Safety spaces for overtaking movements in motorcycle traffic flow

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Abstract: Overtaking movements of motorcycles occur very often in uncongested situations when a higher-speed motorcycle overtakes a lower-speed one. This study classifies overtaking movements into three types in the order of the larger traffic volume: (1) Only one influential motorcycle on the inner lane; (2) Only one influential motorcycle on the outer lane; (3) Two or more influential motorcycles ahead for investigating characteristics of safety spaces in each type. A safety space is defined as a space surrounding a motorcycle determined by the influence of other motorcycles. Here, this influence is measured by the safety level rate and the angle of view. Safety spaces of motorcycles for overtaking movements are calculated using data collected from a road segment in Ho Chi Minh City. This result can be used to develop a simulation model for describing the overtaking behavior of a motorcycle.

Keywords: Traffic safety, Motorcycle, Overtake, Safety space, Simulation

1. INTRODUCTION

A motorcycle is used as a main transportation mode in some Asian developing countries. Movements of motorcycles on urban roads are considered as the non-lane-based. As there is no motorcycle-lane on a road, a motorcycle does not need to follow lane disciplines. A motorcycle could move in any direction that it feels safe and comfortable. It travels alongside of another motorcycle one the same car-lane or follows obliquely a lead vehicle. Such non-lane-based movements are unique for motorcycles. Hence, many studies provided analysis of effects of the non-lane-based movements on traffic congestion. Nguyen et al. (2012) developed a microscopic model to explain the mechanism of non-lane-based movements, focusing on two behaviors: the oblique following behavior and the swerving behavior under congested traffic conditions. A simulation was then developed to derive fundamental diagrams of motorcycle traffic flow.

An overtaking behavior is the most frequent behavior showing non-lane-based movements under uncongested traffic conditions. However, very little attention has been paid to the overtaking behavior of two-wheel vehicles. Minh et al. (2005) conducted a study on the overtaking behavior of motorcycles. They found that the lateral distance and the longitudinal distance during overtaking progress was linearly related to the speed of a motorcycle overtaken. These results were described by linear regression models using data collected at two different road segments. Lee (2008) and Lee et al. (2009) suggested many factors affecting the choice of a motorcyclist for whether or not to make a lateral movement. These factors includes current speed, lateral clearance, gap acceptance, size of a vehicle ahead and an effect of the previous choice. Botma et al. (1991) investigated the characteristics of the bicycle on the passing riding to determine the level of service for bicycle paths. The lateral distance and the longitudinal distance and the thresholds of them were analyzed using data collected at many locations in Netherlands. Khan et al. (2001) studied the passing riding of cyclists in Colorado, United States. They explored the speed and the length of passing event, the correlation between the lateral distance and the speed; the relationship between the passing and passed bicycle.

This study aims to investigate the characteristics of overtaking behavior concerning factors of traffic safety such as safety space, safety level and angle of view. It can be divided the overtaking movements into three types in the order of the larger traffic volume: (1) Only one influential motorcycle on the inner lane; (2) Only one influential motorcycle on the outer lane; (3) Two or more influential motorcycles ahead. The methodology is developed to quantify the safety spaces and to understand the characteristics of these spaces in each type. A safety space is defined as a space surrounding a motorcycle determined by the influence of other motorcycles. Here, the influence is measured by the safety level rate and the angle of view. Time-series trajectory data are collected from a road segment in Ho Chi Minh City in the clear and dry weather during peak hours. The findings from statistic results are provided and discussed for safety improvements in driving as well as the development of a dynamic simulation for the motorcycle.

2. METHODOLOGY

2.1 Safety space

The concept of safety space developed by Nguyen et al. (2012) is applied to describe behaviors of increasing or decreasing speed for non-lane-based movements of motorcycles. It consists of three assumptions as follows:

Assumption 1: Safety space is a space that surrounds a single subject motorcycle when it is running along a road. The boundary of the space determined by the influence of other vehicles on driving behaviors of a subject vehicle is assumed to be the equipotential line, meaning that all vehicles on the same line represent the same safety level, as perceived by the driver of the subject vehicle. In this study, the safety space for a subject motorcycle is assumed to be determined by the combination of a half ellipsoidal boundary and two parallel lines, as illustrated in Figure 1. The ellipsoidal boundary shows a space when the preceding motorcycle runs in front of the subject. Two parallel lines make the clearances on both sides of the subject when two vehicles run side-by-side.

The "threshold" safety space is introduced to define the minimal safety level that a motorcyclist considers acceptable for driving and avoiding a possible accident. As shown in Figure 1, the threshold safety space of a subject motorcycle α is assumed to have an ellipsoidal shape, with the motorcycle placed at the center and the direction of its velocity v_α determining the direction of the major axis. 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 $T_\alpha v_\alpha$, where T_α is the reaction time for motorcycle α. 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 a subject motorcycle and another vehicle. The physical size of a motorcycle on each axis is denoted by d_x, d_y.

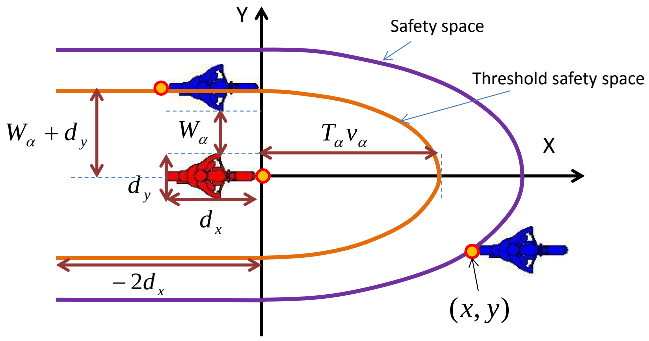


Figure 1. Safety space and the threshold safety space

Assumption 2: When another motorcycle moves closer to or farther away from a subject motorcycle, the safety space becomes smaller or larger; as a result, the perceived safety level decreases or increases. It is assumed that a motorcycle driver simply accelerates or decelerates, with a lag of reaction time T, in response to changes in the size of the safety space with a view to achieving a higher safety level.

Assumption 3: Under heavy traffic conditions, a motorcycle driver responds to the most influential motorcycle at a certain time. Hence, it is important to specify which motorcycle is the most influential. Then it can be assumed that an influential vehicle is chosen to be the most influential if the subject vehicle responds to it with the maximum magnitude of the acceleration. This assumption is reasonable because a subject vehicle may not be able to respond to many influential vehicles at the same time, especially under congested conditions. It focuses 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.

3.2 Safety spaces in three types of overtaking movements

An overtaking movement of motorcycles is observed frequently in the uncongested situations. When traffic density is relative low, a higher speed motorcycle may overtake a lower speed one running on the same lane. This study defines the overtaking movement as a series of activities: a subject motorcycle approaches a preceding motorcycle from behind; it changes the moving direction and increases the speed to pass the preceding one; it moves to a position in front of the preceding in the moving direction. In comparison with the car, there are two different points. Firstly, the car steers gently to the left into the next available lane to pass the preceding; however, the motorcycle does not need to run on the car-lane and it could pass the preceding on the left side or right side that it feels comfort and safe. Secondly, the car may get back into the rightmost lane after passing. The motorcycle rarely represents the same movement because there is no motorcycle-lane for it to get back. As a motorcycle has to focus on many vehicles ahead, it seldom pays attention to another vehicle behind it by checking he side mirror. Therefore, the overtaking progress is stopped when the subject motorcycle approach at a position in the front of the vehicle it wishes to overtake, without moving back to the right.

This study classified overtaking movements into three types in the order of the larger traffic volume.

Type 1 Only one influential motorcycle on the inner lane

In the very low density traffic, it is often observed that a motorcycle overtakes a head motorcycle on the inner lane. A subject motorcycle perceives that it is affected by only one influential motorcycle ahead and it controls the speed and direction to avoid a possible collision with an influential motorcycle *i* as illustrated in Figure 2 (a). The study used the safety level rate L_i to determine the influential degree of a motorcycle *i* at a position x_i, y_i on a subject motorcycle as follows:

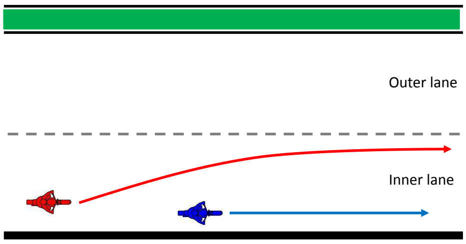
$$L_i = \begin{cases} \dfrac{x_i^2}{(\tau v)^2} + \dfrac{y_i^2}{(W + d_y)^2} & if\ x_i \geq 0 \\ \dfrac{y_i^2}{(W + d_y)^2} & if\ \text{-}2d_x \leq x_i < 0 \end{cases} \tag{1}$$

Equation (1) is an expression for the shape of an ellipsoidal boundary and two parallel lines. As shown in Figure 2 (b), the red curve indicated the threshold safety space explained in Section 3.1, with the length of the semi-major axis τv, measured from the front side of one motorist to the rear side of another on the *x*-axis and the length of the semi-minor axis $W+d_y$, given by the lateral distance on the *y*-axis between one motorcycle and another. Hence, the safety level rate is equal to 1 if an influential motorcycle is running on the threshold safety space. As a subject motorcycle keeps the space equal to threshold safety space, it could avoid a collision with a motorcycle ahead and it feels safe. If the rate is greater than 1; means that the influential is outside of the threshold safety space, a subject motorcycle feels safer. If the rate is lower than 1; means that the influential is inside of the threshold, a subject motorcycle feels less safe.

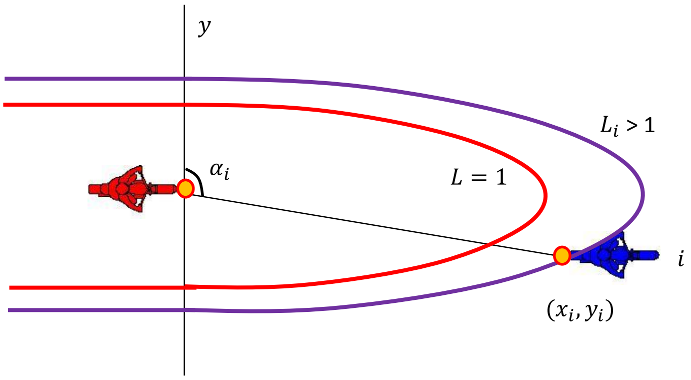
The safety level rate is a measurement of safety distance using data of speed, reaction time and relative position between two motorcycles. Only safety distance is not enough to determine safety spaces for overtaking movements. Hence, the angle of view is also considered to quantify safety spaces. It is defined as an angle made by a space which a motorcycle chooses to move into. In Figure 2 (b), the angle of view α_i is formed by a positive *y*-axis and a straight line connected from the front side of a subject motorcycle to the rear side of a head motorcycle *i*. The safety space for the overtaking movement of a motorcycle is formulated as a product of the safety level rate L_i and the angle of view α_i as:

$$S_i = L_i \cdot \alpha_i \tag{2}$$

The safety space S_i does not show exactly a physical area, it refers to the area of the safety level which a motorist perceives. It is assumed that there is trade-off between the safety level rate L_i and the angle of view α_i and hence a motorist accepts a stable safety space S_i when making the overtaking progress. This study will verify the trade-off relationship in the next chapter.



(a) Overtake in the inner lane



(b) Safety level rate L and angle of view α

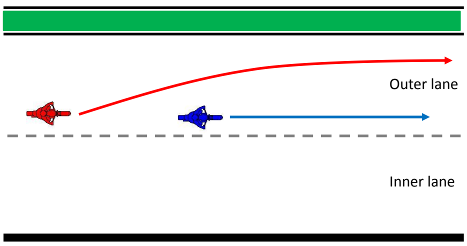
Figure 2. The overtaking movement in type 1

Type 2 Only one influential motorcycle on the outer lane

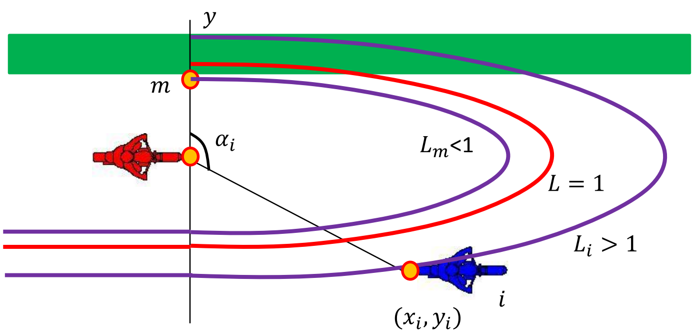
When the inner lane is full of traffic, a motorcycle maybe uses the outer lane for overtaking. In this condition, a subject motorcycle perceives that it is affected by one motorcycle ahead and a median of road. The influence of the median is expressed by a point on the median that is nearest to the subject as illustrated in Figure 3 (a). The reason is because the nearest point to the subject has a biggest influence on it. It is assumed that a subject motorcycle changes the speed and direction to avoid a collision with both the influential motorcycle and the media. Hence, the study used the minimum safety space S between two safety spaces S_i, S_m calculated from the influential motorcycle and the median, respectively, based on Equation (2) to determine the most influential degree on the subject motorcycle as follows:

$$S = \min\{S_i, S_m\} \tag{3}$$

The angle of view is measured by two straight lines, one connected from the front side of a subject motorcycle to the nearest point on a median and another connected from the front side of a subject to the rear side of a head as Figure 3 (b).



(a) Overtake in the outer lane



(b) Safety level rate L and angle of view α

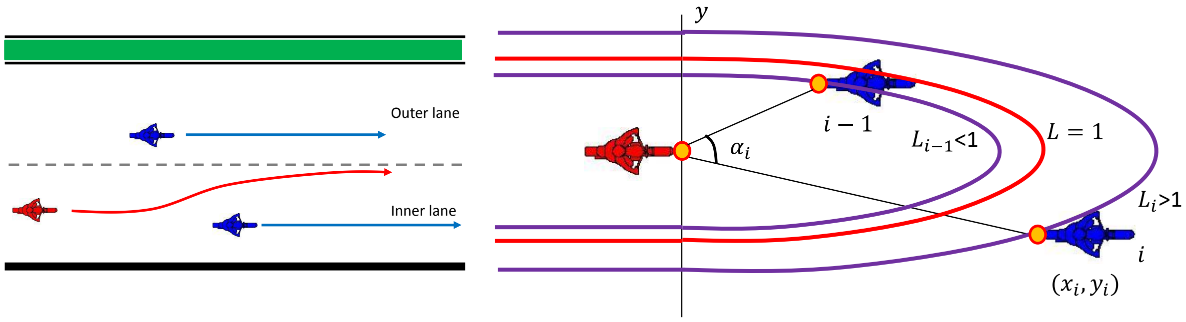
Figure 3. The overtaking movement in type 2

Type 3 Two or more influential motorcycles ahead

When the traffic density is relative high, a motorcycle maybe meets two or more influential motorcycles ahead. When the subject motorcycle tries to overtake the nearest one, it perceives the changes of the safety level rate caused by the motorcycles ahead, as illustrated in Figure 4 (a). It is assumed that a motorcycle changes the speed and direction to avoid a collision with the most influential motorcycle. Hence, the study used the minimum safety space S among many safety spaces S_{i-1}, S_i to determine the influential degree on the subject motorcycle as follows:

$$S = \min\{S_{i-1}, S_i, ...\} \tag{4}$$

The angle of view is measured by two straight lines, each of line connected from the front side of a subject motorcycle to the rear side of a head motorcycle as shown in Figure 4 (b). The physical size of the motorcycle can be affected the accuracy of calculating the angle of view. However, the field data showed that distances between two motorcycles are quite greater than the average width of a motorcycle and hence the error of measuring these angles is expected to be small.



(a) Overtake under many motorcycles ahead (b) Safety level rate L and angle of view α

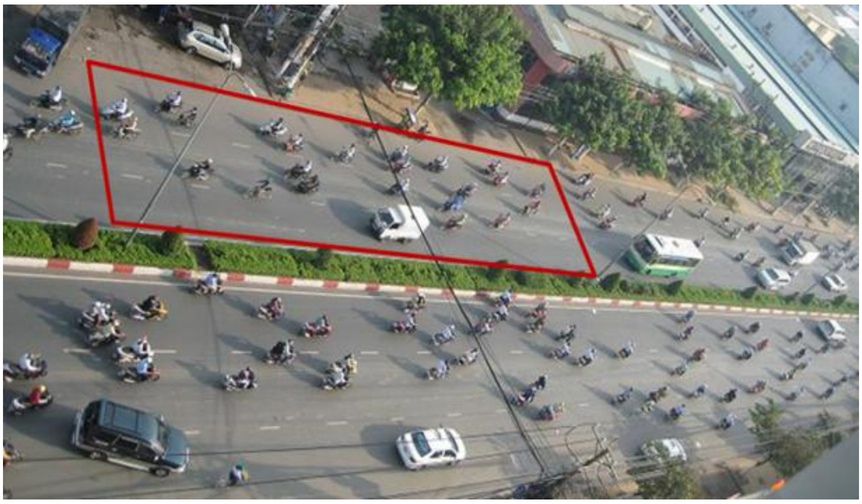
Figure 4. The overtaking movement in type 3

3. DATA COLLECTION

Ho Chi Minh City has a high population of motorcycles, thus a good location to conduct the survey. A road segment with a median on Cong Hoa Street was selected for data collection. The road segment has three lanes in each direction, each lane being 3.65 m wide. The down line in the direction to the airport was chosen for a study site as illustrated in Figure 5. This 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. The survey was conducted in the period of December 30–31, 2010, to observe movements of motorcycles during peak hours.

Time-series trajectory data of each vehicle were recorded using a video camera. A video recorder was set up on a high building near the study location. The 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 ranges from around 30 mm/pixel to 100 mm/pixel. Under ideal situations, the error of tracking data is assumed to range in only one pixel resolution. Therefore, the method of tracking data in this study can provide data sets with high accuracy. Vehicle movements on a 40-m-long road segment in the study direction were captured on video camera at 30 frames/s. The data was collected in the clear and dry weather during peak hours from 6:00 am to 8:00 am and 3:30 pm to 5:30 pm. At last, 4 h worth of a video clip was obtained from the site.

The SEV software developed by Minh et al. (2006) was used to track the trajectory of a subject vehicle and surrounding vehicles. Clicking the mouse on the position of a subject motorcycle and other influential motorcycles at a given time was identified as one observation. The next observation of the same subject vehicle is collected after 0.5 sec. The study collected 8 observations for each subject vehicle. Observations with bicycles, buses and trucks were excluded from data sample. As a result, 719 observations of 80 motorcycles in Cong Hoa Street were used for data analysis.



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

Figure 5. A survey location in Ho Chi Minh City

4. ANALYSIS RESULTS

To simplify the calculation, several parameters were assumed to be constant (see Table 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 was used for the parameter values for vehicle size.

Table 1. Given parameters

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

4.1 Change of the safety space during overtaking progress

From the data set, a subject motorcycle in each type of overtaking movement was chosen to calculate the area of safety spaces during the overtaking progress. There were 8 observations in the moving progress for 4 seconds. The area of safety spaces corresponding to these observations were calculated and shown as in Figure 6. The statistic result showed that the safety space changes gradually over the time during the overtaking progress. The change in area can be described approximately by the discrete lines. The shape of discrete lines has a bottom in the middle and a minimal point in the bottom showed the smallest space. Hence, a motorist accepted the smallest space in a short time 0.5 s ~ 1.0 s to overtake another. This minimum safety space should vary across all the motorists.

The safety space changes depending on type of overtaking. For the type 1, there is only one influential motorcycle ahead resulting in very low traffic density, safety spaces are relative large. In the type 2, when a subject is affected by one influential motorcycle and a median of road, traffic density is higher and safety spaces become smaller. Safety spaces in type 3 are the smallest because the traffic density is rather high as two or more influential motorcycles have an influence on the subject.

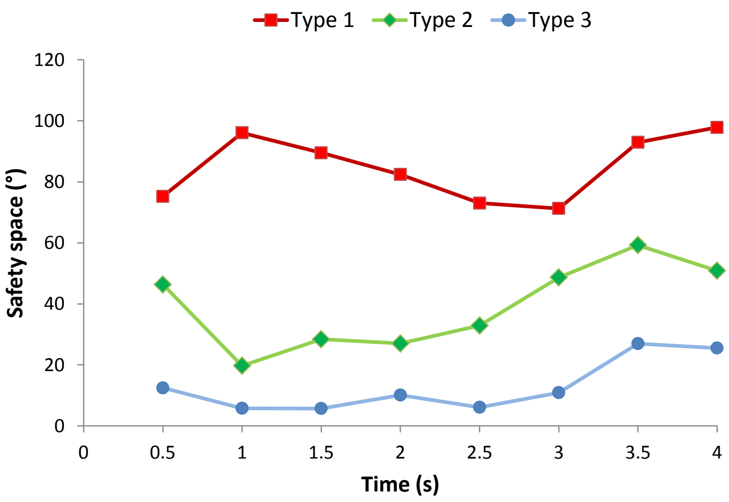


Figure 6. Safety spaces during overtaking progress.

4.2 Trade-off relationship between level safety rate and angle of view

Level safety rate and angle of view were plotted as in Figure 7 to verify the trade-off relationship between them. Only observations at which motorists accepted the smallest safety space during an overtaking event were chosen for plotting. The reason is that observations in the time series for the same motorist could be dependently distributed. Hence, one observation for one motorist will ensure the independence between the analysis data. Moreover, a smallest safety space which a motorist accepts to overtake could expresses the aggressive driving style of a motorist. It should vary across all the motorists.

This study classified the observations by type of overtaking. As a result, 9 observations of type 1, 18 observations of type 2 and 53 observations of type 3 were used to estimate the trade-off relationship. The aggression analysis was conducted using the equation of power function. The correlations between the level safety rate and the angle of view in 3 types are relatively high, greater than 0.48. For each type, the power coefficient of power function is negative; means that the relationship between them is a trade-off. The coefficient becomes higher together with the increasing traffic density from type 1 to type 3. This result makes sense because the angle of view is smaller in the order of the higher traffic density from type 1 to type 3.

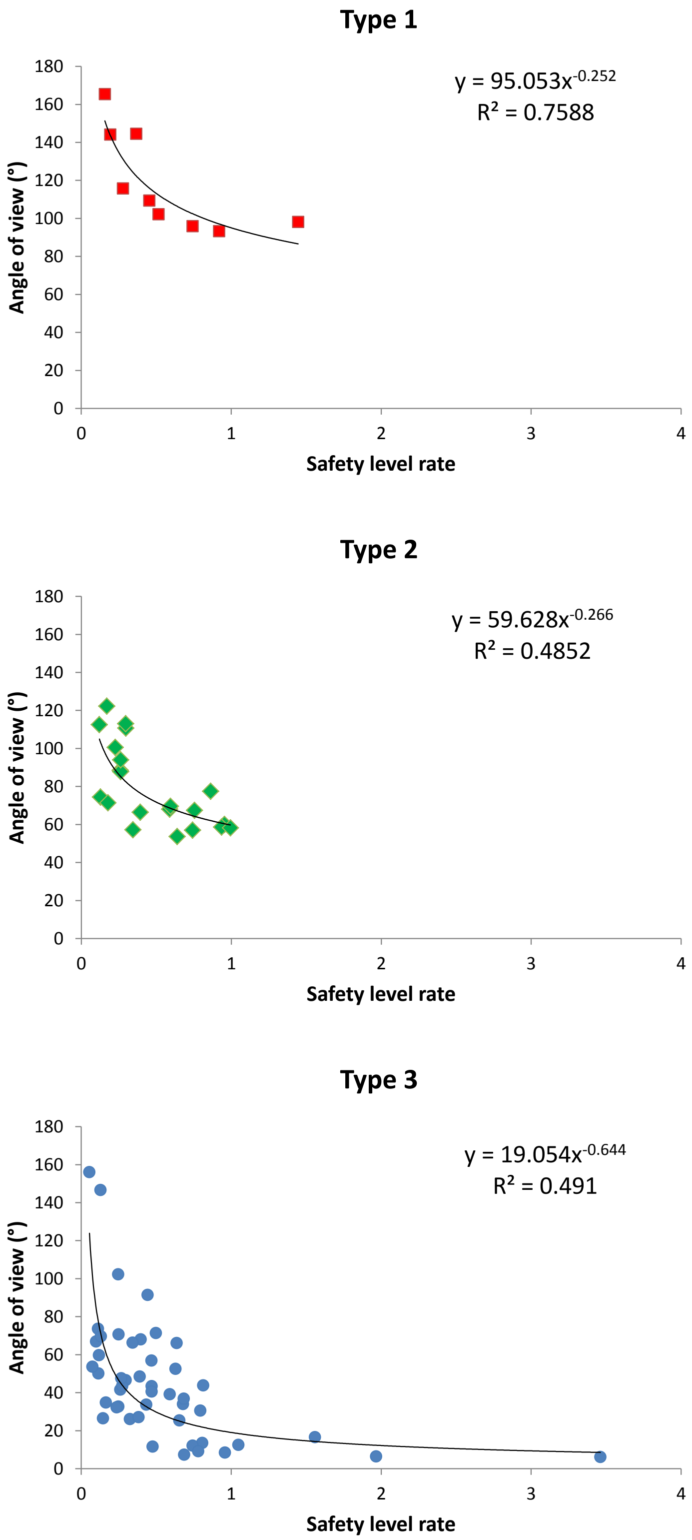


Figure 7. Trade-off relationship between safety level rate and angle of view.

4.3 Discussion on the safety of the overtaking movements

The safety level rate formulated in Equation (1) is applied to discuss on the safety of the overtaking movement. If a motorcycle keeps the threshold safety space when running, the safety level rate is equal to or greater than 1.0; means that it feels safe because it could avoid a collision with a motorcycle ahead. If the rate is lower than 1.0, a motorcycle feels less safe. From the data were used to estimate the trade-off relationship in Section 4.2, it is found that 92.5 % of motorcycles conducted the overtaking progress at safety level rate lower than 1.0. However, this result was calculated based on the assumption that all the motorcycle has the same reaction time 0.5 s. Therefore, a sensitivity analysis was conducted using the whole data collected in Chapter 3, with three values for reaction time 0.3, 0.5, and 0.7 s to confirm the stability of the results. The results were shown in Table 2. Number of observations recorded in every 0.5 s at the safety level rate less than 1 range from 45% to 75% with an average value of 62%. It means that 62% of the overtaking movements possibly lead to traffic accidents.

Table 2. A sensitivity analysis with three values of reaction time

Reaction time (s)	Number of observations at safety level rate less than 1 (%)
0.3	45.4
0.5	62.4
0.7	75.4

The development for the guidelines on keeping the safety distance for the overtaking behaviors is very important. Figure 2(b), 3(b), 4(b) showed the threshold safety spaces described by the red ellipsoidal curves on which the length semi-major axis was expressed by the product of speed and reaction time of a driver; the length of the semi-minor axis was given by the distance of 1.8 m. When a motorcycle controls the speed to keep another outside of the threshold safety space, it runs safely.

5. CONCLUSIONS

This study explored the characteristics of safety spaces of motorcycles for overtaking movements by assuming that a motorcycle tries to keep a safety space during overtaking progress. Three types of overtaking were classified in the order of the larger traffic volume using data collected from a road segment in Ho Chi Minh City. Two findings were explored as follows:

The first finding showed that a safety space changes gradually over the time during the overtaking progress. The statistic data in this study indicated that as traffic density was higher, the safety spaces became smaller. It means that traffic accidents easily occur during the high-density traffic. The safety level rate was applied to discuss on the safety of the overtaking movement. It is found that 92.5% of motorists accepted a risk of collision for overtaking. 62% of the overtaking movements possibly lead to traffic accidents. Therefore, it was very important to introduce many countermeasures for safety improvement. For example, the development for the guidelines on keeping the safety distance for the overtaking behaviors, warnings of the transition or merging area should be considered.

The second finding indicated that there was the trade-off relationship between the level safety rate and angle of view. The power function expressing this relationship can be used to construct essential conditions for choosing an overtaking behavior of a motorcycle. A dynamic simulation for describing the non-lane-based movements of motorcycles could apply these conditions for determining the timing of changing from a following behavior or an overtaking behavior to the other. The outputs of the simulation are useful for analyzing many issues of traffic congestion and traffic safety.

However, this study has some limitations. Though the data sample was divided into three groups to consider an effect of traffic volume and results from three groups are stable, new samples of trajectory data on different location are required to confirm the validation of the results. Moreover, data for representing the transition from the following movement to the overtaking movement might be necessary to ensure that the proposed conditions for determining the timing of choosing the following or the overtaking are valid. These limitations should be paid in attention in further studies.

REFERENCES

Nguyen, L. X., Hanaoka, S., Kawasaki, T. (2012) Describing Non-Lane-Based Motorcycle Movements in Motorcycle-Only Traffic Flow. Transportation Research Record: *Journal of the Transportation Research Board*, 2281, 76-82.

Minh, C. C., Matsumoto, S., Sano, K. (2005) Characteristics of passing and paired riding maneuvers of motorcycle. *Journal of the Eastern Asia Society for Transportation Studies*, 6, 186-197.

Minh, C. C., Sano, K., Matsumoto S. (2006) Deceleration models of motorcycles at signalized 674 intersections. In: Transportation Research Board 85th Annual Meeting, Washington, D.C.

Lee, T. C. (2008) An Agent-Based Model to Simulate Motorcycle Behavior in Mixed Traffic Flow. PhD thesis, Imperial College London.

Lee, T. C., Polak, J. W., Bell, M. G. H. (2009) New approach to modeling mixed traffic 662 containing motorcycles in urban areas. Transportation Research Record: *Journal of the Transportation Research Board*, 2140, 195-205.

Botma, H., Papendrecht, H. (1991) Traffic Operation of Bicycle Traffic. Transportation Research Record: *Journal of the Transportation Research Board*, 1320, 65-72.

Khan, S. I., Raksuntorn, W. (2001) Characteristics of Passing and Meeting Maneuvers on Exclusive Bicycle Paths. Transportation Research Record: *Journal of the Transportation Research Board*, 1776, 220- 228.