Research Article

Lane-Filtering Behavior of Motorcycle Riders at Signalized Urban Intersections

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In developing countries, motorcycle riders typically perform lane filtering at signalized urban intersections. This study aims to determine the factors that affect the lateral clearance of motorcycle riders as they travel between two lanes of mixed traffic at signalized urban intersections in developing countries. In this study, an onboard measurement device was developed to measure the lane-filtering behavior of motorcycle riders. It was installed on a test motorcycle to continuously record the lateral clearance, riding behavior, and surrounding traffic conditions. Thirty participants rode the test motorcycle through a signalized urban intersection. Multilevel linear regression was applied to analyze the relationship between lateral clearance and relevant variables at a significance level of 0.05. The instant speed and side of the filtering motorcycle, condition of the lateral vehicle, type of lateral vehicle, and riding frequency of the motorcycle rider significantly influenced the lateral clearance. The findings of this study can contribute to filtering lane management, connected autonomous vehicles, and microscopic traffic simulations for motorcycles traveling in mixed traffic at signalized urban intersections.

1. Introduction

Motorcycles are the optimal mode of transportation for short daily distances in developing countries because of their affordability. The number of registered motorcycles in the Association of Southeast Asian Nations (ASEAN) countries has increased over the last 5 years (Figure 1) [1]. Meanwhile, the motorcycle fatality rate in these countries is approximately 50%, reaching 75% in Thailand. Consequently, Thailand ranks first among these countries in terms of motorcycle-related fatalities [2]. Over 54% of motorcycle accidents are caused by human error [3, 4].

In developing countries, small-size motorcycles (engine sizes under 150 cc) generally do not adhere to the “first in first out” rule, unlike large-size motorcycles (engine sizes over 150 cc). Most motorcycle riders intend to maneuver ahead of other traffic at signalized intersections. The reasons for the maneuvering of motorcycle riders in a queue may be any or all of the following: (1) an attempt to stop at a favorable position during queue formation; while traveling in a queue during a red-light period, motorcycle riders tend to move forward and stop at the position closest to the stop line; (2) a desire to avoid traveling behind a large vehicle; (3) preparation for making a turn; and (4) an attempt to avoid an obstruction [5]. To stop at the position closest to the stop line, motorcycle riders generally filter between two lanes of other traffic at a mixed traffic signalized intersection, which is known as lane filtering.

The objective of this study was to explore the lane-filtering behavior of motorcycle riders when they filter between two lanes of other queuing vehicles at a mixed traffic signalized urban intersection in developing countries. The factors affecting the lateral clearance of the filtering motorcycles were determined. This study defined the lane filtering of a motorcycle rider as a maneuver in which a motorcycle travels at a low speed (5–30 km/h) between two
lanes of stationary or slow-moving vehicles (less than 30 km/h) and traveling in the same direction at a signalized mixed traffic intersection. This study excluded the behavior of motorcycle riders traveling adjacent to curbs or parked vehicles because of the risk of conflict with roadside pedestrians and parked vehicles. Many states in Australia [6–8] have prohibited motorcycle riders from filtering a lane next to a curb or parked vehicles.

2. Literature Review

2.1. Lane Filtering of Motorcycle. Lane filtering and lane splitting are defined differently by region. Each state in Australia [6–8] has a slightly different definition of lane filtering. Lane filtering occurs when a motorcycle travels at a low speed between two lanes of stopping or slow-moving vehicles traveling in the same direction while the motorcycle is heading into a signalized intersection. Motorcycle riders can perform lane filtering for two or more lanes in the same traffic direction. Lane filtering is permitted when the motorcycle rider travels at a speed not over 30 km/h; however, riders are prohibited from filtering a lane next to a curb or parked vehicles, a lane through a school zone, a lane in merging traffic and speed-reduced zones (e.g., at roundabouts), and a special purpose lane (e.g., bicycle, bus, or tram lanes) [7, 8]. Motorcycle riders either should not [6] or are prohibited from filtering lanes near trucks and buses [7, 8].

In contrast, in the USA, if motorcycle riders use lane filtering at a speed of over 30 km/h, it is called lane splitting. Generally, lane splitting is prohibited because it increases the risk of severe accidents owing to speedy driving [9–11]. However, in 2016, California enacted a rule permitting lane splitting only if it is considered safe for two or more lanes in the same traffic direction. The speed of the traffic flow must not exceed 48 km/h, and motorcycles must not exceed the speed of other vehicles by more than 24 km/h. They are mostly used in road mid-block locations or major highways [12–14].

In developing countries, such as Thailand, lane filtering and lane splitting are illegal. However, police officers mostly do not enforce such rules. In practice, almost all motorcycle riders typically perform lane filtering when approaching signalized urban intersections. They intend to stop at a favorable position closest to the stop line during a red-light period. They aim to avoid stopping closely in front of a truck or bus. They seek to start before other larger vehicles in the queue during early green time to avoid conflicts with larger vehicles, especially while turning.

To the best of our knowledge, no research has been conducted on the lane-filtering behavior of motorcycle riders at signalized urban intersections in developing countries. What are the factors influencing the decision of motorcycle riders when determining lateral clearance from lateral vehicles? The research hypothesis of this study is that the lateral clearance of motorcycle riders is influenced by the instant filtering speed, condition of the lateral vehicle, type of lateral vehicle, side of the filtering motorcycle, and demographics of the motorcycle riders.

2.2. Instrumented Vehicle Studies on Driving Behavior. An instrumented vehicle study is a research method that can measure real-world driving behavior. An onboard measuring device is developed and installed on a test vehicle at a position that causes the least disturbance to the driver. It reflects a result describing the driving behavior as closely as possible to an actual scenario, which is important for strategic planning and safety assessment. Many instrumented vehicle studies have been conducted (Table 1), including the behavior of drivers overtaking bicycles [15–18], behavior of bicyclists overtaken by vehicles [19], and various behaviors of motorcycle riders, including overtaking behavior in an exclusive motorcycle lane [20] and a trajectory on curved road sections [21].

In addition to the aforementioned review of instrumented vehicle studies on driving behavior, several studies
have collected the riding behavior of motorcycle riders using video cameras installed on road infrastructures and buildings, including maneuvering behavior along mixed traffic urban arterials [25–28]. However, only one study has been conducted on maneuvering behavior in queues at signalized urban intersections [5]. Research on the lane-filtering behavior of motorcycle riders at signalized urban intersections is lacking.

3. Methodology

3.1. Development of Onboard Measurement Device. This study explored the lateral clearance of motorcycle riders as they filter between two lanes at a signalized urban intersection. Motorcycle riders would change their lateral clearance instantaneously according to their immediate riding behavior and surrounding circumstances. Therefore, this study developed an onboard measurement device that measured the lane-filtering behavior of a motorcycle rider every second.

Based on a literature review of distance-measuring devices, many types of devices have been applied in instrumented vehicle studies, such as video cameras, ultrasonic sensors, and lidar sensors. Video cameras are economical and easy to install on a test vehicle, but they occasionally have low accuracy owing to the distortion from the installation angle. In addition, they cannot measure the distance at an angle. In a previous study, [29] ultrasonic sensors that measure sound waves were used to detect vehicles traveling on two-lane roads. The study observed that when the traffic was congested, the accuracy decreased. The noise distorted the signal, causing a measurement error. Ultrasonic sensors can accurately measure the positions of all overtaking vehicles with a high-speed-360-degree rotation of the sensor. Lidar sensors have a higher resolution than video cameras [17] and are more accurate than ultrasonic sensors [30, 31]. Lidar sensors use laser technology for measurement, which is not affected by noise from a vehicle’s engine or horn that may cause measurement errors. This technology is currently used to detect objects in automated vehicles. However, lidar sensors can provide a large amount of data, and a supporting program should be written to clean and encode the raw data. Therefore, in this study, a lidar sensor was selected to measure the distance at an angle.

From a literature review of speed measuring devices, it can be seen that the global positioning system (GPS) has been used to measure motorcycle speed via satellites. The accuracy of GPS depends on the orbit of satellites [32]. GPS may yield a low accuracy because of unclear weather or tall buildings [33–35]. Measuring the speed of a motorcycle riding at a low speed may result in a measurement error of approximately 1 m/s. In contrast, a Hall effect sensor uses a magnet as an inductor to generate a pulse signal when a magnetic pole passes through a sensor installed on the wheel axis of a motorcycle. This makes it possible to calculate the speed of a motorcycle’s movement every second. The Hall effect provides high accuracy and can measure low speeds. A previous study [34] developed a Hall effect sensor with a 2.8% threshold of measurement error. Therefore, in this study, a Hall effect sensor was used to measure the instant speed of the test motorcycle.

The developed onboard measurement device consisted of six modules: a lidar sensor, Hall effect sensor, video camera, GPS, rechargeable Li-ion battery, and a microcontroller with memory storage. In this study, small and lightweight sensors were selected and assembled to avoid disturbing the motorcycle rider. The selected lidar model could take measurements over an angle of 180° from the front of the motorcycle. It could measure a distance within 4 m by capturing 400 samples per second. The Hall effect sensor was improved from that of previous studies [33, 35] to measure the instant speed per second of the test motorcycle with higher accuracy. Twenty-two steel pins were installed on the front wheel of the test motorcycle with a circumference of 1.73 m. The minimum speed that could be measured was 0.28 km/h. A GPS device was installed in front

| Authors | Driving behavior | Measuring device | Analytical method |
|---------|------------------|------------------|------------------|
| Walker  [22] | Drivers overtaking cyclists in the United Kingdom | Ultrasonic distance sensor installed on test bicycle | ANOVA |
| Love et al. [15] | Drivers overtaking cyclists | Laser distance sensor, video camera, and data logger installed on test bicycle | Hypothesis test (K–W test) |
| Chapman and Noyce [23] | Drivers overtaking cyclists on rural roads in the United States | Lidar, two cameras | Fever |
| Chuang et al. [19] | Cyclists’ behavior when motorists pass | Video camera installed on a test vehicle | Multiple linear regression |
| Llorca et al. [24] | Drivers overtaking cyclists on two-lane rural roads in Spain | Lidar, two cameras | Frequency |
| Dozza et al. [17] | Drivers overtaking cyclists | Video camera, GPS, and data logger installed in vehicles | ANOVA and multiple linear regression |
| Feng et al. [16] | Drivers overtaking cyclists | Ultrasonic distance sensor, video camera, and data logger | MANOVA and binary logistic regression |
| Ibrahim et al. [20] | Motorcycle riders overtaking in exclusive motorcycle lanes | Ultrasonic and video camera installed on test bicycle | Hierarchical linear model |
| Beck et al. [18] | Drivers passing cyclists | Video camera and GPS | Hypothesis test (t-test) |
| Lemonakis et al. [21] | Motorcycle riders riding on curved roads | Video camera and GPS | Hypothesis test (t-test) |
of the test motorcycle to record its position (updated at 10–18 Hz) and its speed for comparison with the speed measured by the Hall effect sensor. A video camera was installed in front of the test motorcycle to record a 140° circumstance of the test motorcycle. It was used to identify the condition and type of lateral vehicle. All measuring sensors and memory cards were controlled by a microcontroller, which converted all the measured data into a digital format and saved them on an SD memory card. The microcontroller was supplied with electrical power using rechargeable batteries. A working diagram is shown in Figure 2. Sensors were installed on the test motorcycle at various positions to avoid disturbing the riding behavior (Figure 3).

The sensors were validated further. The lidar sensor was validated to measure distances of 1, 2, 3, and 4 m by firing beams at flat objects according to previous studies [18]. The Hall effect sensor and GPS were validated to measure the speed at distances of 500 and 1,000 m with 10 riding tests, according to a previous study [35].

3.2. Selection of Test Motorcycle. This study selected the most popular motorcycle brand in Thailand as a test motorcycle. The number of registered motorcycles in Thailand and Khon Kaen Province for the past 5 years is presented by brand and engine size in Table 2. Honda motorcycles with 101–125 cc engine sizes are the most popular brand, accounting for approximately 75% of the market [36]. Therefore, this study selected a Honda motorcycle, the Wave Model, as the test motorcycle. Its engine size was 110 cc, and its dimensions were W: 709 mm, L: 1,919 mm, and H: 1,080 mm.

3.3. Selection of Study Intersection. We selected the signalized intersection at Khon Kaen University (KKU) as the study area. The KKU is located in Khon Kaen province in the northeastern region of Thailand. Currently, more than 60,000 students and staff travel to this university, and its size and population are as high as those of a middle city. More than half of the students travel by motorcycle. The intersection considered in this study was a three-leg signalized urban intersection with a 30 m crossing distance. The mixed traffic volumes, including motorcycles, passenger cars, trucks, and buses, are depicted in Figure 4. The eastbound approach of this intersection was selected for the study because it has a relatively high proportion of motorcycles traveling with other large vehicles. This approach has two lanes with a width of 3 m, which is the typical lane width of a general signalized urban intersection. The length of the considered segment was 100 m from the stop bar, which is the maximum queen length of this approach. The layout of the study approach is shown in Figure 5.

3.4. Data Collection. The developed onboard measurement device was installed on the test motorcycle to collect the lateral clearance, riding behavior, and surrounding traffic conditions per second. In this study, 30 participants (50% female) were asked to ride the test motorcycle, similar to that in previous studies [20, 37]. KKU students were recruited as participating riders. The criteria were that they must own motorcycles with 101–125 cc engines and have a riding license for at least 2 years to exclude inexperienced riders [20]. The average age of the riders was 21.5 years old, ranging from 20 to 23 years old. Their riding experience ranged from 3 to 7 years, with an average riding experience of 4.9 years. The riding frequency ranged from 4 to 7 days per week, with an average riding frequency of 5.6 days per week. The participants were requested to repeatedly ride the test motorcycle along the route in which the study intersection was located for 1 hour during the peak period.

Visual Basic was applied in Excel to clean and encode the raw data from the lidar sensor. Missing data and other irrelevant data, such as measured distances longer than 2 m (detecting vehicles or other objects far away from the lateral range of the test motorcycle), were removed from the analysis.

3.5. Data Analysis. This study investigated the relationship between the lateral clearance of the filtering motorcycle, that is, the dependent variable and independent variables such as riding behavior, surrounding traffic conditions, and demographic of motorcycle riders. Multivariate data analysis was used to predict changes in the dependent variable in response to changes in the independent variables. Many studies have applied multivariate dependence methods to analyze driving behavior. Kotagi et al. [38] developed a multiple linear regression model to predict the lateral distance and movement of vehicles on urban undivided roads with mixed traffic in India. Kadali et al. [39] developed a multiple linear regression model for the analysis of pedestrian gap acceptance behavior at mid-block crosswalks under mixed traffic conditions. Yasanthi and Mehran [40] developed a multiple linear regression model to study the factors affecting vehicle speed under unfavorable road and weather conditions. However, this study applied a more advanced dependent technique, multilevel linear regression, to account for unobserved heterogeneity across observed data, which is a possible and common source of bias [41].

This study focused on whether filtering lateral clearance varies among motorcycle riders. This study assumed whether the effects of filtering cases tend to compound at the rider level to influence the lateral clearance; that is, do both within-rider level and between-rider level variables influence lateral clearance? Therefore, this study developed a random-intercept model by adding predictors at Level 1 (within-rider level) and Level 2 (between-rider level), that is, the two-level model, to predict the filtering lateral clearance of motorcycle riders.

In this article, the lateral clearance $i$ of motorcycle rider $j$ (cm) ($Y_{ij}$) is expressed by the Level 1 equation:

$$Y_{ij} = \beta_{0j} + \beta_{1j}X_{ij} + \epsilon_{ij},$$

where $\beta_{0j}$ is the intercept or the mean of the lateral clearance for the $j$th motorcycle rider, $X_{ij}$ is the vector of within-rider predictors at Level 1, $\beta_{1j}$ is the vector of the Level 1 fixed-effect coefficient or the vector of the unstandardized
Table 2: Number of registered motorcycles in Thailand.

| No. | Brand   | Engine size (cc) | Khon Kean   | Thailand       |
|-----|---------|------------------|-------------|----------------|
| 1   | HONDA   | 101–125          | 331,998 (76.9%) | 15,520,326 (75.9%) |
| 2   | YAMAHA  | 101–125          | 79,480 (18.4%)  | 3,730,557 (18.3%)  |
| 3   | SUZUKI  | 101–125          | 11,258 (2.6%)   | 748,223 (3.7%)    |
| 4   | KAWASAKI| Up to 151        | 6,468 (1.5%)    | 335,656 (1.6%)    |
| 5   | GPX     | Up to 151        | 2,678 (0.6%)    | 101,298 (0.5%)    |
coefficient, and $\varepsilon_{ij}$ represents the error in estimating the lateral clearance of motorcycle riders.

The variation in the intercept ($\beta_{0j}$) is expressed by adding the vector of the between-rider predictors ($W_j$) into the Level 2 equation:

$$\beta_{0j} = \gamma_{00} + \gamma_{01}W_j + \mu_{0j},$$

where $\gamma_{00}$ is the rider-level intercept, $\mu_{0j}$ is the vector of the Level 2 random effect, or the vector of a random parameter capturing the variation in individual rider means, and $\gamma_{01}$ is a Level 2 fixed-effect coefficient.

The within-rider slope ($\beta_{1j}$) is specified as being fixed, that is, it does not vary across riders, and can be expressed by the Level 2 slope equation:
By substituting the Level 2 intercept equation (2) and Level 2 slope equation (3) into the level 1 equation (1), the mixed model is obtained:

\[ Y_{ij} = \beta_{00} + \beta_{01} W_j + \beta_{10} X_{ij} + \mu_{0j} + \epsilon_{ij}. \]  

The variables considered as predictors in the analysis are listed and described in Table 3. The variables were categorized as (1) riding behavior, including the instant speed and side of the filtering motorcycle, (2) surrounding traffic conditions, including the condition of the lateral vehicle and the type of lateral vehicle, and (3) demographic of riders, including gender, age, riding experience, and riding frequency. The instant speed of the filtering motorcycle, age, riding experience, and riding frequency was the continuous variables. In addition, the side of the filtering motorcycle, condition of the lateral vehicle, type of lateral vehicle, and gender of the motorcycle rider were categorical variables.

In the process of multilevel regression analysis, this study applied the maximum likelihood (ML) to estimate the model parameters. This study began by incorporating all independent variables into the model. Subsequently, some variables were excluded from the model by considering their significant correlation with dependent and independent variables at a significance level of 0.05. Estimated variances were tested using the Wald Z test to determine whether there was a significant variation to be explained at Level 1 and Level 2 of the developed model. The intraclass correlation coefficient (ICC) was estimated to check the level of non-independence or the expected correlation between any two randomly selected filtering cases in the same rider.

### 4. Results and Discussion

#### 4.1. Validation Results for the Developed Onboard Measurement Device

The validation results of the lidar sensor for measuring distance are summarized in Table 4. The maximum difference between the referred and average measured distances was less than 20 mm. The differences in percentages were less than 2%. We can conclude that the lidar sensor of the developed onboard measurement device provided a highly accurate distance measurement.

| Table 3: Variable definition. |
|-------------------------------|
| **Variable**                  | **Description** | **Type** |
| Instant filtering speed       | Instant speed of filtering motorcycle (km/h) | Continuous variable |
| Side of filtering motorcycle  | Side of filtering motorcycle either right side or left side of filtering motorcycle | Categorical variable |
| Condition of lateral vehicle  | Condition of lateral vehicle either moving slowly or stopping | Categorical variable |
| Lateral motorcycle           | Type of lateral vehicle is motorcycle | Categorical variable |
| Lateral large vehicle         | Type of lateral vehicle is large vehicle (truck or bus) | Categorical variable |
| Gender                        | Gender of riders | Categorical variable |
| Age                           | Age of riders, year | Continuous variable |
| Riding experience             | Riding experience, year | Continuous variable |
| Riding frequency              | Frequency of motorcycle use, time per week | Continuous variable |

| Table 4: Validation results of lidar sensor for measuring distance. |
|--------------------------|
| **Number of measuring data** | **Referred distance (mm)** | **Average measured distance (mm)** | **Difference mm (%)** |
| 23,748                   | 1,000           | 1,019             | 19.21 (1.92%)    |
| 17,886                   | 2,000           | 2,004             | 4.45 (0.22%)     |
| 13,759                   | 3,000           | 2,991             | −9.17 (−0.31%)   |
| 8,814                    | 4,000           | 3,988             | −11.18 (−0.30%)  |

*Note.* Validation for a distance of 1–4 m with angles of 0° and 180°.

The variables considered as predictors in the analysis are listed and described in Table 3. The variables were categorized as (1) riding behavior, including the instant speed and side of the filtering motorcycle, (2) surrounding traffic conditions, including the condition of the lateral vehicle and the type of lateral vehicle, and (3) demographic of riders, including gender, age, riding experience, and riding frequency. The instant speed of the filtering motorcycle, age, riding experience, and riding frequency was the continuous variables. In addition, the side of the filtering motorcycle, condition of the lateral vehicle, type of lateral vehicle, and gender of the motorcycle rider were categorical variables.
the developed onboard measurement device achieved a high degree of accuracy in the speed measurements. Consequently, the lidar and Hall effect sensors achieved a high degree of accuracy in measuring the lateral clearance and instant filtering speed of the test motorcycle.

4.2. Results of Data Collection. Thirty participating riders rode the test motorcycle through the study intersection for a total of 96 km. The average distance traveled by each rider was 3.2 km. Nevertheless, the total distance traveled during lane filtering was 14.4 km. The average filtering distance traveled by each rider was 0.48 km. A total of 11,701 filtering cases were recorded.

The measurement results for the lateral clearance of the motorcycle riders are presented in Table 6. The average lateral clearance was 64.3 cm, which is significantly lower than the passing distance of drivers passing cyclists at intersections in Australia (182 cm) [18]. The minimum value was 53.0 cm and the maximum value was 76.3 cm. The standard deviation was 5.6 cm. The mean left lateral clearance was 82.3 cm, whereas the right lateral clearance was 63.2 cm.

Motorcycle riders filtered motorcycles, passenger cars, and large vehicles (i.e., trucks and buses) by 36.8%, 48.2%, and 15.0%, respectively. The average lateral clearances between the filtering motorcycle and lateral motorcycles, passenger cars, and large vehicles were 61.4, 71.0, and 104.0 cm, respectively.

Motorcycle riders filtered other stopping and moving lateral vehicles by 64.3% and 35.7%, respectively. The average lateral clearance between the filtering motorcycle and other stopping lateral vehicles was 65.8 cm, whereas the average lateral clearance between the filtering motorcycle and other moving vehicles was 85.6 cm. The percentages of filtering cases collected by gender, age, riding experience, and riding frequency of motorcycle riders are also presented in this table.

The measurement results for the filtering speed of the motorcycle riders are presented in Table 7. The average speeds of motorcycle riders filtering other motorcycles, passenger cars, and large vehicles were 13.3, 14.4, and 11.2 km/h, respectively. The average speeds of motorcycle riders filtering other stopping vehicles and moving vehicles were 13.0 and 14.4 km/h, respectively. The average filtering speed of motorcycle riders was 13 km/h, which is lower than the average speed of motorcycle riders filtering along urban roads in India (35 km/h) [27]. Moreover, the 85th percentile filtering speed was 17.4 km/h, which is lower than the speed limits of filtering lanes in other developed cities [6–8].

4.3. Results of Multilevel Linear Regression Analysis. Table 8 presents the results of the multilevel linear regression analysis. The developed model explains 70.2% of the variance in the dependent variable. The intraclass correlation coefficient (ICC) was 0.004 (ICC values >0.05 are often considered an indicator of a relevant amount of nonindependence) [41]. This means that clustering in the filtered data, that is, heterogeneity across the filtered data, was insignificant. Eleven predictors were significantly related to the lateral clearance of motorcycle riders, at a significance level of 0.05. There were nine fixed-effect predictors: the intercept, instant filtering speed, side of the filtering motorcycle, lateral vehicle, lateral motorcycle, lateral large vehicle, riding frequency, mean instant speed of the filtering motorcycle, and...
mean large vehicle. There were two covariance predictors: the residual (residual variance) and the intercept (rider variance).

At Level 1 (within-rider level), the instant filtering speed, side of the filtering motorcycle, condition of lateral vehicle, lateral motorcycle, lateral large vehicle, and riding frequency of motorcycle riders were significant predictors of lateral clearance.

The coefficient of instant filtering speed was positive. This means that when the speed of filtering motorcycles increased, the lateral clearance of motorcycles increased. This finding was consistent with that of previous studies. The passing distance is positively related to the speed of vehicles overtaking bicycles on rural roads in Spain [24]. The comfort of motorcycle riders during filtering on urban roads in India depends on the speed of motorcycles [27].

The coefficient of the side of the filtering motorcycle (1 = right side of the filtering motorcycle, 0 = left side of the filtering motorcycle) was negative. This means that the right lateral clearance of the filtering motorcycle was less than that of the left lateral clearance when other influencing predictors were constant. This finding was consistent with a previous study in which the comfort of motorcycle riders during filtering on urban roads depends on the presence of a surrounding right-hand vehicle [27]. Motorcycle riders normally use the right handle grip as a reference to check the right lateral clearance.

The coefficient of the condition of the lateral vehicle (1 = lateral vehicle moving, 0 = lateral vehicle stopping) was positive. This means that the lateral clearance of the

| Variable | Filtering cases (N) | Lateral clearance (cm) |
|----------|---------------------|-----------------------|
|          |                     | Mean | Min | Max | SD  |
| Lateral distance by range (cm) | | | | | |
| 0–25     | 1,002               | 8.6  | 18.5| 14.4| 2.2 |
| 26–50    | 1,878               | 16.0 | 42.5| 25.1| 5.0 |
| 51–75    | 3,147               | 26.9 | 62.1| 50.1| 7.5 |
| 76–100   | 2,991               | 25.6 | 85.7| 75.1| 7.1 |
| >100     | 2,683               | 22.9 | 112.5| 100.1| 6.6 |
| Lateral distance by side of filtering test motorcycle | | | | | |
| Left-hand side | 5,882 | 50.3 | 82.3| 15.1| 131.4 |
| Right-hand side | 5,819 | 49.7 | 63.2| 14.4| 118.6 |
| Lateral distance by type of lateral vehicle | | | | | |
| Motorcycle | 4,303 | 36.8 | 64.1| 14.4| 131.5 |
| Passenger car | 5,642 | 48.2 | 81.0| 14.9| 131.4 |
| Large vehicle | 1,756 | 15.0 | 104.0| 69.8| 131.2 |
| Lateral distance by traffic condition | | | | | |
| Traffic stopping | 7,529 | 64.3 | 65.8| 14.4| 131.4 |
| Traffic moving | 4,172 | 35.7 | 85.6| 44.1| 131.1 |
| Gender | | | | | |
| Male | 5,913 | 50.5 | 73.1| 14.4| 132.4 |
| Female | 5,788 | 49.5 | 74.9| 14.5| 132.6 |
| Age (year) | | | | | |
| 20 | 2,963 | 25.3 | 72.8| 14.5| 130.8 |
| 21 | 2,910 | 24.9 | 73.1| 14.4| 131.1 |
| 22 | 2,913 | 24.9 | 73.3| 14.7| 131.2 |
| 23 | 2,915 | 24.9 | 72.8| 14.4| 131.4 |
| Riding experience (year) | | | | | |
| 3 | 1,383 | 11.8 | 98.0| 75.1| 131.1 |
| 4 | 2,896 | 24.8 | 77.0| 25.3| 131.1 |
| 5 | 3,327 | 28.4 | 70.4| 14.5| 131.4 |
| 6 | 3,311 | 28.3 | 70.7| 14.4| 130.5 |
| 7 | 784 | 6.7 | 32.6| 14.7| 49.9 |
| Riding frequency (day per week) | | | | | |
| 4 | 2,267 | 19.4 | 85.3| 50.0| 131.0 |
| 5 | 3,247 | 27.8 | 69.4| 14.4| 130.8 |
| 6 | 3,256 | 27.8 | 70.4| 14.4| 131.1 |
| 7 | 2,931 | 25.0 | 69.7| 14.7| 131.4 |
| Average | 11,701 | 100.0 | 64.3| 53.0| 76.3 |

Table 7: Measurement results of lateral clearance.

| Variable | Filtering cases (N) | Lateral clearance (cm) |
|----------|---------------------|-----------------------|
|          |                     | Mean | Min | Max | SD  |
| Lane-filtering speed (km/h) | | | | | |
| Average | 13.3 | 7.2 | 20.0| 17.0| 2.7 |
| Motorcycle | 14.4 | 8.0 | 22.0| 17.1| 3.6 |
| Passenger car | 11.2 | 7.0 | 17.8| 18.2| 2.7 |
| Normal | 13.0 | 7.1 | 22.0| 17.1| 3.3 |
| Average | 14.4 | 7.0 | 21.0| 17.4| 3.2 |
| Lateral distance by range (cm) | | | | | |
| 0–25 | 1,002 | 8.6 | 18.5| 14.4| 2.2 |
| 26–50 | 1,878 | 16.0 | 42.5| 25.1| 5.0 |
| 51–75 | 3,147 | 26.9 | 62.1| 50.1| 7.5 |
| 76–100 | 2,991 | 25.6 | 85.7| 75.1| 7.1 |
| >100 | 2,683 | 22.9 | 112.5| 100.1| 6.6 |

Table 8: Results of multilevel linear regression analysis.
motorcycle filtering the moving lateral vehicle was higher than that of filtering the stopping lateral vehicle when the other influencing predictors were constant. Motorcycle riders perceived a lower risk while they were filtering beside stopping lateral vehicles.

The coefficient of the lateral motorcycle (1 = type of lateral vehicle is motorcycle, 0 = other vehicle types, including passenger cars and large vehicles) was negative, but the coefficient of the lateral large vehicle (1 = type of lateral vehicle is large vehicle, 0 = other vehicle types, including motorcycle and passenger car) was positive. This means that if the lateral vehicle was a motorcycle, the lateral clearance would be lower than that of other larger vehicles when the other influencing predictors were constant. In contrast, the lateral vehicle was large vehicle, for example, truck or bus, and the lateral clearance was higher than that of other smaller vehicles when other influencing predictors were constant. These findings were consistent with those of previous studies on drivers’ behavior while overtaking bicycles. Overtaking heavy vehicles increases the passing distance on rural roads in Spain [24] and the United States [23]. Motorcycle riders intended to move out of their current lane if they were following a heavy vehicle when they maneuvered in a queue at signalized intersections in Vietnam [5]. This caused a risk perception of vulnerable road users, that is, bicyclists and motorcyclists, when they traveled in mixed traffic.

The coefficient of riding frequency was negative. This means that motorcycle riders who rode the motorcycle more often had a lower lateral clearance.

At level 2 (between-rider level), the mean instant filtering speed and mean lateral large vehicle were positive and significant predictors of lateral clearance. This result indicated that motorcycle riders with higher average filtering speeds had longer lateral clearances. Motorcycle riders with higher average filtering of large vehicles had longer lateral clearances.

The residual variance, which reflects the variation in residual, in the lateral clearance was 259.142. The rider variance, which reflects the variation in intercepts, in the lateral clearance was 1.148. Based on the results of the Wald Z test, the residual variance was statistically significant, but the rider variance was not statistically significant. This may be considered as evidence of no clustering effects in the data, that is, a low level of nonindependence.

5. Conclusions and Recommendations

The aim of this study was to determine the factors affecting the lateral clearance of motorcycle riders when filtering between two lanes at a signalized urban intersection. An onboard measurement device was developed and installed on a test motorcycle to collect the lateral clearance, riding behavior, and surrounding traffic conditions every second. Thirty participants rode the test motorcycle through the studied signalized urban intersection. Multilevel linear regression was applied to analyze the relationship between the lateral clearance of the filtering motorcycle and the influencing variables at a significance level of 0.05. The developed model could account for unobserved heterogeneity across the observed filtering data. The model information criteria implied that unobserved heterogeneity across the filtering data was insignificant.

This study observed that the factors influencing the lateral clearance of motorcycles filtering a lane at a signalized urban intersection were the instant filtering speed, side of the filtering motorcycle, condition of the lateral vehicle, type of lateral vehicle, and riding frequency of the motorcycle riders. The findings of this study can contribute to mixed traffic management at signalized urban intersections, for instance, the design of a filtering lane, including pavement markings for filtering lanes and speed limit/speed warning signs for filtering motorcycles. This filtering lane is used by motorcycle riders to penetrate a queue and stop at an advanced stop line at signalized intersections. The filtering lane channelizes motorcycle riders to penetrate the queue in a discipline lane, where other road users can expect their trajectory and are aware of a potential conflict with motorcycles. Moreover, the findings can support connected autonomous vehicles [42] for controlling autonomous motorcycles and microscopic traffic simulations when motorcycles filter lanes in mixed traffic at signalized urban intersections.

This study was limited by the fact that the developed onboard measurement device was installed on a single test motorcycle. Thirty motorcycle riders were requested to ride on a test motorcycle. They may have been ridden slightly more carefully than usual since they were unfamiliar with the test motorcycle. Future research should design an onboard measurement device that can be installed on the motorcycles of the participants without requiring any modifications. This approach can capture the more natural riding behavior of motorcycle riders. For real-world data collection, more participants with diverse demographics and other types of motorcycles, such as higher or lower internal combustion engine motorcycles or electric motorcycles, can be included. Furthermore, as participants ride motorcycles between their homes and destinations, data from additional signalized intersections with varying traffic conditions and mixed traffic characteristics can be obtained more easily. The research should be extended in the future to investigate motorcycle lane filtering in rural signalized intersections, where there are no roadside pedestrians or parking vehicles, and filtering a lane adjacent to the curb may be safe. In addition, the accident or conflict of motorcycle filtering between two lanes at a signalized urban intersection should be further investigated to develop a safer road for vulnerable road users according to a safe system approach.

Data Availability

The datasets are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
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