or on its side. It is assumed that a subject vehicle responds to only one influential vehicle at a time. The influential vehicle is determined by Equation 3.4. Generally, there are four cases of interactions; case 1: the subject vehicle is a motorcycle, the influential vehicle is a car, case 2: the subject vehicle is a car, the influential vehicle is a motorcycle, case 3: both the subject vehicle and the influential vehicle are motorcycles, case 4: both the subject vehicle and the influential vehicle are cars. In this research, case 3 was already considered in the chapter 3. Case 4 is excluded due to a lack of survey data, and due to the fact that this scenario is already investigated in many conventional literatures. Hence, case 1 and case 2 are analyzed in this chapter. Based on the concept of safety space, this research constructs safety spaces for car and motorcycle to describe the movements of each type of vehicles in two different cases of interaction.

Case 1 the subject vehicle is a motorcycle, the influential vehicle is a car

The safety space for a subject motorcycle is assumed to be determined by the combination of a half ellipsoidal boundary and two parallel lines, similar to the safety space in Chapter 3. Here, the safety space of a subject motorcycle crosses the center of the car's rear (see Figure 5.1). The distance (*x*,*y*) between two vehicles is measured from the center of the front side of motorcycle α to the rear side of car β.

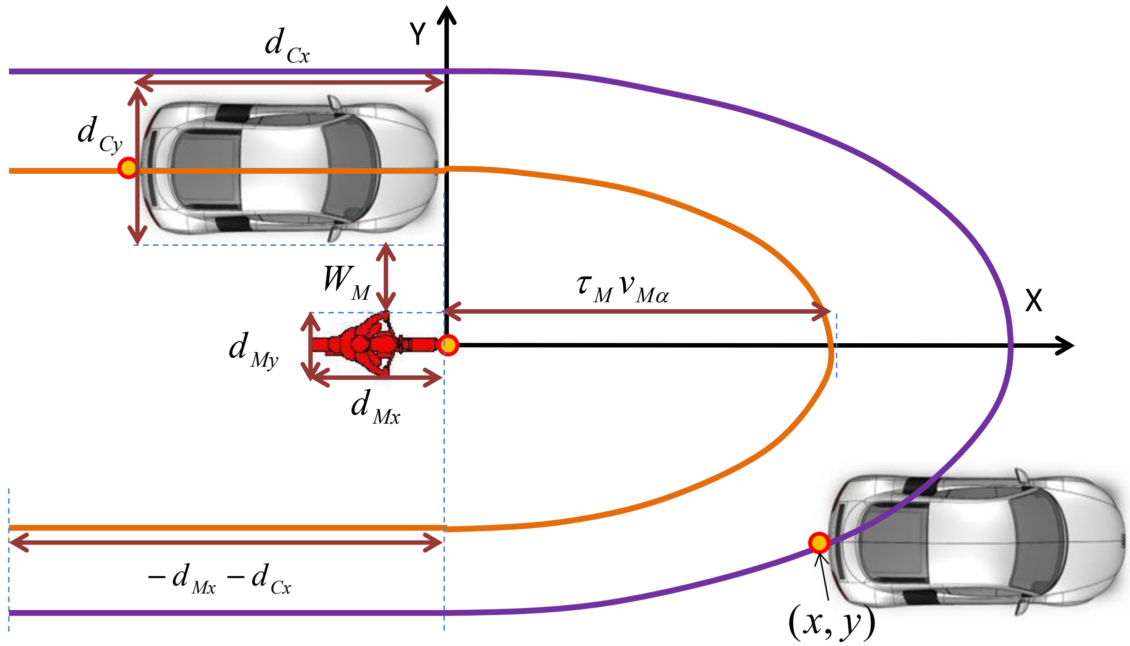


Figure 5.1 Safety spaces for a motorcycle when an influential vehicle is a car

The threshold safety space is defined as the minimum level safety space that could still be considered safe. The safety distance on the semi-major axis denoted by $\tau_M v_{M\alpha}$, where τ_M is the average relaxation time of motorcycles and $v_{M\alpha}$ is the speed of a subject motorcycle α. The safety distance on the semi-minor axis is given by $W_M + 0.5d_{My} + 0.5d_{Cy}$, where W_M is the lateral distance between a motorcycle and a car when two vehicles run side by side. d_{Mx} and d_{My} denote the size of the motorcycle and d_{Cx} and d_{Cy} denote the size of the car. Hence, the acceleration of a subject motorcycle, $a_{M\alpha}$ affected by an influential car can be expressed by Equation 3.2, and this equation becomes:

$$a_{M\alpha}(t+T)=\begin{cases}-\nabla_{\vec{v}_{M\alpha C\beta}}\left(A_M\exp\left(-\left(\dfrac{x^2}{(\tau_M v_{M\alpha})^2}+\dfrac{y^2}{(W_M+0.5d_{My}+0.5d_{Cy})^2}\right)\Big/B_M\right)\right) & if\ \ x\geq 0\\ -\nabla_{\vec{v}_{M\alpha C\beta}}\left(A_M\exp\left(-\left(\dfrac{y^2}{(W_M+0.5d_{My}+0.5d_{Cy})^2}\right)\Big/B_M\right)\right) & if\ \ -d_{Mx}-d_{Cx}\leq x\leq 0\end{cases} \tag{5.1}$$

where A_M and B_M are acceleration parameters of a motorcycle; T is average reaction time, 0.5 s; t is real time; x and y are distances between two vehicles in the x-axis and the y-axis; $\vec{v}_{M\alpha C\beta}$ denotes the relative speed vector between the motorcycle α and the car β.

Case 2 the subject vehicle is a car, the influential vehicle is a motorcycle

The safety space of a car has a different shape from that of a motorcycle. As cars only run on lane, its safety space is assumed to be a rectangle which consists of two sides parallel to each other, one side crossing the center of the car's front and another side crossing the center of the influential motorcycle's rear. Observations of the situation in which cars and motorcycles run on the same lane have showed that cars also can swerve left or right in the same lane when approaching motorcycles. In the survey location, each lane of the road is around 3.6 m wide and the average width of the car is measured at around 1.6 m. Therefore, cars have a side clearance of 1 m wide on both sides and they can turn left or right within this clearance. Based on the observations, the safety space of cars consists of a rectangle in the middle and a quarter of the ellipse on each side as illustrated in Figure 5.2. The distance (x,y) between two vehicles is measured from the center of the front side of the motorcycle α to the rear side of the car α.

The threshold safety space for the car is defined in the similar way to case 1. The safety distance on the semi-major axis is denoted by $\tau_C v_{C\alpha}$, where τ_C is the average relaxation time of cars and $v_{C\alpha}$ is the speed of a subject car α. The safety distance in the semi-major axis is given by $W_C + 0.5d_{My} + 0.5d_{Cy}$, where W_C is the lateral distance or the side clearance when two vehicles run side by side. Therefore, the acceleration of a subject car, $a_{C\alpha}$ affected by an influential motorcycle can be based on Equation 3.2, and this equation becomes:

$$a_{C\alpha}(t+T) = \begin{cases} -\nabla_{\vec{v}_{C\alpha M\beta}}\left(A_C \exp\left(-\left(\dfrac{x^2}{(\tau_C v_{C\alpha})^2} + \dfrac{y^2}{(W_C + 0.5d_{My} + 0.5d_{Cy})^2}\right)\Big/ B_C\right)\right) & if\ |y| > 0.5d_{Cy}, x \geq 0 \\ -\nabla_{\vec{v}_{C\alpha M\beta}}\left(A_C \exp\left(-\left(\dfrac{x^2}{(\tau_C v_{C\alpha})^2}\right)\Big/ B_C\right)\right) & if\ |y| \leq 0.5d_{Cy}, x \geq 0 \\ -\nabla_{\vec{v}_{C\alpha M\beta}}\left(A_C \exp\left(-\left(\dfrac{y^2}{(W_C + 0.5d_{My} + 0.5d_{Cy})^2}\right)\Big/ B_C\right)\right) & if\ -0.5d_{Mx} - 0.5d_{Cx} < x < 0 \end{cases} \quad (5.2)$$

where A_C and B_C are acceleration parameters of the car, and $\vec{v}_{C\alpha M\beta}$ denotes the relative speed vector between the car α and the motorcycle β.

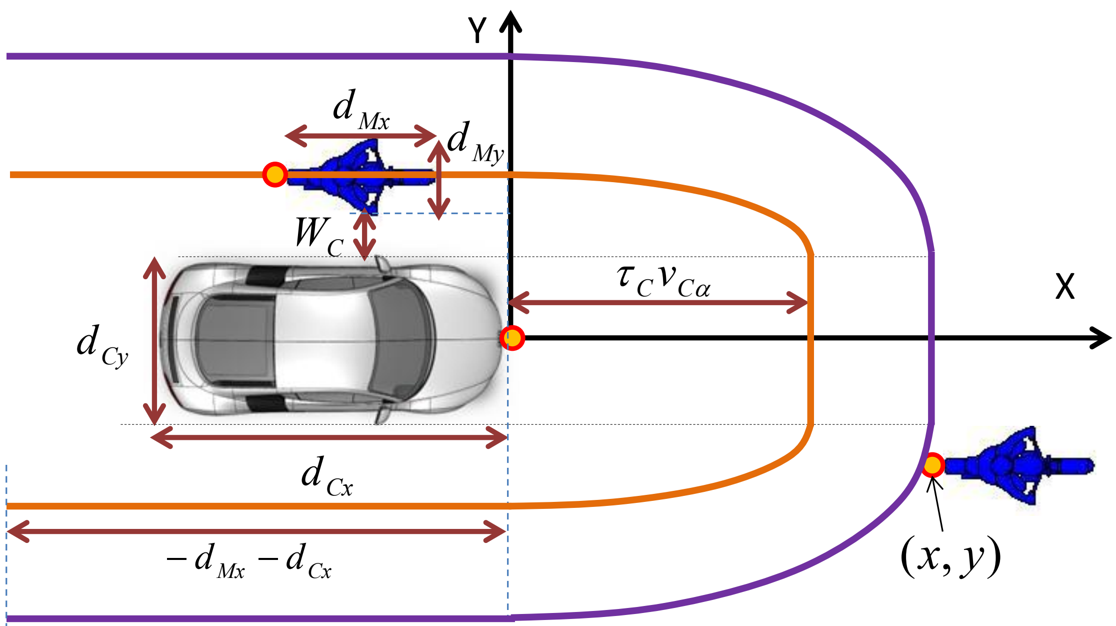


Figure 5.2 Safety spaces for a car when an influential vehicle is a motorcycle

5.3 Parameter calibration

The study used the data collected on Cong Hoa Street in calibrating the model. The methodology of collecting data for the mixed flow is similar to the one for the motorcycle-only flow in Chapter 3. Observations for the mixed flow capturing cars and motorcycles were recorded every 0.5 sec. Observations during uncongested conditions and observations with bicycles, buses and trucks were excluded from data sample. In case 1, one observation records one subject motorcycle, one influential car and other influential motorcycles surrounding the subject. In the case 2, one observation includes one subject car and other influential motorcycles. For each subject vehicle, there are 7 ~ 10 observations. As a result, 631 observations for 108 subject motorcycles were used to estimate the parameters in the case 1, and 615 observations for 82 subject cars were used to estimate the parameters in the case 2.

The proposed equations of calculating acceleration were calibrated by regression analysis method. In the case 1, the subject vehicle is a motorcycle and the influential vehicle could either be a car or a motorcycle. If the influential vehicle is a car, acceleration is formulated as shown in Equation (5.1). If the influential vehicle is a motorcycle, acceleration is formulated based on Equation (3.2). Therefore, parameters which were estimated in Equation 3.2 are used as given parameters for calibrating parameters in case 1. Moreover, to simplify the calculation of the nonlinear function, several parameters are assumed to be constant. Reaction time T is 0.5 sec across all the drivers. W_M is the lateral distance, 1.8 m, measured from the field data when two vehicles run side by side. d_{Mx} and d_{My} denote the size of the motorcycle which is 1.9 m long and 0.8 m wide. d_{Cx} and d_{Cy} denote the size of the car measured to be 4.8 m long and 1.6 m wide (see Table 5.1).

Table 5.1 Given parameters for case 1: the subject vehicle is a motorcycle, the influential vehicle is a car

Parameter	Value
Reaction time T	0.5 s
Lateral distance W_M	1.8 m
Motorcycle size d_{Mx}, d_{My}	length = 1.9 m, width = 0.8 m
Car size d_{Cx}, d_{Cy}	length = 4.8 m, width = 1.6 m
A (case 3)	6.954
B (case 3)	0.510
τ (s) (case 3)	0.496

In the case 2, the model is formulated as shown in Equation (5.2). Several parameters are assumed to be similar to case 1. The lateral distance W_C of the car is hypothesized to be equal to the side clearance of 1 m (see Table 5.2). The reason for this is that the width of each road lane is around 3.6 m wide and the average width of the car is around 1.6 m; thus, cars enjoy a side clearance of 1 m wide on both sides.

Table 5.2 Given parameters for case 2: the subject vehicle is a car, the influential vehicle is a motorcycle

Parameter	Value
Reaction time T	0.5 s
Lateral distance W_C	1.0 m
Motorcycle size d_{Mx}, d_{My}	length = 1.9 m, width = 0.8 m
Car size d_{Cx}, d_{Cy}	length = 4.8 m, width = 1.6 m

SPSS software was used to derive the other parameters by solving the nonlinear regression problem (Table 5.3). All the parameters had a statistical significance level of 1% except for parameter B_C whose t-value is 1.42. The relaxation time of motorcycle is 0.457 s, smaller than the relaxation time estimated in Chapter 3 which is nearly 0.5 s. This means that motorcycles keep a smaller safety space when moving near a car than when moving near another motorcycle. It makes sense because cars seldom change their directions, and seldom suddenly change their speed, compared with motorcycles. The relaxation time of the car is 1.529 s, longer than the one of the motorcycle. This is clear because field observations on the mixed traffic flow showed that the car keeps a longer headway than the motorcycle.

Table 5.3 Derived parameters of acceleration for the motorcycle and the car in the mixed flow

Case 1 (Motorcycle)				**Case 2 (Car)**			
Parameter	Estimate	Std. Error	t-value	Parameter	Estimate	Std. Error	t-value
A_M	10.127	2.995	3.38	A_C	2.616	0.307	8.52
B_M	0.402	0.129	3.11	B_C	10.932	7.689	1.42
τ_M(s)	0.457	0.059	7.77	τ_C(s)	1.529	0.256	5.97

Errors for the speed of motorcycles and cars in two cases were calculated (see Table 5.4). Speed RMS error and RMS percent error are very small. The mean speed error and percent error is nearly 0. These indicators show that the proposed model well replicate the actual speed. Table 5.4 shows that 67.5% and 63.2 % of the observed maneuvers for the motorcycle and car, respectively, could be reproduced by the proposed model.

Table 5.4 Statistical measures for the speed and the ratio of swerving maneuvers of the motorcycle and the car in the mixed traffic flow

Statistical Measurement	Value	
	Case 1 (Motorcycle)	Case 2 (Car)
RMS error (m/s)	0.674	0.539
RMS percent error	0.108	0.064
Mean error (m/s)	-0.029	0.041
Mean percent error	0.003	0.008
Ratio of swerving modeled correctly (%)	66.4	63.2

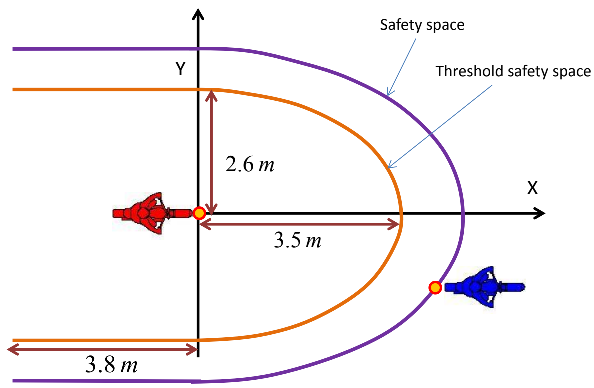
5.4 DISCUSSIONS ON SAFETY SPACES OF THE MOTORCYCLE AND THE CAR

This section will provide discussions on the threshold safety space and acceleration for the motorcycle and the car based on the resulting parameters estimated in three cases: case 1, 2 and 3.

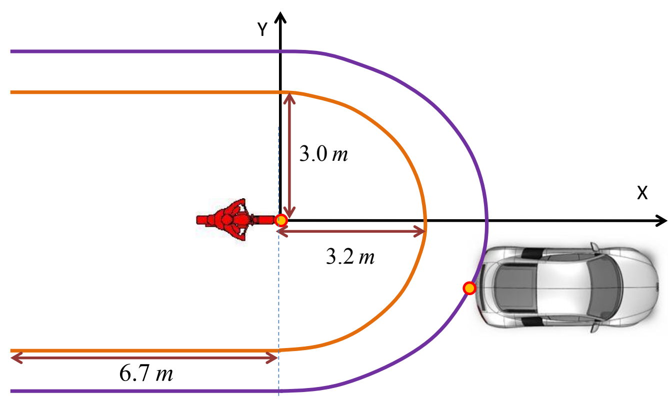
5.4.1 Threshold safety space for motorcycle and car

As the average speed of a subject vehicle is assumed to be 7.0 m/s, the threshold safety space of the car and the motorcycle in three cases are illustrated in Figure 5.3. By comparing case 3 to case 1, it was found that motorcycles keep a smaller safety space in front when moving near a car than when moving near another motorcycle. Motorcycles feel safer when running behind cars because cars usually run on lane and do not change direction very often. This could be a big risk for collision between cars and motorcycles because the headway between them was measured to be only 0.457 s, which is shorter than the reaction time, 0.5 s. This finding could explain the statistic results of Hung and Nguyen (2008). They reported in a paper that in 2008 in Hanoi, the number of collision per 10,000 vehicles between car and motorcycle accounted for 48% while the number of collision between motorcycle and motorcycle accounts for 29%.

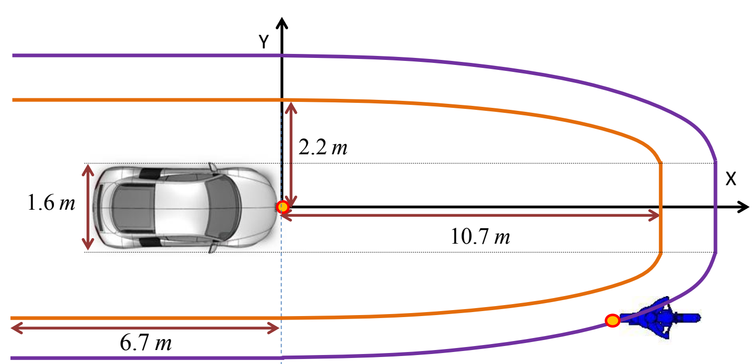
From the results of case 1 and case 2, while cars keep a very long headway of 10m, motorcycle run behind the car at around 3 m. This explains the phenomenon by which motorcycles prefer to move to the lane of cars to enjoy the clearance of 10 m. The more motorcycles switch to the car-lane, the more cars decrease speed to keep the safe distance. As a result, the speed of the car becomes lower than that of the motorcycle in the congested situations (Kov and Yai, 2010).



Case 3: Both a subject vehicle and an influential vehicle are motorcycles



Case 1: A subject vehicle is the motorcycle, an influential vehicle is the car



Case 2: A subject vehicle is the car, an influential vehicle is the motorcycle

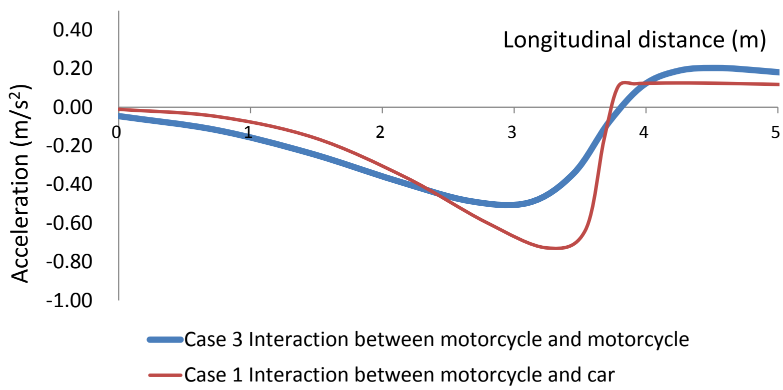
Figure 5.3 Threshold safety space for the motorcycle and the car in the mixed traffic flow

5.4.2 Comparison of acceleration between motorcycle and car

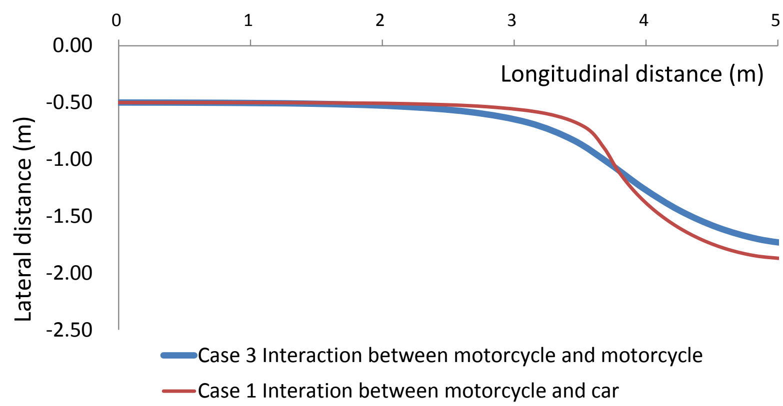
This research compares the difference in acceleration between the cases of motorcycle to motorcycle interaction (case 3) and motorcycle to car interaction (case 1). Suppose that a subject motorcycle is approaching its influential vehicle (car or motorcycle) ahead, at an initial position of 5 m longitudinal distance and 0.5 m lateral distance, in the speed of 7.0 m/s and relative speed of -1.5 m/s. There, the influential vehicle ahead does not change its speed, the subject motorcycle has to decrease its speed and change its direction of movement. Based on these assumptions, the accelerations with respect to distances in both case 1 and case 3 were computed. Figure 5.4 (a) indicated that a subject motorcycle starts applying a brake later when the influential vehicle is a car than when the influential vehicle is another motorcycle. Therefore, its acceleration is slower when it is farther and becomes suddenly faster when it is nearer to avoid a possible accident with the car. When the relative speed of two vehicles is zero at a distance of around 1.3 m, a subject motorcycle begins to increase its speed to follow the head vehicle. Figure 5.4 (b) confirms the swerving of the motorcycle when changing its direction to avoid an accident. When two vehicles run side by side at the longitudinal distance of 0 m, the two vehicles keep the lateral distance of around 1.8 m long enough to avoid a side collision. In summary, motorcycles are likely to decelerate its speed in the later time when running behind cars and hence they need a harder brake to escape the rear-end accident with cars.

There are difficulties when comparing acceleration of the motorcycle in case 1 to the car in case 2 under the same situations because, apparently, cars keep headways of around 3 times longer than motorcycles do. With this observation, this research further examines the shape of the car acceleration in case 2.

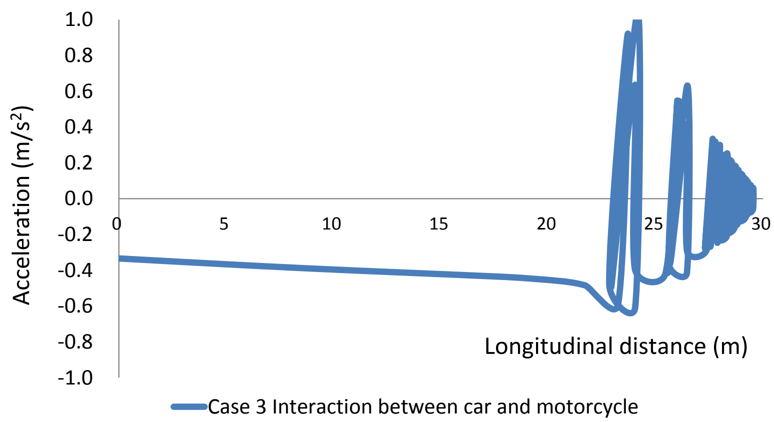
It is assumed that a car is approaching its influential motorcycle ahead on one-dimensional coordinate system at an initial position of 30 m with the speed of 7.0 m/s and relative speed of - 4.0 m/s. If the influential motorcycle ahead does not change its speed, the subject car has to decrease its speed. The acceleration results are illustrated in Figure 5.4 (c). It was found that cars start braking from a very long distance of over 30 m. The deceleration increases slowly until the relative speed between the car and the motorcycle ahead of it is zero. Then, when the speed of a car is slower than that of the motorcycle, the car will increase its speed to follow the leader. After the speed of the car is higher than that of the motorcycle, the car will again brake to decrease its speed. This process is repeated over time while the distance between them is smaller. In conclusion, cars are found to respond to motorcycles ahead at a farther headway than motorcycles do because cars cannot change their movement direction in the same manner as motorcycles can.



(a)



(b)



(c)

Figure 5.4 Relationships between acceleration and distance in 3 cases of interaction

5.5 SUMMARY

To investigate the characteristics of the mixed traffic flow related to issues of traffic safety, this research introduces an application of safety space to describe movements of motorcycles and cars under congested traffic conditions. Safety spaces for the car and the motorcycle are examined by considering their interactions in two cases: case (1) the subject vehicle is a motorcycle, the influential vehicle is a car, case (2) the subject vehicle is a car, the influential vehicle is a motorcycle. For each case, acceleration parameters were estimated using field data collected on Cong Hoa Street, Ho Chi Minh City. Almost all the parameters were significant at the significance level of 0.01.

This research also quantified threshold safety space for the car and the motorcycle. By comparing acceleration in three cases of interaction, this research could explain the differences between driving characteristics of two types of vehicles. First, motorcycles are likely to decelerate its speed in a later time when running behind cars hence they need a harder brake to escape a possible rear-end accident with cars. Secondly, cars are found to respond to motorcycles ahead at a farther headway than motorcycles because cars cannot change their direction of movement in the same manner as motorcycles.

Chapter 6 MOTORCYLE SAFETY ASSESSMENT IN VIETNAM

6.1 INTRODUCTION

In Vietnam, motorcycle traffic safety is difficult to assess due to the lack of accident data as well as effective estimation models for the motorcycle. Hence, the approaches to describe driving behaviors based on microscopic models are the important tools to address this problem. Results from microscopic simulations are expected to be very useful in understanding the characteristics of driving safety for the motorcycle traffic flow in developing countries.

In the second section, the chapter presents new features of the safety space model to assess the traffic conflict for motorcycle by considering factors such as acceleration and deceleration, and conditions of choosing a lead vehicle to accelerate. In the third section, the model calibration for parameters estimation is summarized. As a model application in the fourth section, a computer simulation is applied to evaluate traffic conflict for motorcycle by calculating the probability of sudden braking when the density of the motorcycle flow is altered. The last section summarizes the content of this chapter.

6.2 A MODEL FOR MOTORCYCLE TRAFFIC SAFETY ASSESSMENT

A model is developed to assess motorcycle traffic safety based on the concept of safety space. The safety space approach has a good potential in the analysis of traffic safety. Many factors related to accident potential evaluation, are considered in the approach.

6.2.1 Acceleration and deceleration

A rear-end collision happens when a preceding vehicle brakes suddenly and a vehicle following crashes into it. A side-swipe collision is caused when a preceding motorcycle swerves left or right suddenly and is hit on the side by a following motorcycle. In order to consider two types of collision, the safety space is determined by two parallel lines connected to a half ellipsoidal boundary (see Figure 3.2). Equation (3.2) of acceleration is rewritten after taking the derivative, as follows:

$$a_\alpha = \begin{cases} A\exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2} + \dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/ B\right)(v_{\alpha\beta})^{-1}\left(\dfrac{xv_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{yv_y}{(W_\alpha + d_y)^2}\right) & if\, x \geq 0 \\ A\exp\left(-\left(\dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/ B\right)(v_{\alpha\beta})^{-1}\left(\dfrac{yv_y}{(W_\alpha + d_y)^2}\right) & if\, -2d_x \leq x < 0 \end{cases} \tag{6.1}$$

where v_x and v_y are relative speeds between a subject motorcycle and an influential motorcycle in the axis x and y, respectively.

To verify the difference of numerical values between acceleration and braking, the study distinguishes acceleration and deceleration by replacing the original parameters (A,B) in equation (6.1) with two new parameter sets (A_{acc},B_{acc}) and (A_{dec},B_{dec}).

When the acceleration is positive, i.e., $\dfrac{xv_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{yv_y}{(W_\alpha + d_y)^2} \geq 0$, then

$$a_\alpha = \begin{cases} A_{acc}\exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2} + \dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/ B_{acc}\right)(v_{\alpha\beta})^{-1}\left(\dfrac{xv_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{yv_y}{(W_\alpha + d_y)^2}\right) & if\, x \geq 0 \\ A_{acc}\exp\left(-\left(\dfrac{y^2}{(W_\alpha + d_y)^2}\right)\Big/ B_{acc}\right)(v_{\alpha\beta})^{-1}\left(\dfrac{yv_y}{(W_\alpha + d_y)^2}\right) & if\, -2d_x \leq x < 0 \end{cases} \tag{6.2a}$$

When the acceleration is negative, i.e., $\dfrac{xv_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{yv_y}{(W_\alpha + d_y)^2} < 0$, then

$$
a_\alpha = \begin{cases} A_{bcc} \exp\left(-\left(\dfrac{x^2}{(\tau_\alpha v_\alpha)^2} + \dfrac{y^2}{(W_\alpha + d_y)^2} \right) \Big/ B_{bcc} \right) (v_{\alpha\beta})^{-1} \left(\dfrac{x v_x}{(\tau_\alpha v_\alpha)^2} + \dfrac{y v_y}{(W_\alpha + d_y)^2} \right) & if\, x \geq 0 \\ A_{bcc} \exp\left(-\left(\dfrac{y^2}{(W_\alpha + d_y)^2} \right) \Big/ B_{bcc} \right) (v_{\alpha\beta})^{-1} \left(\dfrac{y v_y}{(W_\alpha + d_y)^2} \right) & if\ -2d_x \leq x < 0 \end{cases}
$$

(6.2b)

Equation (6.2a) and (6.2b) show that the acceleration will be zero when two motorcycles come near each other, i.e., the distance between two motorcycles is zero. This result is reasonable when a subject vehicle reacts to only one influential vehicle during the journey, which is the same as in the case of car-following model. However, under congested situation, a motorcycle has to respond to many motorcycles, hence, a motorcycle is assumed to achieve maximum deceleration when nearing another motorcycle. The formulation of variable x and y at the maximum deceleration is easily derived from equation (6.1) by taking the derivative of this function with respects to variables of x and y as follows:

$$
(x, y) = \begin{cases} \left(x_0 = d_x + \tau_\alpha v_\alpha \sqrt{\dfrac{B_{dec}}{2} - \dfrac{y^2}{(W_\alpha + d_y)^2}}, y \right) & if\ x < x_0, x \geq 0 \\ \left(x, y_0 = \pm (W_\alpha + d_y) \sqrt{\dfrac{B_{dec}}{2}} \right) & if\ \ y < y_0, -2d_x \leq x < 0 \end{cases} \tag{6.3}
$$

where x_0 is a value at which the derivative of the acceleration with respect to x when $x \geq 0$, is zero; y_0 is a value at which derivative of the acceleration with respect to y when $-2d_x \leq x < 0$, is zero.

6.2.2 Conditions of choosing a lead vehicle to accelerate

A subject motorcycle needs to choose a lead motorcycle so as to accelerate its speed and follow the leader. The conditions of choosing a leader are as follows:

Critical following angle φ_0

A motorcycle feels safe and comfortable to accelerate and follow a leader travelling ahead from it with an angle φ, which is smaller than the critical following angle φ_0 (See Figure 6.1). The critical following angle is related to maximum swerving angle when a vehicle turns left or right to follow its leader.

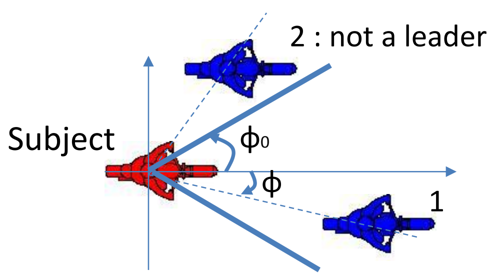


Figure 6.1 The critical following angle of the motorcycle

Following route width RW_α

A subject motorcycle will accelerate and follow any vehicle ahead of it if there are no other vehicles on the following route. Consider vehicle 4 in Figure 6.2, the subject vehicle could not follow it because vehicles 2 and 3 are inside the virtual "following route". The width RW_α of the following route decides whether a vehicle runs on the route or not. The route width is used when calibrating the parameters of the proposed model because calibration data were discrete based on trajectory observations in every 0.5 s in choosing a leader among many preceding vehicles after every 0.5 s.

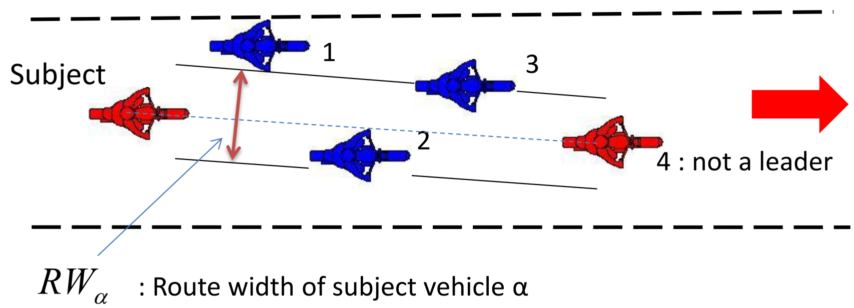


Figure 6.2 The following route for the motorcycle to follow a leader

6.3 MODEL CALIBRATION

We used the same data sets in Chapter 3 for calibrating the model. Discrete observations for a target motorcycle and other influential motorcycles were recorded every 0.5 sec. There are 6 to 12 observations for the subject motorcycle. Observations in uncongested conditions and observations with cars and bicycles were excluded from data sample. As a result, 826 observations for 144 motorcycles in Phan Dang Luu Street and 579 observations for 152 motorcycles in Cong Hoa Street were used to estimate the parameters of the proposed model.

6.3.1 Parameter calibration

The proposed non-lane-based model based on the concept of safety space was calibrated by the regression analysis method. This model is formulated in Equation (6.3). To simplify the calculation of the nonlinear function, all drivers were assumed to have the same reaction time T and several parameters were assumed to be constant (see Table 6.1). The reaction time of a motorcycle is taken to be equal to the mean value of the reaction time distribution, i.e., 0.5 s (Minh et al., 2006). The lateral distance of the threshold safety space was measured from the field to be 1.8 m for two vehicles riding side by side. Average size of the real motorcycles in the field is used for the parameter values for vehicle size. Critical following angle is set to be 30^0 and the width of following route is 2.0 m to achieve small errors of the estimation result.

Table 6.1 Given parameters when distinguishing acceleration and deceleration

Parameter	Value
Reaction time T (s)	0.5
Lateral distance W (m)	1.8
Vehicle size dx (m), dy (m)	length = 1.9, width = 0.8
Critical following angle(^{0})	30
Following route width (m)	2.0

SPSS software was used to derive the other parameters by solving the nonlinear regression problem (Table 6.2). All the parameters have statistical significance level of 1% except for parameters B_{acc} on Cong Hoa Street which t-value is 1.22. The signs of the parameters A, B, and τ are positive because the magnitude of the safety space must have positive values. The relaxation times τ at the two different locations observed were 0.57 s and 0.68 s. As relaxation time is taken as the time required for the combination of the steering movement (to change direction) and the braking movement (to change speed) in order to avoid a possible collision, it does not differ largely for different locations. These values of relaxation time are higher than the one, 0.5s estimated in Chapter 3 because when distinguishing acceleration and deceleration, motorcycles tend to increase speeds to follow the further leaders, and as a result, the threshold space becomes larger than the one in Chapter 3. The differences in the values of parameters A and B between the two locations show that drivers on Phan Dang Luu Street have a smaller rate of acceleration than those on Cong Hoa Street. Cong Hoa Street has three lanes and vehicles travelling have an average speed of 30 km/h, which is higher than the 20 km/h in Phan Dang Luu Street. A higher average speed implies a greater rate of acceleration.

Table 6.2 Estimated parameters when distinguishing acceleration and deceleration

Parameter	Phan Dang Luu Street			Cong Hoa Street		
	Estimate	Std. Error	t-value	Estimate	Std. Error	t-value
A_{acc}	2.147	0.476	4.51	4.850	1.000	4.85
B_{acc}	3.046	1.242	2.45	3.005	2.461	1.22
A_{dec}	11.976	3.608	3.32	20.752	6.049	3.43
B_{dec}	0.142	0.039	3.64	0.131	0.034	3.85
τ (s)	0.573	0.052	11.02	0.678	0.065	10.43

6.3.2 Model validation

These errors were calculated for the speed of motorcycles (see Table 6.3). RMS error and RMS percent error of speed are very small. These indicators show that the proposed model well replicates the actual speed. To validate the zigzag movements of motorcycles, the observed swerving maneuvers to the left or right from the current position were compared with the estimated swerving maneuvers based on all the observations. The results in Table 6.3 show that 63.0% and 63.7% of the observed maneuvers in the two locations, respectively, could be reproduced by the proposed model. The rates of acceleration were also compared in the same way. 59.8% and 57.9% of the observed behaviors can be modeled correctly.

Table 6.3 Statistical measures of speed, ratio of swerving and acceleration modeled correctly when distinguishing acceleration and deceleration

Parameter	Phan Dang Luu Street	Cong Hoa Street
RMS error (m/s)	0.481	0.576
RMS percent error	0.091	0.064
Mean error (m/s)	0.026	0.041
Mean percent error	0.010	0.007
Ratio of swerving modeled correctly (%)	63.0	63.7
Ratio of acceleration modeled correctly (%)	59.8	57.9

6.4 AN APPLICATION TO TRAFFIC SAFETY ASSESSMENT

In this section, traffic conflict situations in road segments are categorized by types of maneuver. A measure for determining these conflict situations using microscopic simulation is introduced. Then, a microscopic simulation is applied to calculate the safety level using the proposed traffic conflict measure. Lastly, the results on traffic safety assessment are discussed.

6.4.1 Conflict situations at a road segment

Situations with many conflicts have a higher probability of accidents. This research classified conflict situations at a road segment under congested conditions into three basic types:

Type 1: a preceding vehicle applies a brake suddenly (rear-end collision).

Type 2: a preceding vehicle swerves left or right suddenly (side-swipe collision).

Type 3: two side by side vehicles speed up to follow a leader at the same time (side-swipe collision).

6.4.2 Safety index: Deceleration Rate

Safety index is used for measuring the frequency and severity of conflicts such as Gap Time, Time to Collision, Deceleration Rate. Here deceleration rate (DR) is adopted to be a safety index for the motorcycle. DR is the value of deceleration taken by the subject vehicle when it applies a brake to avoid a possible collision with other influential vehicles. DR indicates an accident possibility and severity which was linked to crash angle and crash speed. If DRs exceed a given critical value, "sudden braking" is assumed to happen. Because deceleration rates are available directly in the simulation model at each time step, the probability of "sudden braking" can be calculated easily from the simulation result.

6.4.3 Scenario settings for computer simulation

The simulator developed in Chapter 4 is employed to calculate the safety level and acceleration of motorcycles.

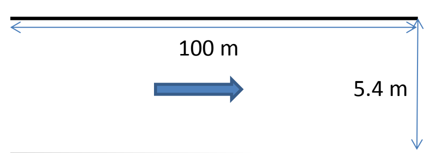


Figure 6.3 Non-lane-based road segment for simulation

The simulation conditions included a 100-m-long and 5.4-m-wide road segment (Figure 6.3). All the vehicles are assumed to be identical. The estimated parameters of the model for the case of Phan Dang Luu Street from Table 6.2 and the other parameters shown in Table 6.1 were used. The free speed was set as 25 km/h, the maximum speed taken from the data sample. Table 6.4 summarizes the basic settings of the scenario.

Table 6.4 Simulation parameters

Road size (length, width, in m)	(100.0, 5.4)
Free speed (km/h)	25.0
Aacc, *Bacc*	(2.147,3.046)
Adec, *Bdec*	(11.976,0.142)
Relaxation time τ (s)	0.573
Reaction time T (s)	0.5
Swerving angle (^{o})	30
Route width (m)	2.0
Lateral distance W (m)	1.8
Vehicle size (meter length, meter width)	(1.9, 0.8)

6.4.4 Effects of flow density on traffic conflict

The simulation is performed for two purposes: (1) to test whether different types of collision in a congested traffic situation can be reproduced or not, and (2) to verify effects of flow density on the probability of "sudden braking" which increases accident potential.

For the first purpose, 3 types of collision were confirmed when two vehicles overlap each other. When a vehicle brakes suddenly and its reaction time is not short enough to avoid a collision, the overlap will happen. Because overlapping vehicles still keep their maximum deceleration during the overlap time, they will separate from each other after a short time.

For the second purpose, it was found that higher flow density led to a greater increase in probability of "sudden braking" in 2 cases of the given critical deceleration rates, -0.4 m/s^2 and -0.6 m/s^2 as illustrated in Figure 6.4. This is clear, because safety level decreases quickly as motorcycles run near each other. Under congested condition, when a motorcycle increase speed to turn left or right to follow its leader, an alongside-travelling motorcycle perceives its safety space becomes smaller thus pushes a brake to escape a side-swipe collision. As a result, a vehicle behind the alongside travelling vehicle also applies a brake to avoid a rear-end accident.

Although the probability of sudden braking cannot estimate the number of accidents, the increase in probability of sudden braking at high level flow density could reflect the increase in probability of accident rates (Gettman and Head, 2003; FHWA, 1985; Kaub, 2002). Further research to investigate the relationship between sudden braking counts and the number of traffic accidents should be taken into consideration in the future.

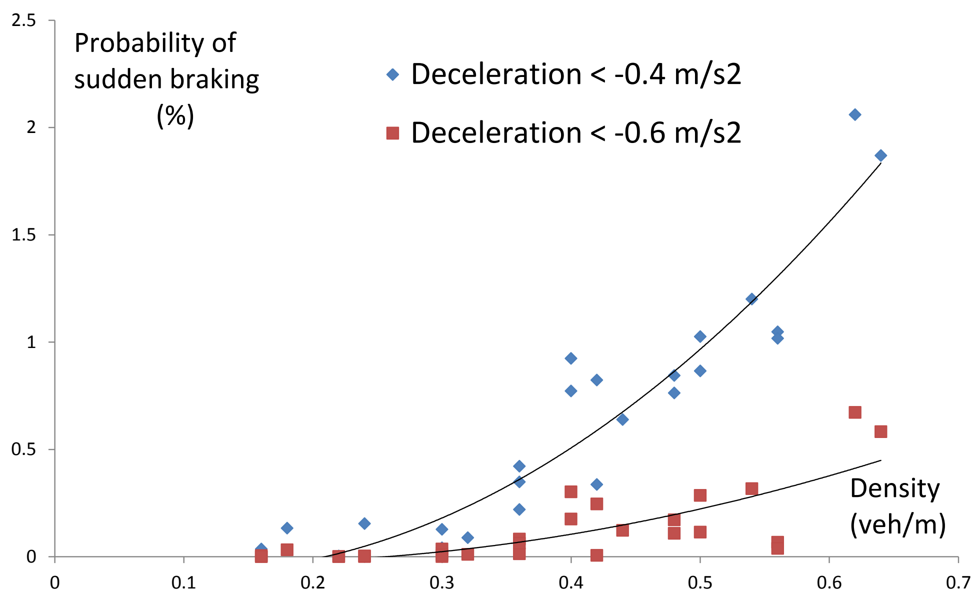


Figure 6.4 Effects of flow density on probability of sudden braking

6.5 SUMMARY

This study proposed new features of the motorcycle-following model to assess the traffic conflict of the motorcycle. First, the difference of numerical values between acceleration and braking was considered by introducing two new parameter sets for acceleration and decelerate. Second, the conditions considered in choosing a leader were described, such as the critical following angle and the following route width.

Parameters of deceleration and acceleration are estimated. The observed speed can be predicted by the proposed model with small RMS error. The proposed model can correctly reproduced more than 63% of swerving behaviors, to the left or right, and around 58% of acceleration behaviors.

Conflict situations and an index of deceleration rate for the safety assessment were discussed. A computer simulation was developed to assess the traffic conflict by calculating deceleration rates at each time step when the density of the motorcycle flow was changed. Simulation results confirmed 3 types of collision. The findings highlighted that higher flow density led to a greater increase in probability of traffic accident.

Chapter 7 CONCLUSIONS AND FUTURE WORK

This chapter begins with the conclusions corresponding to the research objectives in chapter 1. Then, the recommendations on future work are presented at the end of the chapter.

7.1 CONCLUSIONS

1) To investigate the characteristics of non-lane-based movements of motorcycles by considering driving behaviors in the congested conditions.

The basic difference between the car and the motorcycle is related to the lane-based movement of the former and the non-lane-based movement of the latter. In comparison with the car, the motorcycle on the road possesses a smaller size and a better ability of swerving to the left or right easily due to its two wheels. The observed driving behaviors related to the non-lane-based movements were categorized by traffic situation and road geometry. This research focuses only on the behaviors at the road segment under congested situations such as alongside travelling, oblique following and swerving movement. In this study, these behaviors are described by the motorcycle-following model.

The literature reviews focused on conventional car-following models, the mixed traffic flow models, and the pedestrian movement models. It is concluded that the difficulties of developing a model to describe the non-lane-based movement comes from the assumptions of the relationship between the longitudinal movement and the lateral movement. For the motorcycle, the more freedom it gets, the more attention it pays to safety. Therefore, safety factors such as reaction time, safety distance, and speed difference related to the description of collision avoidance behavior should be taken into account.

2) To propose a concept of safety space to describe these behaviors, i.e., dynamic movements of motorcycles in traffic made up only of motorcycles.

The study presented the concept of safety space developed for describing the non-lane-based movement of the motorcycle. Safety space was introduced to describe the changes in acceleration or deceleration in response to the changes of safety level of the safety space, whose boundary is determined by the influence of other motorcycles. The proposed concept can deal with the limitations of the previous models

The survey was conducted on 30th - 31th December 2010 in Ho Chi Minh City, from 3:30 pm to 5:30 pm to observe traffic in the peak hours. Two road segments were selected for survey locations. Vehicle movements on 40 m long road segment in one direction were captured in videotape at the pace of 30 frames per second. Observation data on the positions of vehicles (X-axis and Y-axis coordinate) was extracted by using SEV software.

In the calibration result, all the parameters were calibrated at a significance level of 1%. The average relaxation time τ at two different locations was nearly equal to reaction, i.e. 0.5s. This stable estimation result strongly supports the reliability of the proposed concept.

In the model validation, the speed of the motorcycle was predicted by the proposed model with a small RMS error and RMS percent error of speed. The proposed model could correctly describe around 61% of swerving behaviors to the left or right. Another sample of trajectory data on the same Cong Hoa Street, but in the other direction, was extracted to confirm the validation of the model. Statistical analysis showed stable predictions for the two different samples.

3) To develop a microscopic traffic simulator based on the concept of safety space to verify the zigzag movements of the motorcycle.

A simulator was developed based on the proposed motorcycle-following model. The computer simulation reproduced the two basic types of non-lane-based movements: oblique following and swerving movement under congested situations.

A comparison of the fundamental diagrams between the non-lane-based movement and the lane-based movement was carried out. The findings indicate that the lane-based traffic flow shows a better performance, i.e., higher speed, traffic flow, and density then the non-lane-based.

4) To investigate the characteristics of the mixed traffic flow that affect traffic safety.

This research introduced an application of safety space to describe movements of motorcycles and cars in the mixed traffic flow under congested traffic conditions. Safety spaces for the car and the motorcycle are examined by considering the interactions between cars and motorcycles in two cases of interactions: case (1) the subject vehicle is a motorcycle, the influential vehicle is a car; case (2) the subject vehicle is a car, the influential vehicle is a motorcycle. For each case, acceleration parameters were estimated using field data collected on Cong Hoa Street, Ho Chi Minh City. Almost all the parameters were significant at statistical significance level of 1%.

This research also quantified threshold safety spaces for the car and the motorcycle. By comparing acceleration in cases of interaction, this research could explain the differences between driving characteristics of car and motorcycle. Firstly, motorcycles are likely to decelerate its speed in a much later time than when running behind other motorcycles and hence they need a harder brake to escape the rear-end accident with cars. Secondly, cars are found to respond to motorcycles ahead at a farther headway than motorcycles because cars cannot change moving directions in the similar as motorcycles.

5) To assess the motorcycle traffic conflict brought by the non-lane-based movements

This study proposes new features of the motorcycle-following model to assess the motorcycle traffic conflict. First, the difference of numerical values between acceleration and braking was clarified. Second, the conditions in choosing a leader were described; namely, the critical following angle and the following route width.

Conflict situations and an index of deceleration rate for the safety assessment were discussed. A computer simulation was developed to assess the traffic conflict by calculating deceleration rates at each time step when the density of the motorcycle flow is assumed to be changed. The findings highlighted that higher flow density led to a greater increase in probability of traffic accident.

7.2 FUTURE WORK

The proposed model has many limitations. Recommendations on future researches are discussed as below:

1) It appeared that different drivers react to different types of stimuli. The research assumed that the drivers respond to only the most influential vehicle in their motorcycle-following movements. It is acceptable in the congested situation. However, other drivers also consider the second and third influential vehicles. The differences make sense for a flow of vehicles driving in non-dense traffic when they do not need to follow a leader but try to overtake the leaders or filtering through lateral clearances between two other vehicles. In the mixed flow, a motorcycle driver driving behind a truck may feel difficult to consider more leaders. Hence, the influence of parameter heterogeneity in model specifications on the driver behaviors of different drivers should be considered carefully in specific situations.

2) The reaction time in the model calibration was assumed to be constant for all the motorcycle. In the real world, the reaction time varies across different motorcycles. To understand the impact of heterogeneity in the randomness of reaction time for different drivers on the stability of simulation results, a new calibration method should be proposed.

3) Validation for evaluating motorcycle traffic conflict should be implemented. For example, data on traffic conflict and traffic density at a survey location could be collected. The hypothesis on the relationship between the number of traffic conflict counts and traffic density can be tested by comparing the observed data to the simulated data.

4) The model was not designed to cover other behaviors of individual motorcycle drivers. The driving behaviors under uncongested situations such as free-speed travelling, overtaking and filtering; or at the intersections such as free deceleration, oblique following, left or right turning could be developed in future research.

5) Other human factors affect driving behaviors. For example, sleepiness and fatigue caused by long hours or working time of day could increase crash risk. Moreover, aggressive attitudes and driving experiences have effects on traffic accidents. How these human factors affect driving behavior and traffic accident are interesting issues.

Appendix A

This research attempts to apply social force approach to motorcycles. Helbing et al., 1995, 1998, 2001) used this approach to describe the movement of pedestrian (. In social force approach, the driving behaviors are taken as social forces that influence the interactions and movements of a driver. A social force is different with a physical force because it comes from the mind of a driver and shows the effect of a psychological behavior on the movement. Social forces can be put into an equation of motion to describe changes in movements of a driver.

A.1 SOCIAL FORCE MODEL FOR THE MOTORCYCLE

Social forces for the motorcycle are discussed below.

1. *Acceleration force*

A motorcycle driver α prefers to run with desired speed v_α^0 in a desired direction $\vec{e}_\alpha$ ($\|\vec{e}_\alpha\| = 1$) oriented toward the destination. If the motorcycle runs on mid-block, its direction of movement is parallel to the direction of the road. If the motorcycle turns right/left at the intersections, it performs two directions of movement toward the destinations: first is toward the right/left lane of its current road, and second, toward the right/left lane of the next cross-road. A driver will change from actual speed $\vec{v}_\alpha$ to desired speed $v_\alpha^0\vec{e}_\alpha$ within a certain time τ_α (relaxation time) given no obstacle in front. This behavior of changing speed can be described by the acceleration forces $\vec{F}_\alpha^A$ shown below.

$$\vec{F}_\alpha^A = \frac{1}{\tau_\alpha}\left(v_\alpha^0\vec{e}_\alpha - \vec{v}_\alpha\right) \tag{A.1}$$

2. *Repulsive force of other driver*

A subject motorcycle α keeps a "safety space" from other vehicle β to avoid a collision. When a motorcycle approaches another, it reduces its speed. The closer they are, the lower the motorcycle's speed become. Consequently, the effect of reduction in speed can be explained by the repulsive force $\vec{F}^{R}_{\alpha,\beta}$ of other driver β on the subject driver α and is given by

$$\vec{F}^{R}_{\alpha\beta} = V_{\alpha\beta}(b(\vec{r}_{\alpha\beta})) \tag{A.2}$$

where $\vec{r}_{\alpha\beta} = \vec{r}_{\alpha} - \vec{r}_{\beta}$ is distance vector between motorcycle α and motorcycle β. $V_{\alpha\beta}$ is assumed to be equipotential lines shown in Figure A.1. These lines have the form of an ellipse with semi-minor axis *b*. Repulsive function $V_{\alpha\beta}(b)$ is monotonically a decreasing function of *b*. Based on these assumption, one safety space around a motorcycle driver can be drawn by a closed curve of ellipse. When other vehicle comes closer to a target vehicle, the semi-minor axis of the ellipse becomes smaller, and as a result, repulsive force gets bigger.

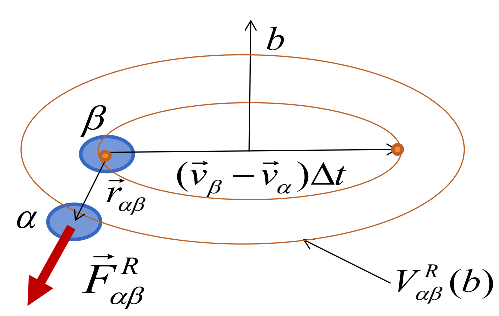


Figure A.1 Equipotential lines of repulsive force

Field observations showed that the subject motorcycle estimates the movement of other motorcycles in advance within time step Δt (i.e. the moving estimation time). Therefore, it is reasonable to assume that the distance between two focus points of an ellipse is equal to $(\vec{v}_{\beta} - \vec{v}_{\alpha})\Delta t$. This means that the semi-minor b axis of the ellipse is perpendicular to direction of the relative speed vector between two drivers. This is because, based on the property of ellipses, the sum of the distances from any motorcycle on the elliptical curve to the two focal points is constant

$$\left\|\vec{r}_{\alpha} - \vec{r}_{\beta}\right\| + \left\|\vec{r}_{\alpha} - \vec{r}_{\beta} - (\vec{v}_{\beta} - \vec{v}_{\alpha})\Delta t\right\| = 2\sqrt{b^2 + \left(\frac{1}{2}\left\|\vec{v}_{\beta} - \vec{v}_{\alpha}\right\|\Delta t\right)^2} = const \tag{A.3}$$

, semi-minor b can be derived from (A.3) as below:

$$b = \frac{1}{2}\sqrt{\left(\left\|\vec{r}_{\alpha} - \vec{r}_{\beta}\right\| + \left\|\vec{r}_{\alpha} - \vec{r}_{\beta} - (\vec{v}_{\beta} - \vec{v}_{\alpha})\Delta t\right\|\right)^2 - \left(\left\|\vec{v}_{\beta} - \vec{v}_{\alpha}\right\|\Delta t\right)^2} \tag{A.4}$$

3. Repulsive force of border

A motorcycle α keeps a distance from border B (median strip, guardrail) to avoid hitting it. If the motorcycle runs close to the guardrail, it reduces the speed and changes the direction to move away from it. This effect can be explained by repulsive force $\vec{F}_{\alpha}^{B}$ of the border as below:

$$\vec{F}_{\alpha}^{B} = U_{\alpha B}\left(\left\|\vec{r}_{\alpha B}\right\|\right) \tag{A.5}$$

Equation (A.5) has the same formulation as Equation (A.2). Therefore, the assumptions of repulsive force of other driver can be applied in repulsive force of border.

$\|\vec{r}_{\alpha B}\| = \|\vec{r}_{\alpha} - \vec{r}_{B}\|$ indicate the distance from location of motorcycle to border *B* which is nearest to the motorcycle. $U_{\alpha B}$ is assumed to be the repulsive function which is monotonically decreasing in distance $\|\vec{r}_{\alpha B}\|$.

4. *Angle of sight*

Motorcycle drivers can only see objects in their angle of sight (Figure A.2). If objects are out of its angle of sight, the motorcycle cannot see them. Therefore, repulsive force holds for situations within the angle of sight φ; and, it has a weaker influence c ($0 < c < 1$) for situations happening behind the driver.

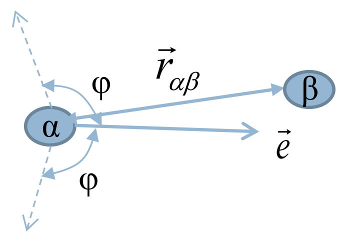


Figure A.2 Angle of sight for motorcycle

The weight factor is introduced here to capture this affect:

$$w = \begin{cases} 1 & if \quad \vec{r}_{\alpha\beta}\vec{e} \geq \|\vec{r}_{\alpha\beta}\| \cos\varphi \\ c & otherwise \end{cases} \tag{A.6}$$

where $\vec{r}_{\alpha\beta}\vec{e} = \|\vec{r}_{\alpha\beta}\|.\|\vec{e}\|.\cos(\vec{r}_{\alpha\beta}, \vec{e}) = \|\vec{r}_{\alpha\beta}\|.\cos(\vec{r}_{\alpha\beta}, \vec{e})$. Therefore, Equation (A.6) means that if motorcycle α is in the angle of sight, i.e. $\cos(\vec{r}_{\alpha\beta}, \vec{e}) \geq cos\varphi$, the weight factor is equal to 1. If motorcycle α is out of the angle sight, weight factor become *c*. The weight factor is used to modify Equation (A.2) for calculating repulse force of other vehicle as follows:

$$\vec{F}^{R}_{\alpha\beta} = wV_{\alpha\beta}(b(\vec{r}_{\alpha\beta})) \tag{A.7}$$

After describing behaviors of motorcycles by equations of social forces, equation of motion for a motorcycle can now be derived. Equation of motion is defined as the total of social forces which is equal to the change of actual speed $\vec{v}_\alpha$ within a certain time dt :

$$\frac{d\vec{v}_\alpha}{dt} = \vec{F}^{A}_{\alpha} + \sum_{\beta} \vec{F}^{R}_{\alpha\beta} + \sum_{B} \vec{F}^{B}_{\alpha} + fluctuations \tag{A.8}$$

Fluctuations term in the Equation (A.8) captures other behaviors that cannot be measured. This can be assumed to be normally distributed.

A.2 PARAMETER CALIBRATION

This study calibrated the parameters using two different data sets of motorcycle trajectory collected at two road segments in Ho Chi Minh City (see Section 3.5). The parameters of desired speed and moving estimation time for calibration are illustrated in Table A.1 because these parameters have strong correlations with other estimation parameters of acceleration. A sensitivity analysis was conducted, with two values for moving estimation time, 1.0 s and 2.0 s, and two values for desired speeds, the observed maximum speed and another lower value, so as to confirm the stability of the simulation results.

Table A.1 Given parameters for motorcycles in the social force model

Parameters	**Phan Dang Luu Street**				**Cong Hoa Street**			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
Desired speed v^0 (m/s)	11	11	8	8	13	13	10	10
Moving estimation time Δt (s)	2	1	2	1	2	1	2	1

Because of lack of data, repulsive force of border cannot be calibrated this time. Repulsive forces of other motorcycle are assumed to decrease exponentially as shown below:

$$V_{\alpha\beta} = V^0 (b - b^0)^{-\sigma} \tag{A.9}$$

where V^0, b^0, σ are estimated parameters of repulsive force. Relaxation time τ in the acceleration force formula is the time which a vehicle needs to reach the desired velocity. For simplicity, it is assumed to be constant for all motorcycles. Hence, all the parameters needed to estimate the proposed model are summarized as below:

Parameters
Repulsive force (V^0, b^0, σ)
Relaxation time τ

The computer software SPSS was used to estimate these parameters by solving the non-linear regression problem. Due to the difficulties in attaining convergent solutions, all the estimated parameters were constrained to be greater than the value of 0.01. These constraints are appropriate for social force equations because estimated values of parameters should be positive. Therefore, sequential quadratic programming is applied under these constraints to minimize errors in running the acceleration equation. The resulting parameter values are shown in Table A.2. All the parameters are estimated with low t-value when t-test is employed.

Table A.2 Parameter estimates for motorcycles in the social force model

Parameters	**Phan Dang Luu Street**											
	Case 1			Case 2			Case 3			Case 4		
	Mean	Std. Error	t-value	Mean	Std. Error	t-value	Mean	Std. Error	t-value	Mean	Std. Error	t-value
V^0	0.059	0.271	0.22	0.098	0.986	0.10	0.010	0.679	0.01	0.085	0.712	0.1
b^0	0.010	1.649	0.01	0.010	2.155	0.00	0.010	9.584	0.00	0.010	3.091	0.0
σ	2.592	6.380	0.41	4.679	13.164	0.36	7.778	112.03	0.07	2.546	7.811	0.3
τ	277.31	326.8	0.85	309.99	362.05	0.86	637.02	1735.7	0.37	76.698	28.714	2.7

Parameters	**Phan Dang Luu Street**											
	Case 1			Case 2			Case 3			Case 4		
	Mean	Std. Error	t-value	Mean	Std. Error	t-value	Mean	Std. Error	t-value	Mean	Std. Error	t-value
V^0	0.184	0.779	0.24	0.184	0.769	0.24	0.291	2.606	0.11	0.291	2.560	0.11
b^0	0.010	1.476	0.01	0.010	1.460	0.01	0.010	2.663	0.00	0.010	2.616	0.00
Σ	2.563	4.407	0.58	2.563	4.364	0.59	3.226	7.904	0.41	3.226	7.757	0.42
τ	2.0E+5	1.9E+8	0.00	1.9E+5	1.8E+8	0.00	1.7E+5	1.3E+8	0.00	1.6E+5	1.2E+8	0.00

The statistical errors are calculated for the speed of motorcycle using two data sets collected on different locations, and using two different models, i.e. the proposed model and the social force model (see Table A.3). The RMS error and RMS percent error of speed in the proposed model are much smaller than those of the social force model. For the swerving movement to the left or right, the proposed model shows better values for the ratio between the estimated values and the observed values. These results imply that the proposed model could perform better estimations than the social force model.

The social force model provided many interesting ideas to address issues on how to capture the interactions between vehicles using the equation of motion and the effects of density on changes in driving behaviors. This research referred to the ideas of the social force model to develop the concept of safety space.

Table A.3 Statistical measures for the speed of motorcycles in the social force model

Statistical Measurement	**The proposed model**		**The social force model (Case 1)**	
	Phan Dang Luu Street	**Cong Hoa Street**	**Phan Dang Luu Street**	**Cong Hoa Street**
RMS error (m/s)	0.485	0.581	0.503	0.604
RMS percent error	0.090	0.065	0.093	0.241
Mean error (m/s)	-0.002	0.021	-0.010	-0.698
Mean percent error	0.006	0.005	0.005	0.011
Ratio of swerving modeled correctly (%)	61.4	64.1	50.5	47.2

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