An Application of Social Force Approach for Motorcycle Dynamics

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Abstract: There are many researches on the characteristics of car traffic flow. However, we have little knowledge of mixed traffic flow which is very common in developing countries. In the mixed traffic flow, the behavior of cars and buses can be considered as lane-based movements. But motorcycles have non-lane movements because they are observed to change their direction and speed very often. Therefore, the paper aims to investigate the mechanisms of interaction between motorcycles to give a good measure of the mixed traffic volume in congested situation. This study develops a new approach to describe dynamic movement of motorcycles based on social force approach for pedestrians. Microscopic data for model validation was collected from video images taken in the road intersection of Hanoi, Vietnam. Parameters were estimated by using SPSS software with non-linear aggression method. The result shows that proposed approach can make reasonable estimate of the histogram choice for the speed and direction of motorcycle dynamic movement.

Key Words: mixed traffic flow, motorcycle dynamics, social force, non-lane based movement

1. INTRODUCTION

There are many researches on the characteristics of car traffic flow. However, we have little knowledge of mixed traffic flow which is very common in developing countries. The mixed traffic flow can be defined as a flow that includes many transport modes such as cars, motorcycles, buses and non-motorised transportation. Figure 1 shows that several big cities in Asia use motorcycle as the main transportation mode in their transport system. Motorcycle has a high mobility of speed because it is smaller and easier to run than car in the mixed traffic lane of urban road. Motorcycle also shows its high accessibility of door-to-door. This vehicle takes small parking space and people usually keep motorcycle in their houses. Figure 2 illustrates the high ownership of motorcycle in several cities. The main reason is related to the cost of motorcycle that is cheaper many times than car. Motorcycle is a best choice for a low or middle income family and each working members can own one motorcycle. But this reason is not right for Taipei city. Taipei became a high income city but the level of usage is still high. In the past, Taiwan developed strongly motorcycle market and motorcycle users now are familiar with the high mobility and high accessibility of motorcycle.

As in the case of Taiwan, it is difficult to change the habit of using motorcycle if people used motorcycle once. Therefore, the mixed traffic flow will exist for a long time in the future. The physical characteristics of the mixed flow and different properties between mixed flow and car flow needs to be better understood. There has been a series of researches in this field. Minh et al. (2005) looked at some basic characteristics of motorcycle flow such as speed-flow relationship, distribution of headway. Motorcyclist has several behaviors which are the same
as car driver. Motorcyclists follow their leader and decelerate to avoid a tail-head collision. Car-following model was applied for this movement (Van et al., 2009). The behavior which a motorcycle with a higher speed overtakes a front vehicle is modeled by multinomial logit model (Lee, 2008). Motorcyclists decide randomly whether to change lane or not depending on the utility function with affective factors like speed, gap acceptance and others. However, there are a number of different characteristics between car and motorcycle.

Due to big size and shape, a car needs more occupancy than a motorcycle to move. Kov and Yai (2009) conducted the data survey on the mixed flow with high proportion of light vehicle in Phnom Penh, Cambodia. This study indicated that mean speed decrease tremendously when number of light vehicle increase. The speed of car in heavy traffic is smaller than motorcycle and motorcycles will be obstructed by a front car. The other different point between car and motorcycle is related to movement of cars and non-lane based movement of motorcycles. Car runs in lane, but motorcycle changes its direction very often. This causes the interactions between car and motorcycle in lateral distance and result in traffic congestion. Therefore, many researchers try to propose their approaches to explain non-lane based movement of motorcycle drivers. Some of them assume that motorcycles run on a virtual lane and change to next virtual lane randomly. This lane-changing behavior is modeled by using a multinomial logit model (Lee, 2008). But they faced difficulties in deciding the width of virtual lane and in differentiating lane-changing behavior with oblique following just by seeing traffic recording video.

The paper aims (i) to propose a new approach to describe non-lane based movement of motorcycle based on social force approach, and (ii) to capture the interactions between motorcycles. The study also shows a validation method for motorcycle dynamic movements by considering the choice of their direction and speed at every step time.

2. AN SOCIAL FORCE APPROACH FOR MOTORCYCLE DYNAMICS

The research applies social force approach for motorcycle. Social force approach was used to describe the movement of pedestrian by Helbing (1995, 1998, 2001). We assume that a motorcycle driver usually does not make complicated decisions to choose alternative behaviors, but simply takes optimized behaviors learned through past experiences. For example, when motorcycle drivers follow a leader, they keep a safety distance to avoid a tail collision. Sometimes they change their direction to move to wider space if they feel uncomfortable in a current position. In social force approach, these psychological behaviors can be assumed to be social forces that make interactions on the movements of a driver.
Social force is different with physical forces. It comes from inside of a driver and shows the effects of psychological behaviors on movement. We can put social forces into an equation of motion to describe the changes of movement. Social forces for motorcycle are discussed as below.

2.1 Acceleration force
A motorcycle driver $\alpha$ prefers to run with desired speed $v_0^\alpha$ in a desired direction $\vec{e}_\alpha$ ($\|\vec{e}_\alpha\|=1$) oriented towards the destination. If the motorcycle runs on the mid-block, it has a destination that it can go straight. If the motorcycle turns right/left in the intersections, it has two destinations: the first one on the right/left lane of the running road and the second one on the lane of the next right/left-turn road. A driver will change from actual speed $v^\alpha_r$ to desired speed $v_0^\alpha e^\alpha_r$ within a certain time $\tau_\alpha$ (relaxation time) if there is no obstacle in front. This behavior of changing speed can be described by the acceleration forces $F^A_\alpha$ as below.

$$F^A_\alpha = \frac{1}{\tau_\alpha} \left( v_0^\alpha e^\alpha_r - v^\alpha_r \right)$$  \hspace{1cm} (1)

To considering the randomness of desired speed, it is assumed to be normally distributed, $v^\alpha_0 \sim N(0, \sigma^2)$.

2.2 Repulsive force of other driver
One target motorcycle $\alpha$ keeps a “safety sphere” from other vehicle $\beta$ to avoid a collision. When a motorcycle approaches close to another, it will reduce its speed. The closer they come, the lower motorcycle speed become. Consequently, the effect of reduction in speed can be explained by the repulsive force $F^R_{\alpha\beta}$ of other driver on target driver and is given by

$$F^R_{\alpha\beta} = V_{\alpha\beta}(b(\vec{r}_{\alpha\beta}))$$  \hspace{1cm} (2)

where $\vec{r}_{\alpha\beta} = \vec{r}_\alpha - \vec{r}_\beta$ is distance vector between motorcycle $\alpha$ and motorcycle $\beta$. $V_{\alpha\beta}$ is assumed to be as equipotential lines in Figure 3. These lines have the form of ellipse with semi-minor axis $b$. Repulsive function $V_{\alpha\beta}(b)$ is monotonically decreasing function of $b$. Based on these assumption, one safety sphere 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 3 Equipotential lines of repulsive force](image)

Realistic observations show that target motorcycle estimates the movement of other motorcycles in next time step $\Delta t$ (i.e. the reaction time) in advance. Therefore, it is reasonable to put an assumption 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 relative speed vector between two drivers. Because the sum of the distances from any motorcycle on the ellipse to those two focus points is constant
\[ \left\| \vec{r}_a - \vec{r}_\beta \right\| + \left\| \vec{r}_a - \vec{r}_\beta - (\vec{v}_\beta - \vec{v}_a) \Delta t \right\| = 2 \sqrt{b^2 + \left( \frac{1}{2} \left\| \vec{v}_\beta - \vec{v}_a \right\| \Delta t \right)^2} = \text{const} \]  (3)

Then, semi-minor \( b \) can be derived by
\[ b = \frac{1}{2} \sqrt{\left( \left\| \vec{r}_a - \vec{r}_\beta \right\| + \left\| \vec{r}_a - \vec{r}_\beta - (\vec{v}_\beta - \vec{v}_a) \Delta t \right\| \right)^2 - \left( \left\| \vec{v}_\beta - \vec{v}_a \right\| \Delta t \right)^2} \]  (4)

### 2.3 Repulsive force of border

A motorcycle driver \( \alpha \) keeps a distance from border B (median strip, guardrail) to avoid hitting them. If it runs close to the guardrail, it will reduce the speed and change the direction to go far from it. This effect can be explained by repulsive force \( \vec{F}_a^R \) of the border as below.

\[ \vec{F}_a^R = U_{al} \left( \left\| \vec{r}_{ae} \right\| \right) \]  (5)

Equation (5) has the same formulation as Equation (2). Therefore, the assumptions of repulsive force of other driver can be applied in repulsive force of border. \( \left\| \vec{r}_{ae} \right\| = \left\| \vec{r}_a - \vec{r}_e \right\| \) indicated the distance from location of motorcycle to border B which is nearest to motorcycle. \( U_{al} \) is assumed to be the repulsive function which is monotonically decreasing in distance \( \left\| \vec{r}_{ae} \right\| \).

### 2.4 Angle of sight

Motorcycle drivers can see objects in their angle of sight (Figure 4). If objects are out of its angle of sight, it cannot see them. Therefore, repulsive force should be hold for a situation in angle of sight \( \varphi \) and has a weaker influence \( c \) \((0 < c < 1)\) for a situation located behind the driver.

![Angle of sight for motorcycle](image)

The weight factor is introduced here to capture this affect as below.

\[ w = \begin{cases} 1 & \text{if } \vec{r}_{ae}\hat{e} \geq \left\| \vec{r}_{ae} \right\| \cos \varphi \\ c & \text{otherwise} \end{cases} \]  (6)

where \( \vec{r}_{ae}\hat{e} = \left\| \vec{r}_{ae} \right\| \cos (\vec{r}_{ae}, \hat{e}) = \left\| \vec{r}_{ae} \right\| \cos (\vec{r}_{ae}, \hat{e}) \). Therefore, the Equation (6) means that if motorcycle \( \beta \) is in angle of sight \((\vec{r}_{ae}, \hat{e}) \leq \varphi \), weight factor is equal to 1. If motorcycle \( \beta \) is out of the angle sight \((\vec{r}_{ae}, \hat{e}) > \varphi \), weight factor become \( c \). Use the weight factor to modify Equation (2) for calculating repulse force of other vehicle as follows.

\[ \vec{F}_{ab}^R = wV_{ab}(b(\vec{r}_{ae})) \]  (7)

After describing behavior of motorcycles by equations of social forces, now we can derive the equation of motion for one motorcycle here. Equation of motion is defined as the total of social forces which are equal to the change of actual speed \( \vec{v}_a \) within a certain time \( dt \).
\[
\frac{d\bar{v}_a}{dt} = \bar{F}_a^A + \sum_{p} \bar{F}_{ap}^p + \sum_{a} \bar{F}_a^B + \text{fluctuations}
\] 

(8)

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

### 3. DATA COLLECTION

To analyze the dynamic movements of motorcycle, data on position of all vehicles over the time are necessary. Therefore, trajectory data of each vehicle on the time-series were collected. One sample contains information of a target motorcycle and other motorcycles in the interactions of motion between them. The next sample for the same target was taken after 0.5 second to capture sufficiently the change of speed and direction. Samples were also selected to exclude the conflicts of car on motorcycle behavior. The reason for this is that the interactions between car and motorcycle will not be the main part and should be discussed in another study.

#### 3.1 Survey location

Hanoi city in Vietnam with high population of motorcycles is the best location to conduct the survey. To understand the changes of dynamic motion in terms of traffic density, a two-phased signalized intersection with 3 lanes in each direction was selected. The width of each lane is 4.5 meter. When there are no cars or trucks on inner lane, motorcycle can run in any lane that they want.

A video recorder was set up on the high building near the intersection. Vehicle movements over 40 meters in length of one direction were captured in videotape at the pace of 5 frames per second. The survey was conducted from 6:30 am to 9:00 am to take in account the peak hours (7:30 am -8:00 am). At last, an image video file with a resolution 640x480 pixels was recorded to tracking the trajectory of motorcycles.

#### 3.2 Data analysis

Computer software SEV was used to convert from video screen coordinates into roadway coordinates. The input is video file and the output is Excel file which contains the trajectory data of traffic. One trajectory data set (X-axis and Y-axis coordinate) for one vehicle is extracted by clicking on position of that vehicle in the monitor at every 0.5 second interval. The error of clicking by hand which was estimated around 20 cm can be accepted to estimate parameters. 298 observations for 69 motorcycles were used to estimate parameters of the model.

### 4. NUMERICAL RESULTS

#### 4.1 Parameter calibration

The study calibrated parameters by using a data set of 298 observations of motorcycle’s movements. The assumed parameters of desired speed and reaction time for calibration are given as illustrated in Table 1 because those parameters cannot be estimated by only using data set. Desired speed was taken value of observed maximum speed. Reaction time for motorcycle to keep safety distance (safety headway) was taken from study of Minh (2005).
Table 1 Given parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired speed $v^0$</td>
<td>10 m/s</td>
</tr>
<tr>
<td>Reaction time $\Delta t$</td>
<td>2s</td>
</tr>
</tbody>
</table>

Relaxation time in the formulation of acceleration force is the time which a vehicle needs to reach the desired velocity. For simplicity, it was assumed to be a constant at all the motorcycles. Because of the lack of data, repulsive force of border cannot be calibrated this time. Repulsive force of other motorcycle were assumed to decrease exponentially as below

$$ V_{ap} = V^0 \left( b - b^0 \right)^{-\sigma} $$

(9)

Table 2 summarizes all the parameters that are needed to estimate the propose model.

Table 2 Estimated parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repulsive force $(V^0, b^0, \sigma)$</td>
<td></td>
</tr>
<tr>
<td>Relaxation time $\tau$</td>
<td></td>
</tr>
</tbody>
</table>

The computer software SPSS was used to estimate those parameter by solving the non-linear regression problem. We found the parameter values as shown in Table 3.

Table 3 Parameter estimates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>$V^0$</td>
<td>0.314</td>
<td>0.276</td>
<td>-0.231</td>
</tr>
<tr>
<td>$b^0$</td>
<td>0.500</td>
<td>0.683</td>
<td>-0.848</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.960</td>
<td>0.707</td>
<td>-0.436</td>
</tr>
<tr>
<td>$\tau$</td>
<td>5.882</td>
<td>24.390</td>
<td>3.968</td>
</tr>
</tbody>
</table>

4.2 Validation

This research applied validation method of discrete choice model for pedestrian behavior to motorcycle movements. This method assumed that pedestrians choose their direction and speed at every step time to reach destination from the choice set as illustrated in the Figure 5.
The spatial choice set includes 3 choices of speed (acceleration, constant and deceleration) and 7 choices of angle (3 degree in middle side and 2, 3, 4 degree in both left and right side) to make a nest of spatial 21 choices. When a motorcycle moves in the next time, the next position can be determined by one of those choices. Based on the spatial choice set, it is easy to predict the share of each choice for all the vehicles. The correlation coefficient between estimated share and observed share of each choice was used to evaluate how correctly the proposed model can explain the real dynamic motions of motorcycle.

The histogram of predicted share and observed share of each choice are shown in Figure 6.

![Figure 6 Number of shares](image)

Quantile - quantile plot was made to find the relationship between data result and estimation result (Figure 7). Correlation coefficient is 1.136 which is close to 1. It means that the proposed model can explain the histogram of spatial choices well.

![Figure 7 Quantile - quantile plot](image)

5. CONCLUSION

The paper outlines an application of social force model to describe non-lane based movement of motorcycle and describes the dynamic motion of motorcycles through a simple model with a few parameters utilizing field data. This study also introduces validation method for
motorcycle dynamics based on the method of discrete choice model for pedestrian behavior. The result shows that the histogram of spatial choices can be predicted by the proposed model. However, for the simplicity of the non-linear regression analysis, a few parameters were assumed to be constant. Parameters were estimated at the low t-value of parameters when t-test is employed for testing the parameters to be near 0 or not. Because the sample size of the survey is very low and the survey was conducted at only one place in a particular time period, the proposed model could not cover the overall characteristics of motorcycle behaviors. These limitations will be considered in the further research.

The proposed model can be extended to simulate motorcycle behaviors in different traffic conditions. It is planned to develop a simulator based on the proposed model. The computer simulations can help to understand characteristics of the traffic mixed flow such as speed–flow relationship, interactions between car and motorcycle considering variations of car rate. These results can be used for geometric designs of intersection to improve the traffic congestion.

REFERENCES