Modeling Mixed Traffic Flow with Motorcycles Based on Discrete Choice Approach

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Abstract: This study aims to develop a microscopic model depicting the traffic flow, where motorcycles and passenger cars are mixed. In the model, both behaviors of motorcycles and passenger cars are represented by considering the interaction between them. Concretely, the non-lane based discrete choice approach is applied, because (i) in the mixed traffic flow with motorcycles most vehicles do not follow the lane markings and (ii) the discrete choice approach can represent the highly flexible movement and capture the characteristics of the driver's perception of surrounding traffic situation appropriately. The model parameters are specified by using the vehicle trajectory data observed at Hanoi. As a result, it is found that the discrete choice approach is useful to model mixed traffic flow and that while a rider of a motorcycle pays much attention to the surrounding passenger cars, a driver of a passenger car pays less attention to the surrounding motorcycles. (149 words).

Keywords: Mixed Traffic, Motorcycles, Cross-Nested Logit Model, Traffic Flow, Traffic Simulation

1. INTRODUCTION

In most of the Southeast Asian cities, motorcycles are widely used as one of the urban transportation modes because they are more reasonable than passenger cars in terms of not only the price for purchasing and maintaining but also the high flexibility in route choice and congestion avoidance. Although the number of passenger cars is rapidly increasing due to the recent economic growth in Asian countries, the motorcycles are still dominant in some cities and as a result motorcycles and passenger cars are mutually mixed in the urban traffic flow. This heterogeneous and mixed traffic situation in terms of the size, speed and the characteristics of the movement causes inefficient and unsafe road traffic. The mixed traffic situation is common not only in Southeast Asia, but also in Western countries these days as shared space, where road surface markings and traffic signs are removed and demarcations between vehicles traffic and pedestrians are minimized, though the methods of assessing the efficiency and safety of the mixed traffic have not been established yet.

For the assessment of the efficiency and safety of traffic flow, traffic simulation is one of the most effective tools and practically in use. Most of traffic simulations, however, focus on homogeneous traffic flow composed by four-wheeled vehicles or pedestrians, while the cases focusing on the heterogeneous and mixed traffic flow with various modes, particularly with motorcycles and passenger cars, are still under development. From macroscopic approach, Khan and Maini (1999), Powell (2000) and Nair et al. (2011) developed mixed traffic flow models, though macroscopic approach is not valid to assess the safety of traffic flow. From microscopic approach, some literatures can be found. Minh et al. (2005a and 2005b) investigated the following and overtaking behaviors of motorcycles in mixed traffic situation and developed motorcycles behavior models. Meng et al. (2007) developed the simulation targeting the mixed traffic flow with motorcycles and passenger cars by applying Cellular Automata (CA) and investigated the fundamental diagram of mixed traffic flow as well as the relationship between the density and the number of lane changes. Matsuhashi et al. (2005) and Van et al. (2009) simulated mixed traffic flow by using VISSIM. These studies, however, represent the behavior of motorcycles by the same way as passenger cars, though it is apparent that the behaviors of motorcycles in motorcycle-dominant traffic flow are totally different from that of passenger cars. Lee (2007) developed the agent-based motorcycle behavior model considering the motorcycle specific movement composed by the longitudinal headway model, the oblique and lateral headway model and the path choice model. Though, the proposed model has several limitations to be improved: i) the following behavior and oblique behavior were considered independently, ii) this study applied dynamic virtual lanes and the following behavior and lane-changing behavior were not integrated, and iii) the movement of passenger cars reacting to motorcycles was not modeled. Nguyen and Hanaoka (2011) developed a non-lane based mixed traffic flow model by applying social force model (Helbing and Molnar, 1995). The study successfully captured the motorcycle behavior, but it is still necessary to model the behavior of passenger cars considering the interaction with motorcycles to represent the entire traffic flow.

This study aims to develop a microscopic model depicting the traffic flow dominated by motorcycles, where motorcycles and passenger cars are mutually mixed. In the model, both behaviors of motorcycles and passenger cars are modeled respectively to represent the interaction between them. Concretely, the non-lane based discrete choice approach developed by Robin et al. (2009) is applied to the both behavior models because of the following reasons; (i) in the traffic flow dominated by motorcycles no vehicles follow the lane markings or in the most case the lane markings are worn-out in Southeast Asian cities, (ii) the discrete choice approach can represent the highly flexible movement and (iii) the approach can capture the characteristics of the driver's perception of surrounding traffic situation appropriately. Finally, the developed model is calibrated and validated from both aspects of the consistency of the estimated parameters and the accuracy of the estimated trajectory based on the vehicle trajectory data observed at a downstream section of an intersection in Hanoi, Vietnam. Besides, the robustness of the estimated parameters is also examined.

The rest part of the paper is organized as follow. Section 2 describes the details of the proposed model of both motorcycles and passenger cars. In section 3 the data used in the study is summarized and section 4 summarizes the estimation and validation results. Finally section 5 concludes the study and mentions the future works.

2. MODELING MOTORCYCLES AND PASSENGER CARS BEHAVIOR

2.1 Basic Concepts of Modeling Mixed Traffic Flow

Traffic flow dominated by motorcycles in the Southeast Asian cities is characterized by the following points; (i) most vehicles move freely from the definition of the lanes and (ii) motorcycles and passenger cars, which are totally different in terms of the field of view, size, weight, maneuvering methods, turning radius, acceleration and deceleration characteristics, are mutually mixed. Generally, the degree of freedom of motorcycles movement is much higher than passenger cars. Thus, the pedestrian behavior, which flexibly reacts to the surrounding situation in turning the moving direction, accelerating and decelerating, might have more robust similarity with motorcycles behavior, compared with the passenger car behavior, which is mainly composed by the following and lane-changing behaviors.

Among several microscopic approaches modeling pedestrian behaviors, this study applies the discrete choice based model developed by Antonini et al. (2006) because of the following reasons. Compared to social force model, the discrete choice model has higher flexibility and extendability that various kinds of factors can be considered as explanatory variables. Actually, the extended models, in which, for example, the mixed traffic situation with pedestrians and passenger cars was represented (Kitagawa et al., 2009) or the visibility of obstructers was considered (Yaginuma et al., 2010), have been proposed. In addition, statistical approach, namely likelihood maximization, can be applied for model calibration and the accuracy and validity of the developed model can be statistically evaluated.

In the proposing model, it is assumed that riders of motorcycles and drivers of passenger cars discretely choose their acceleration (or deceleration) and turning angle simultaneously at every Δt seconds with taking consideration into the surrounding situation. In other words, riders and drivers are assumed to choose a discrete area from a choice set which is defined by the limitations specific to each vehicle such as acceleration, deceleration and turning radius. Note that the data for the parameter estimation was collected in Hanoi, Vietnam, and accordingly the both behavior model was developed to follow the traffic law in Vietnam.

2.2 Formulating Motorcycles Behavior

It is assumed that the choice set is defined as the fan-shaped area shown in Figure 1, which consists of 15 alternatives. We assume a correlation structure depending on the speed and moving direction and identify 5 nests; acceleration/deceleration, constant speed, keep direction, turning right and turning left as shown in Figure 2. Note that acceleration and deceleration belong to the same nest because both behaviors have the similarity in terms of changing the speed. All the alternatives belong to more than one nest, thus, Cross-Nested Logit (hereafter, "CNL") model is applied to represent the motorcycles movements and the probability that motorcycle n chooses alternative i, $P_n(i)$, is written as

$$P_n(i) = \sum_{m=1}^{M} \frac{\left(\sum_{j\in C} \alpha_{j_m}^{\mu_m/\mu} y_{nj}^{\mu_m}\right)^{\frac{\mu}{\mu_m}}}{\sum_{k=1}^{M}\left(\sum_{j\in C} \alpha_{j_k}^{\mu_k/\mu} y_{nj}^{\mu_k}\right)^{\frac{\mu}{\mu_k}}} \cdot \frac{\alpha_{i_m}^{\mu_m/\mu} y_{ni}^{\mu_m}}{\sum_{j\in C} \alpha_{j_m}^{\mu_m/\mu} y_{nj}^{\mu_m}}, \tag{1}$$

where y_{ni} = exp(V_{ni}), V_{ni} denotes the utility of alternative i for a given choice maker n, α_{im} denotes the degree of membership of alternative i to nest m and should satisfy the constrains; $0 \leq \alpha_{im} \leq 1.0$ and $\Sigma\alpha_{im} = 1.0$, μ denotes the global scale parameter, and μ_m denotes the scale parameter specific to nest m.

The utility function of alternative i of motorcycle n is defined as follow.

$$V_{ni}^{m} = I_L\beta_{dir,L}\theta_{i,dir} + I_R\beta_{dir,R}\theta_{i,dir} \tag{2.1}$$

$$+ I_L\beta_{des,L}\theta_{i,des} + I_K\beta_{des,K}\theta_{i,des} + I_R\beta_{des,R}\theta_{i,des} \tag{2.2}$$

$$+ I_a\beta_{v,a}\left(\frac{v_n}{v_{\max}}\right)^{\lambda_{ad}} + I_d\beta_{v,d}\left(\frac{v_n}{v_{\max}}\right)^{\lambda_{ad}} \tag{2.3}$$

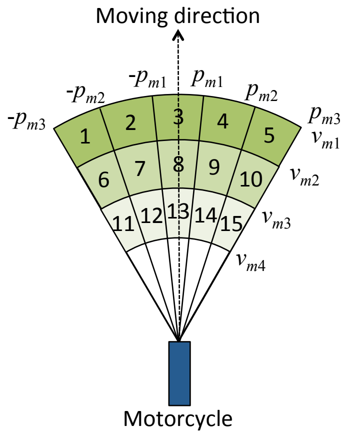


Figure 1 Choice set of a motorcycle

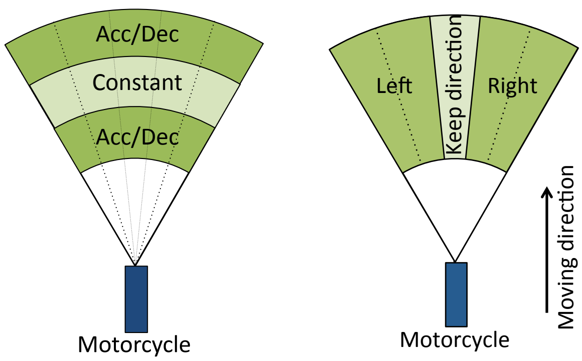


Figure 2 Nest structure of CNL model

$$+ I_K \beta_{w,K} \frac{w_n}{W} + I_R \beta_{w,R} \frac{w_n}{W} \tag{2.4}$$

$$+ I_a \beta_{ml,a} \frac{v_n - v_{ml} \cos \Delta\theta_{ml}}{D_{ml}{}^{\lambda_{Dm}}} + I_d \beta_{ml,d} \frac{v_n - v_{ml} \cos \Delta\theta_{ml}}{D_{ml}{}^{\lambda_{Dm}}} \tag{2.5}$$

$$+ I_a \beta_{cl,a} \frac{v_n - v_{cl} \cos \Delta\theta_{cl}}{D_{cl}{}^{\lambda_{Dc}}} + I_d \beta_{cl,d} \frac{v_n - v_{cl} \cos \Delta\theta_{cl}}{D_{cl}{}^{\lambda_{Dc}}} \tag{2.6}$$

$$+ \beta_{am} \left(\frac{\min_{k_m} d_{ink_m}}{d_{m\max}} \right)^{\lambda_{am}} \tag{2.7}$$

$$+ \beta_{ac} \left(\frac{\min_{k_c} d_{ink_c}}{d_{c\max}} \right)^{\lambda_{ac}} \tag{2.8}$$

In the utility function, Eq. (2.1) - (2.4) relate to unconstrained situation, while the others relate to constrained situation. I_L, I_R, I_K, I_a, I_d are 1 if alternative i belongs to the nest of turning left, the nest of turning right, the nest of keep direction, alternatives 1 to 5 and alternatives 11 to 15 respectively, and 0 otherwise. Each term of the utility function is defined as follow.

2.2.1 Keep direction

The terms shown in Eq. (2.1) capture the behavioral characteristic that a motorcycle basically keeps the moving direction. $\beta_{dir,L}$ and $\beta_{dir,R}$ are parameters to be estimated. $\theta_{i,dir}$ indicates the absolute value of the angle in radian between the current moving direction and the direction towards the center point of alternative i. Because a motorcycle would basically keep the current moving direction, $\beta_{dir,L}$ and $\beta_{dir,R}$ are expected to be negative respectively.

2.2.2 Towards destination

The terms shown in Eq. (2.2) capture the behavioral characteristic that a motorcycle would move toward the destination. In this study, we focus only on the single-way section so that the destination is defined as the direction to downstream. $\theta_{i,des}$ is defined as the absolute value of the angle between the direction towards the downstream and the direction towards the center point of alternative i. $\beta_{des,L}$, $\beta_{des,K}$ and $\beta_{des,R}$, which are unknown parameters, are expected to be negative.

2.2.3 Acceleration in unconstrained condition

When the speed of a motorcycle is high (or low) enough, it is expected that the motorcycle is not likely to accelerate (or decelerate) further. Eq. (2.3), in which v_n, v_{max} and λ_{ad} denote the speed of motorcycle n, the maximum speed of motorcycles and a positive parameter respectively, captures such behavioral characteristics. Thus, the unknown parameters, $\beta_{v,a}$ and $\beta_{v,d}$ are expected to be negative and positive, respectively.

2.2.4 Keep-right rule

According to the road traffic law in Vietnam, motorcycles should drive on the outside lane, though most riders do not follow the rule strictly. To capture the influence of keep right rule, the terms shown in Eq. (2.4) are considered. w_n denotes the distance of motorcycle n from the outside boundary of the road section, while W denotes the total width of the section. When a motorcycle drives on the inside, the motorcycle would try to move toward the outside position to follow the keep right rule, or at least keep the lateral position. Thus, it is expected that the unknown parameters, $\beta_{w,K}$ and $\beta_{w,R}$ are positive.

2.2.5 Following to motorcycles

The terms shown in Eq. (2.5) indicate the following behavior to the other motorcycles ahead. The leaders are defined for 5 directions. Concretely, among the motorcycles whose backs are located in each cone as shown in Figure 3, the one, satisfying the conditions that the distance from the front of the decision maker to the back of the candidate, D_{ml}, is the minimum and less than d_{max}, is defined as the leader of the direction. If there is no leader for the direction, D_{ml} is set as ∞. In Eq. (2.5), v_n, v_{ml}, $\Delta\theta_{ml}$ and λ_{Dm} denote the speed of the decision maker, the speed of the leader, the differences between the moving direction of the leader and the direction to the center point of the alternative and a positive parameter, respectively. It assumes that the decision maker will accelerate or decelerate according to the distance to the leader and the differences in the moving speed, and if the distance is longer and the speed difference is smaller, a decision maker would accelerate and vice versa. In other words, if the

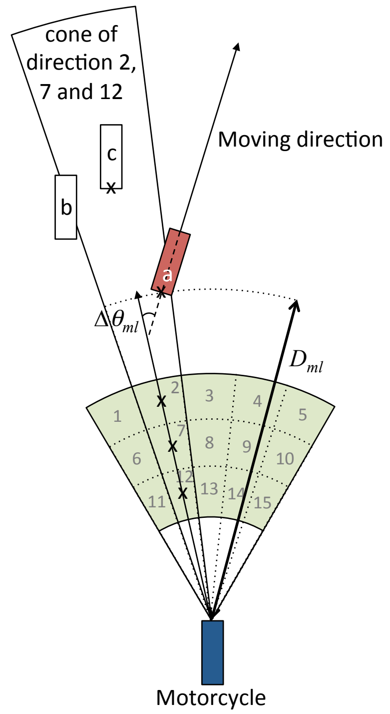


Figure 3 Following to a motorcycle

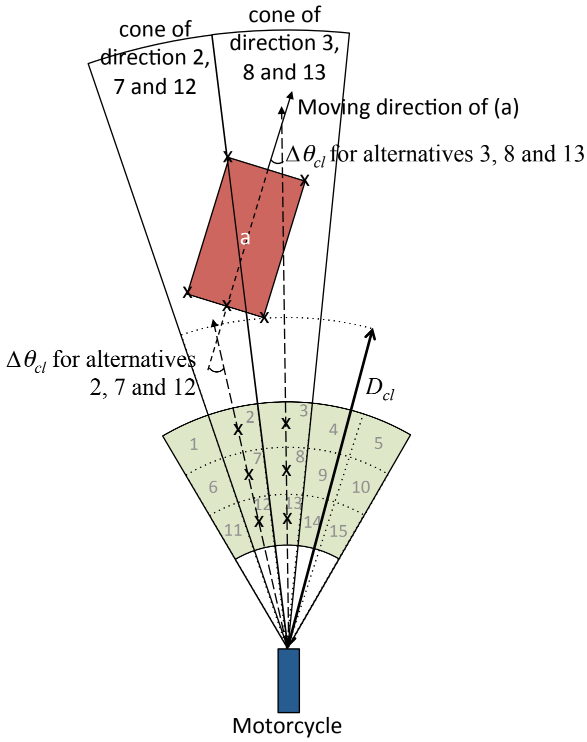


Figure 4 Following to a passenger car

term, $\left(v_n - v_{ml}\cos\Delta\theta_{ml}\right)/D_{ml}{}^{\lambda_{Dm}}$, gets smaller, a follower would be motivated to accelerate. Thus, the unknown parameters, $\beta_{ml,a}$ and $\beta_{ml,d}$, are expected to be negative and positive, respectively.

2.2.6 Following to passenger cars

In this study, the influence from surrounding motorcycles and passenger cars is explicitly separated. The terms of Eq. (2.6) indicate the following behavior to the leading passenger cars. The leaders are defined for 5 directions as the passenger cars that the distance from the decision maker is the shortest among the ones that parts of them are in the cones. In the case of Figure 4, for example, vehicle *a* is considered as the leader for alternatives 2, 3, 7, 8, 12 and 13. In Eq. (2.6), D_{cl}, v_n, v_{cl}, $\Delta\theta_{cl}$ and λ_{Dc} denote the distance from the decision maker to the leader, the speed of the decision maker, the speed of the leader, the differences in radian between the moving direction of the leader and the direction to the center point of the corresponding alternative and a positive parameter, respectively. Concretely, D_{cl} is defined as the shortest distance from the head of the decision maker to the reference points of the leader which are four corners and the midpoint of the back line. As same as the case of motorcycles, if the term, $\left(v_n - v_{cl}\cos\Delta\theta_{cl}\right)/D_{cl}{}^{\lambda_{Dc}}$, gets smaller, a follower would be motivated to accelerate to catch up with the leader, and less motivated to decelerate. Thus, the unknown parameters, $\beta_{cl,a}$ and $\beta_{cl,d}$, are expected to be negative and positive, respectively.

2.2.7 Interactions with motorcycles

It can be said that a rider would anticipate the movement of the surrounding motorcycles till the next time step and choose the way not to collide with others. This term captures the

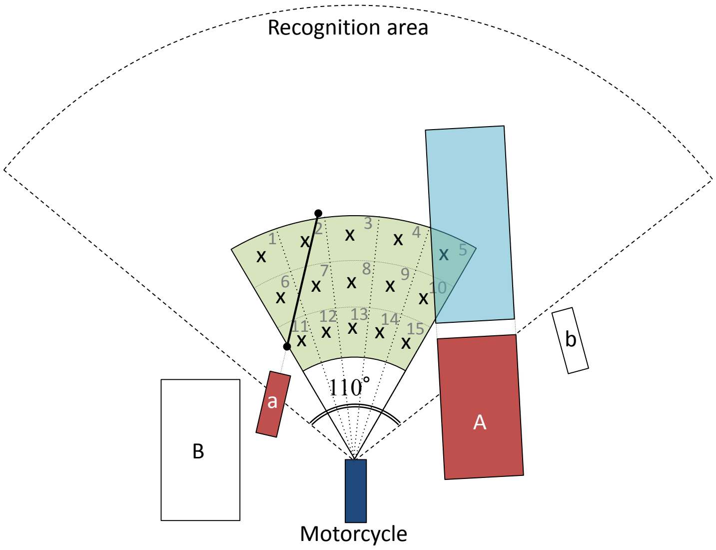


Figure 5 Interaction with motorcycles and passenger cars.

(This figure illustrates the situation that a decision maker recognizes only motorcycle *a* and passenger car *A*, and considers interaction with these two among the surrounding four vehicles (a, b, A and B).)

interaction with other motorcycles. The surrounding vehicles are defined as the ones entering the decision maker's field of vision, which is assumed as a sector shape and whose inner angle is assumed to be 110 degree according to OECD reports (2006) as shown in Figure 5. Although a rider can pay attention to traffic behind by using a wing mirror, it is not considered in this study. To formulate the interaction, the possible trajectories of the surrounding motorcycles, which can be drawn by the segments of lines connecting the point where the head of surrounding vehicle can reach if it accelerates to the maximum to the point where the back of it can reach if it decelerates to the maximum, are considered. Then, the minimum distance from the center point of alternative i to the possible trajectory of surrounding vehicle k_m is defined as d_{inkm}. Give d_{inkm} 0 if the decision maker should cross the possible trajectory to get to the alternative. For example, in Figure 5, d_{inkm} of alternatives 1, 2 and 6 are 0. In Eq. (2.7), the variable that the minimum d_{inkm} among all the surrounding motorcycles is divided by $d_{m\max}$, beyond which the decision maker would no longer be influenced by the surrounding motorcycles, is considered to capture the interaction. λ_{am} is a constant positive parameter less than 1. It is natural that if the term, $\min_{k_m} d_{ink_m} \big/ d_{m\max}$, gets larger, the decision maker is more likely to choose the corresponding alternative because the probability to be interrupted by surrounding motorcycles is less. Thus, the unknown parameter β_{am} is expected to be positive.

2.2.8 Interactions with passenger cars

The basic idea to capture the interaction with passenger cars is same as the interaction with motorcycles. Contrary to motorcycles, the possible trajectories of passenger cars become rectangle areas occupied by the vehicles. Thus, d_{inkc} is defined as the minimum distance from the center point of alternative i to any point on the boundary of the rectangle area occupied by surrounding passenger car k_c. Give d_{inkc} 0, if the center point of alternative i is in the rectangle area or the decision maker should cross the possible trajectory to get to the alternative. For example, in Figure 5, d_{inkm} of alternatives 5 is 0. As same as the case of motorcycles, in Eq. (2.8) the maximum distance $d_{c\max}$ and a constant positive parameter λ_{ac} are considered, and

β_{ac} is expected to be positive.

2.3 Formulating Passenger Cars Behavior

As same as the case of motorcycles, it is assumed that the choice set is defined as the fan-shaped area. Because passenger cars do not change their moving direction as frequently and drastically as motorcycles, the choice set is assumed to consist of 9 alternatives, which belong to two nests related to the speed change; acceleration/deceleration nest and constant speed nest as shown in Figure 6. Accordingly, the normal Nested Logit (NL) model is applied for passenger cars behaviors. Note that Figure 6 limitedly depicts the area where the front-left part of the vehicle will move after a certain time step, though the area actually occupied by a passenger car is wider. It should be carefully evaluated to identify the influence of the leader-follower relationship and the interaction with the surrounding vehicles. The choice probability for alternative i in nest m for passenger car k, $P_k(i,m)$, is written as Eq. (3).

$$P_k(i,m) = \frac{\left(\sum_{j\in C_m} y_{kj}^{\mu_m}\right)^{\frac{\mu}{\mu_m}}}{\sum_{h=1}^{M}\left(\sum_{j\in C_h} y_{kj}^{\mu_h}\right)^{\frac{\mu}{\mu_h}}} \cdot \frac{y_{ki}^{\mu_m}}{\sum_{j\in C_m} y_{kj}^{\mu_m}}, \tag{3}$$

where y_{ki} = exp(V_{ki}), V_{ki} denotes the utility of alternative i for a given choice maker k, μ denotes the global scale parameter, and μ_m denotes the scale parameter specific to nest m. C_m denotes the set of alternatives in nest m.

The utility of passenger car k to choose alternative i is written as follow.

$$V_{ki}^{p} = I_L\beta_{dir,L}\theta_{i,dir} + I_R\beta_{dir,R}\theta_{i,dir} \tag{4.1}$$

$$+ I_L\beta_{des,L}\theta_{i,des} + I_K\beta_{des,K}\theta_{i,des} + I_R\beta_{des,R}\theta_{i,des} \tag{4.2}$$

$$+ I_a\beta_{v,a}\left(\frac{v_k}{v_{\max}}\right)^{\lambda_{ad}} + I_d\beta_{v,d}\left(\frac{v_k}{v_{\max}}\right)^{\lambda_{ad}} \tag{4.3}$$

$$+ I_K\beta_{w,K}\frac{w_n}{W} + I_R\beta_{w,R}\frac{w_n}{W} \tag{4.4}$$

$$+ I_a\beta_{ml,a}\frac{v_k - v_{ml}\cos\Delta\theta_{ml}}{D_{ml}^{\lambda_{Dm}}} + I_d\beta_{ml,d}\frac{v_k - v_{ml}\cos\Delta\theta_{ml}}{D_{ml}^{\lambda_{Dm}}} \tag{4.5}$$

$$+ I_a\beta_{cl,a}\frac{v_k - v_{cl}\cos\Delta\theta_{cl}}{D_{cl}^{\lambda_{Dc}}} + I_d\beta_{cl,d}\frac{v_k - v_{cl}\cos\Delta\theta_{cl}}{D_{cl}^{\lambda_{Dc}}} \tag{4.6}$$

$$+ \beta_{am}\left(\frac{\min_{j_m} d_{ikj_m}}{d_{m\max}}\right)^{\lambda_{am}} \tag{4.7}$$

$$+ \beta_{ac}\left(\frac{\min_{j_c} d_{inj_c}}{d_{c\max}}\right)^{\lambda_{ac}} \tag{4.8}$$

As same as motorcycles, Eq. (4.1) - (4.4) relate to unconstrained situation, and the others relate to constrained situation. I_L, I_R, I_K, I_a, I_d are 1 if alternative i belongs to the subset of 1, 4, 7, the subset of 3, 6, 9, the subset of 2, 5, 7, the subset of 1, 2, 3 and the subset of 4, 8, 9, respectively. Each term of the utility function is defined as follow.

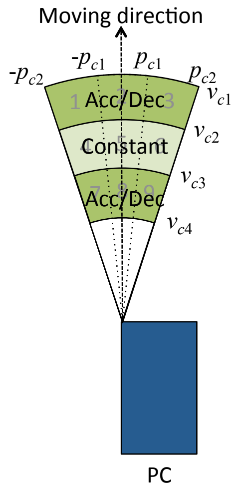


Figure 6 Choice set of passenger cars

2.3.1 Keep direction

The terms shown in Eq. (4.1) indicates the behavioral characteristics to keep the current moving direction. A driver of a passenger car is expected to basically keep the moving direction.

2.3.2 Towards destination

This term in Eq. (4.2) indicates the behavior to go toward the destination. In this study, traffic flow in one-way section is focused and the destination is defined as the downstream direction for all vehicles.

2.3.3 Acceleration in unconstrained condition

Eq. (4.3) captures the acceleration and deceleration behavior in unconstrained condition. When the speed of a passenger car is high (or low) enough, it is expected that the passenger car is not likely to accelerate (or decelerate) further.

2.3.4 Follow a lane

Usually a passenger car follow traffic lane indicated by lane markings, but in this research field lane markings are mostly worn-out and the definition of each lane is unclear. Thus, to take account of the constrain that a passenger car cannot go beyond the median divider, the term Eq. (4.4) is included in the utility function.

2.3.5 Following to motorcycles and passenger cars

Contrary to motorcycles, a driver of a passenger car does not consider the leader to follow them for each direction, because the width of a passenger car is not negligible and it does not change the moving direction so often. Thus, the leader is defined to each passenger car as follow. Among the vehicles within the rectangle target area in front of the decision maker as

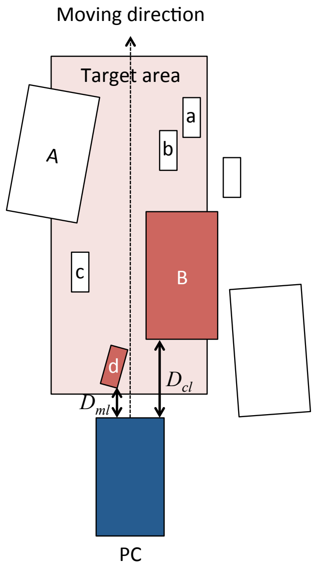


Figure 7 Following to the leaders

shown in Figure 7, the motorcycle (d) and the passenger car (B) that the distance from the decision maker to them are the minimum are determined as the lead motorcycle and passenger car, respectively. Note that the width of the target area is defined as the summation of the vehicle width and the recognition error of the driver to the width of the vehicle. The variables in Eq. (4.5) and (4.6) are defined as same as the case of motorcycles.

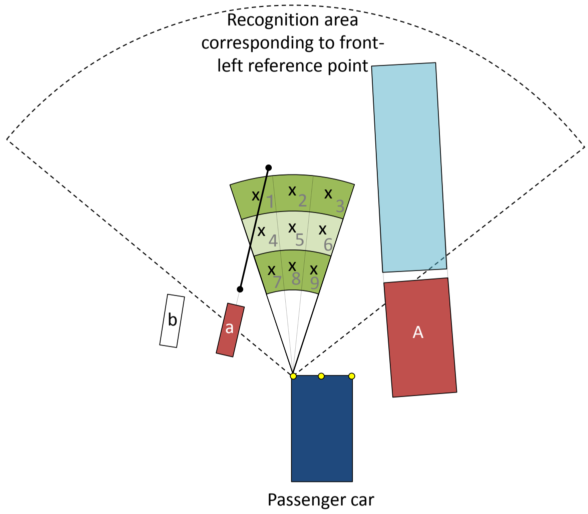
2.3.6 Interactions with motorcycles and passenger cars

Eq. (4.7) and (4.8) capture the driver's anticipation of surrounding vehicles movement and avoidance from collision. As same as the motorcycles, the fun-shaped recognition area is defined. The minimum distance from the center point of each alternative to the anticipated trajectories of surrounding motorcycles or the anticipated occupied area by the surrounding passenger cars is considered as the explanatory variables. It should be noted that contrary to motorcycles the width of passenger cars should be considered to calculate the distance accurately. Thus, we consider three reference points of a passenger car; front-left point, front-center point and front-right point. The coordinates of the center point of each alternative are calculated for corresponding reference point as shown in Figure 8. Among the three distances from the alternatives to the anticipated trajectory or occupied area, the minimum one is defined as the variable. Give d_{ikjm} and d_{ikjc} 0, if the center point of alternative i is located across the trajectory, in the anticipated rectangle area or across the anticipated area. In the case of Figure 8, the distance from alternative 1 to the anticipated trajectory of motorcycle a is 0 because to the center point of alternative 1 the decision maker should across the trajectory when the front-left reference point is considered. Accordingly, the distance from alternative 3 and 6 to the anticipated occupied area of passenger car A is 0.

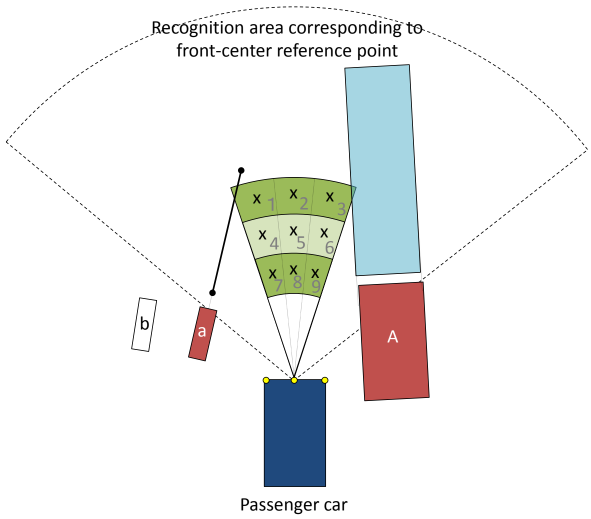
3. DATA DESCRIPTION

3.1 Traffic Survey

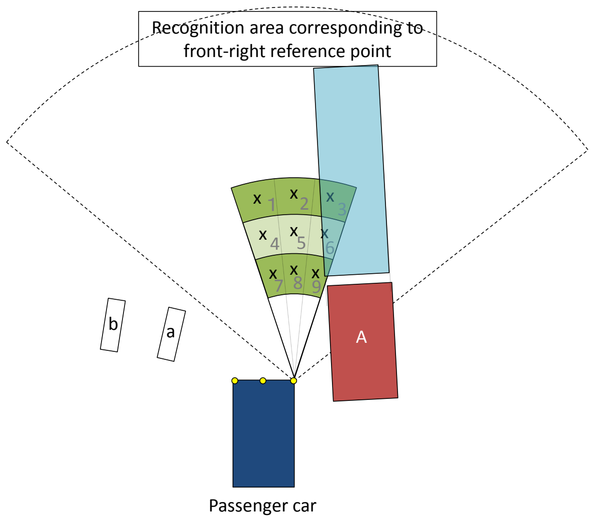
In order to calibrate and validate the proposed model, traffic surveys were conducted by using



(a) Front-left reference point



(b) Front-center reference point



(c) Front-right reference point

Figure 8 Interaction of passenger cars with surrounding vehicles a DV camera at an intersection in Hanoi city. Such observation site was selected that satisfies the following requirements:

1) passenger car and motorcycle volumes should be large enough to observe mutually mixed traffic flow,
2) a DV camera can be set from a high position and
3) there are no bus stops and parking lots near the site.

Consequently, the site 30 m downstream of the west approach of Kim-MA St. - Nguyen Chi Thanh St. intersection was selected. Traffic flow was observed by a DV camera shooting the road section of 40 m length and 10 m width in Hanoi city (see Figure 9) on 29, Sep 2009, from 9:00 to 11:00.

3.2 Data Collection

To collect the vehicle trajectories data, the video image of 67 seconds, which corresponded to the split time of the upstream intersection, was selected because no large vehicles were observed. The coordinates of all vehicles on a screen were obtained by clicking the point of the front tire on grounding for motorcycles and the left-front edge and the left-back edge for passenger cars every 0.1 seconds by using a manual trajectory acquisition system developed for this analysis. As a result, in total trajectories of 179 motorcycles and 36 passenger cars (including 2 street-parking vehicles) were extracted. The extracted trajectories contain some errors caused by the manually clicking and the coordination transition from the screen to the real-world. Consequently, some trajectories exhibit somewhat unrealistic movement. To correct these errors, thus, a smoothing spline algorithm was applied.

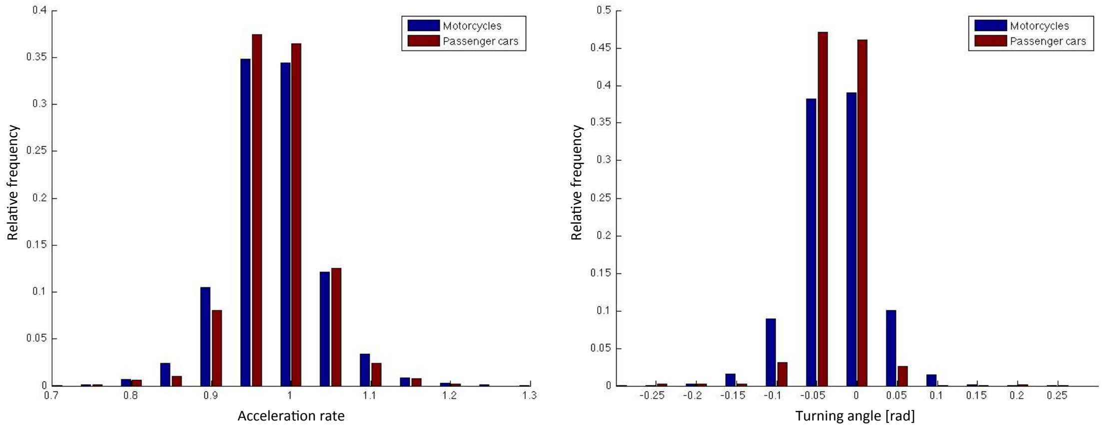
3.3 Definition of Choice Sets

It is critical to optimally define the size of each alternative in the choice set. To examine it, the observed distributions of acceleration rate, which is defined as the ratio of the speed at the current time step to the speed at the previous time step, and turning angle, which is defined as the differences between the moving direction at the current time step and the previous time step, were investigated. In this study, time step size was defined as 0.7 seconds, assuming that each driver and rider chooses the point where he/she will reach 0.7 seconds after by adjusting the speed and moving direction, though finding the optimal step size would be a future topic. Note that tuning angle is defined to be positive when motorcycles or passenger cars move to right-hand direction. Figure 10 depicts both histograms of acceleration rate and turning angle. It can be seen that acceleration rate distributes within the region from 0.7 to 1.3 and turning angle distributes within ± 0.25 for motorcycles and ±0.15 for passenger cars. Focusing on the differences between motorcycles and passenger cars, as for acceleration rate there cannot be found the clear distinction, while as for turning angle motorcycles are likely to change the moving direction more than passenger cars. Based on the results, the parameters in Figure 1 and Figure 6 are defined as follow: p_{m1} = 0.052 rad (= 3°), p_{m2} = 0.157 rad (= 9°), p_{m3} = 0.262 rad (= 9°), p_{c1} = 0.052 rad, p_{c2} = 0.157 rad, $v_{m1} = v_{c1} = 1.3v_t$, $v_{m2} = v_{c2} = 1.05v_t$, $v_{m3} = v_{c3} = 0.95v_t$ and $v_{m4} = v_{c4} = 0.7v_t$, where v_t indicates the speed at the current time step. Defining the optimal parameters for the choice set would be a future topic.

4. ESTIMATION RESULTS AND MODEL VALIDATION

4.1 Motorcycle Behavior Model

Figure 9 Traffic flow in the target section



(a) Acceleration rate (b) Turning angle

Figure 10 Histograms of acceleration rate and turning angle

The unknown parameters of Eq. (2) are estimated based on the observation data by using BIOGEME (2003). To specify CNL model, nonlinear parameters are given beforehand as follow: λ_{ad} = 1.5, λ_{Dm} = -1.5, λ_{Dc} = -1.5, λ_{am} = 0.6 and λ_{ac} = 0.6. Considering Antonini et al. (2006) as a reference, we fix the degrees of membership to the different nests (α_{jm}) to the constant value 0.5. The parameter μ is normalized to 1, and the nest parameters are estimated; μ_C for the nest of constant, μ_L for the nest of turning left, μ_K for the nest of keep direction and μ_R for the nest of turning right, while μ_{AD} for the nest of acceleration and deceleration is fixed to 1.

The estimation results are summarized in Table 1. Focusing on the nest parameters, all of them are significantly larger than 1, implying that the assumptions of the correlation structure are valid. Adjusted ρ^2 is 0.52, which is considered that the proposed model can produce sufficiently good-fitting to the observation. It can be seen that all the coefficients of explanatory variables are estimated as significant. The detailed discussion follows.

4.1.1 Keep direction

Both coefficients are significantly negative, implying that basically motorcycles tend to keep the current moving direction.

4.1.2 Towards destination

Both coefficients turn to be negative as expected. It means that motorcycles basically move

Table 1 Result of model specification for motorcycles

Variables		Coefficient estimate	Std. Err.	t test
Keep direction	$\beta_{dir,L}$	-8.53	1.43	-5.95 *
	$\beta_{dir,R}$	-15.80	2.29	-6.87 *
Toward destination	$\beta_{des,L}$	-5.90	1.04	-5.67 *
	$\beta_{des,K}$	-13.00	1.11	-11.62 *
	$\beta_{des,R}$	-12.90	1.19	-10.85 *
Acceleration in unconstrained condition	$\beta_{v,a}$	-2.54	0.21	-11.95 *
	$\beta_{v,d}$	-3.80	0.21	-18.32 *
Keep-right rule	$\beta_{w,K}$	2.12	0.23	9.21 *
	$\beta_{w,R}$	2.70	0.41	6.54 *
Following to motorcycles	$\beta_{ml,a}$	-1.95	0.54	-3.62 *
	$\beta_{ml,d}$	1.99	0.41	4.92 *
Following to passenger cars	$\beta_{cl,a}$	-1.52	0.54	-2.79 **
	$\beta_{cl,d}$	0.74	0.45	1.66 ***
Interactions with motorcycles	β_{am}	4.53	0.96	4.71 *
Interactions with passenger cars	β_{ac}	12.30	2.09	5.90 *
Nest parameters	μ_C	1.65	0.20	8.27 *
	μ_L	5.15	2.34	2.20 **
	μ_K	2.21	0.45	4.93 *
	μ_R	1.71	0.36	4.80 *
N		3632		
Init log-likelihood		-9835.64		
Final Log-likelihood		-4685.77		
Adjust-ρ^2		0.52		

* p<0.01, **p<0.05, ***p<0.10

toward the direction of downstream.

4.1.3 Acceleration in unconstrained condition

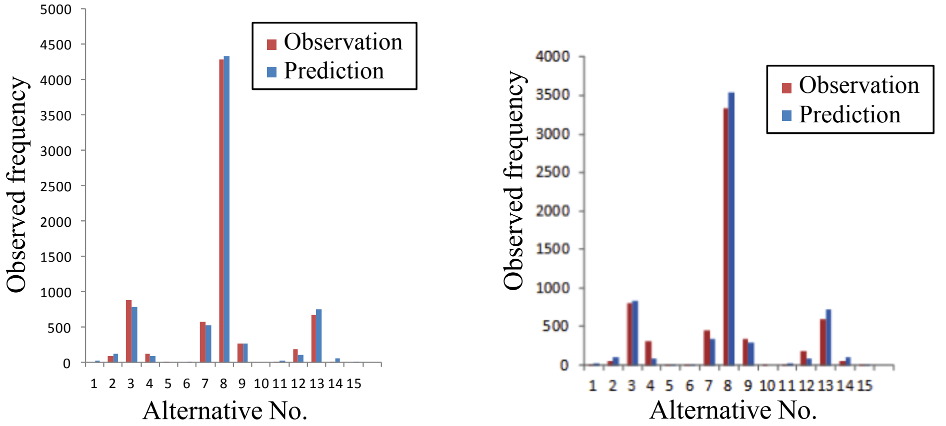
The coefficient for the alternatives of acceleration is negative as expected, while the coefficient for the alternatives of deceleration is also significantly negative, contrary to the expectation. The possible explanation is that when a motorcycle moves at high speed, it is considered that the motorcycle is likely to be in unconstrained condition and it may have no reason to decelerate and tends to keep the current speed.

4.1.4 Keep-right rule

Both coefficients are positive and the coefficient for the alternatives belonging to the nest of turning right is larger than that of the nest of keep direction, indicating that if a motorcycle moves on the inner position of the target section, it will move to the outer position or at least keep the position, not moving to the inner further. This result implies that a rider of a motorcycle basically follows the keep-right rule.

4.1.5 Following to motorcycles or passenger cars

The coefficient of the alternatives belonging to acceleration is negative, while that of the alternatives belonging to deceleration is positive, both for motorcycles and passenger cars as expected. Comparing between motorcycles and passenger cars, the absolute values of the coefficients for motorcycles are larger than passenger cars. It implies that in terms of the



(a) Data for model specification (b) Data for model validation

Figure 11 Validation of motorcycle behavior model

following behavior to a leading vehicle, a rider of a motorcycle is influenced more by the leading motorcycles than passenger cars.

4.1.6 Interactions with motorcycles or passenger cars

Both for motorcycles and passenger cars, the coefficients are positive as expected. It means that a rider or a driver anticipates the behavior of surrounding vehicles and choosing the way to avoid the collision with them. It should be noted that the absolute value of the coefficient of passenger cars is much larger than motorcycles; implying that a motorcycle rider pays much more attention to surrounding passenger cars than motorcycles, or he/she is more averse to collide with passenger cars than motorcycles.

To validate the specification, the observed share of each alternative is compared with the prediction by using two data sets; one is the same data for the model specification, and the other is the data set observed in the different time duration. Figure 11 summarizes the validation results. It can be seen that as a whole both results present the good prediction to the observation, though some disturbances can be seen. Thus, we can conclude that the established model accurately predicts behavior of motorcycles considering the interaction with passenger cars.

4.2 Passenger Car Behavior Model

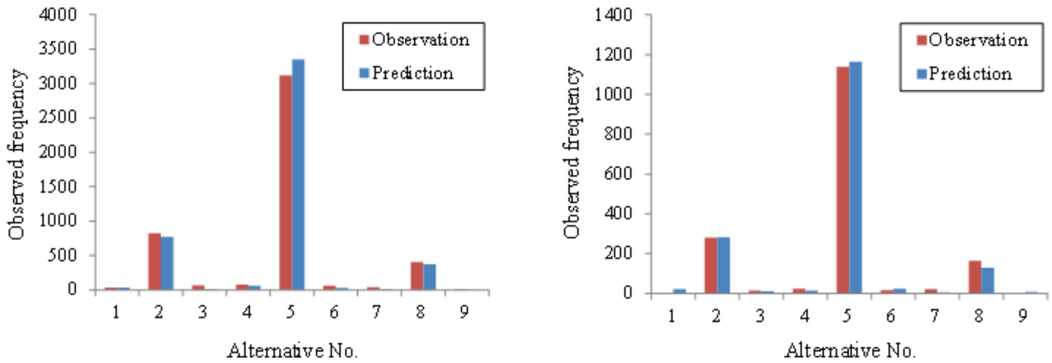
As same as the case of motorcycles, the unknown parameters are estimated by using BIOGEME (2003), and nonlinear parameters are given beforehand as follow: λ_{ad} = 1.5, λ_{Dm} = -1.5, λ_{Dc} = -1.5, λ_{am} = 0.6 and λ_{ac} = 0.6. The parameter μ is normalized to 1, and the nest parameters are estimated; μ_C for the nest of constant and μ_{AD} for the nest of acceleration.

The estimation results are summarized in Table 2. Adjusted-ρ^2 is 0.615, indicating that the model presents the good-fitness to the observation, and both nest parameters are significantly larger than 1, showing that the assumption on the nest structure is validated. Focusing on the coefficients of each explanatory variable, it can be seen that some of them are insignificant at the 10%-significance level. Concretely, both coefficients of keep direction are insignificant. It might be because a passenger car does not change the moving direction frequently and drastically and its moving direction is basically toward the destination so that the correlations between the variables of keep direction and toward destination is high. As for

Table 2 Results of model specification for passenger cars

Variables		Coefficient estimate	Std. Err.	t test
Keep direction	$\beta_{dir,L}$	5.43	3.34	1.62
	$\beta_{dir,R}$	-2.71	4.88	-0.56
Toward destination	$\beta_{des,L}$	-5.70	2.37	-2.40 **
	$\beta_{des,K}$	-4.72	2.50	-1.88 ***
	$\beta_{des,R}$	-7.98	3.03	-2.63 **
Acceleration in unconstrained condition	$\beta_{v,a}$	-4.47	0.31	-14.28 *
	$\beta_{v,d}$	-2.55	0.26	-9.85 *
Follow a lane	$\beta_{w,K}$	1.27	0.46	2.75 **
	$\beta_{w,R}$	1.14	0.73	1.56
Following to motorcycles	$\beta_{ml,a}$	0.78	0.61	1.28
	$\beta_{ml,d}$	2.22	1.06	2.10 **
Following to passenger cars	$\beta_{cl,a}$	-1.03	1.10	-0.94
	$\beta_{cl,d}$	6.45	2.48	2.60 **
Interactions with motorcycles	β_{am}	-0.53	0.79	-0.67
Interactions with passenger cars	β_{ac}	8.74	2.43	3.59 *
Nest parameters	μ_{AD}	3.25	0.83	3.91 **
	μ_{C}	5.06	1.41	3.59 **
N		1338		
Init log-likelihood		-2939.89		
Final Log-likelihood		-1115.64		
Adjust-ρ^2		0.615		

* p<0.01, **p<0.05, ***p<0.10



(a) Data for model specification (b) Data for model validation

Figure 11 Validation of passenger car behavior model

the coefficient of follow a lane for alternatives of turning right, it might be caused by the fact that passenger cars do not change the moving direction so much. Variables of following to motorcycles and passenger cars for alternatives of acceleration are also insignificant, which implies that in the target section a passenger car is less motivated to accelerate by the surrounding vehicles behavior. Finally, it is worth noting that the variable of interaction with motorcycles is insignificant. This result implies that a driver of a passenger car does not pay much attention to the surrounding motorcycles. It is possible to mention that the carelessness of a driver to the surrounding motorcycles may cause the hazardous traffic situation, though further investigation is required. The other significant coefficients show the same tendency with motorcycles behavior model, and we can clearly see the similarity and the differences between motorcycle behavior and passenger behavior.

To validate the passenger car behavior model, the observed share of each alternative is compared with the prediction for two data sets; one is the same data for the model specification, and the other is the data set observed in the different time duration (see Figure 12). It can be seen that for both cases the prediction can present the good-fitness of the share of chosen alternatives. Thus, we can conclude that the established model captures the behavioral characteristics of passenger cars in the target section.

5. CONCLUSIONS

This study focused on the mixed traffic situation common in Southeast Asian cities and formulated the microscopic models of mixed traffic flow applying the discrete choice approach. Concretely, CNL model was applied to capture the motorcycle movement, which was free from the lane markings and frequently changed the moving direction to overtaking the leaders and avoid the collision with the surrounding vehicles, while NL model was applied to capture the passenger car movement. In both models, it is assumed that a rider or a driver chooses the discrete area reached at after a certain time step taking into consideration the surrounding traffic situation. The models were specified by using trajectory data observed in Hanoi city, and also validated. As a result, it can be concluded that:

i) According to the specification results, the assumptive structure of correlation among alternative was validated, likelihood ratio was high enough and all the coefficients of explanatory variables turned to be understandable. It implies that the discrete choice approach is useful to model mixed traffic flow.

ii) As the result of the interpretation of specified parameters, it was revealed that while a rider of a motorcycle pays much attention to the surrounding passenger cars, while a driver of a passenger car pays less attention to the surrounding motorcycles. This asymmetric relationship may cause the hazardous situation for motorcycle riders if a rider fails to notice the existence of surrounding passenger cars, though further investigation is required for more detail.

Future works are recommended as follow:

(i) In the motorcycle behavior model, the number of riders on a motorcycle is not considered, though in Southeast Asian countries motorcycles ridden by two or more persons can be easily found. The differences in behavioral characteristics between single-ride motorcycles and motorcycles with more than one passenger should be investigated and formulated.

(ii) The length of target section is not so long enough to observe the lane-changing behavior of passenger cars and this model does not represent it appropriately, though the behavior of changing the moving direction is captured in the model. The passenger car behavior model should be extended to capture the lane-changing behavior.

(iii) The method to assess the efficiency and safety of the mixed traffic flow should be developed by using the established model. Then, we can examine effective policies of operating and managing mixed traffic flow to improve the efficiency and safety.

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