Evaluation of Spatial Motorcycle Segregation at Isolated Signalized Intersections Considering Traffic Flow Conditions

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Abstract: In Southeast Asia, motorcycles constitute a substantial portion of road traffic. Thus, a passenger-car-oriented traffic control system cannot operate effectively, and traffic efficiency is decreased. To achieve a sustainable and environmentally friendly society, a traffic control system suitable for mixed traffic including motorcycles is highly necessary. Although some traffic policies targeting motorcycles have been implemented, the criteria for implementing them are still unclear. Indeed, the characteristics of motorcycle-dominant traffic flow are not well understood. Thus, this study attempts to qualify the effect of motorcycle-oriented traffic operations and find the criteria for implementing them on the basis of detailed investigations of mixed traffic flow with motorcycles in various cities with differing traffic conditions. The results show that (1) unclear definition of traffic lanes may severely decrease the efficiency of traffic flow and (2) the most effective traffic scheme varies with traffic conditions.

Key Words: mixed traffic flow with motorcycles, traffic capacity, signalized intersection

1. INTRODUCTION

It is evident that the proportion of motorcycles in the traffic flow in many Asian countries is higher than that in the developed countries in Asia. For example, in Thailand, where the economic conditions improved during the 1990s, motorcycles are widely used as a reasonable mode of transportation, considering the vehicle, maintenance, and other costs of passenger cars; moreover, motorcycles are not influenced by the impact of traffic congestion in Bangkok. Therefore, due to the above-mentioned and other similar reasons, the number of motorcycles in Asian cities has increased and the situation of motorcycle-dominant traffic flow has been realized. However, the current traffic control strategy mainly focuses on the traffic flow of passenger cars so that the control of signalized intersections can be considered relatively ineffective in such motorcycle-dominant situation. Therefore, it is necessary to suggest an effective strategy for mixed traffic flow conditions. For example, measures such as setting a waiting area for motorcycles while the signal is red or preparing a motorcycle lane, which have already been implemented in several countries (Hsu, 2004), should be considered according to the proportion of motorcycle traffic or the amount of traffic demand. A manual of these measures has been proposed (Cuong, 2009), but the criteria for implementing these measures should also be clarified according to the characteristics of traffic flow for several levels of motorcycle traffic.

To suggest a suitable traffic control strategy for mixed traffic flow with motorcycles, this study first compares the relationship between the number of motorcycles and passenger cars...
under saturation flow in two types of cities (motorized cities and motorizing cities) in terms of traffic efficiency and identifies the factors causing inefficient traffic flow. Then, by establishing a method of estimating traffic capacity at isolated signalized intersections, where traffic flow is assumed not to be influenced by any other intersections, considering the proportion of motorcycles, intersection configuration, and traffic situation, the most suitable traffic operation for each city will be discussed in terms of implementation.

2. LITERATURE REVIEW

In developed countries, the effect of motorcycles on traffic flow is not given sufficient attention. For example, the Highway Capacity Manual 2000 considers the following adjustment factors that affect the saturated flow rate: lane width, heavy vehicles, approach grade, existence of a parking lane and parking activity, blocking effect of local busses that stop within intersection area, area type, lane use, left and right turns in lane groups, pedestrians, and bicyclists; motorcycles are not considered. In the Japanese handbook of traffic engineering (Kotsu Kogaku Handbook), only a passenger car equivalent (PCE) value for motorcycles was determined. On the other hand, in developing countries, some studies of mixed traffic flow with motorcycles have been reported. These studies generally consider one of two subjects: modeling motorcycle behavior or traffic operation for mixed traffic flow. Hereafter, the literature related to these two subjects is summarized.

2.1 Modeling Motorcycle Behavior

Matsuhashi et al. (2005) investigated the motorcycle speed distribution in Ho Chi Minh City, Vietnam using video image data. Then, the mixed traffic flow was represented by the traffic simulation software VISSIM. Meng et al. (2007) adopted a single-lane cellular automaton model to describe mixed traffic flow. By performing numerical simulations under a periodic boundary condition, some density-flow relations and the lane-changing behavior of motorcycles were investigated in detail. The following findings were obtained: (i) the maximum car flow decreased because of the lane-changing behavior of motorcycles and (ii) with increasing motorcycle density, the lane-changing rate first increases and later decreases. These studies treated motorcycles simply as small passenger cars, i.e., characteristics specific to motorcycles were not considered. In particular, they assumed that cars and motorcycles are randomly distributed on the target roadway section. In reality, however, motorcycles are stacked near the stop lines of signalized intersections during red intervals. Thus, motorcycle platoons are formed owing to this stacking phenomenon and their maneuvering characteristics should be considered.

Powell (2000) focused on the number of QFLIERS, defined as motorcycles that set off from the front of the queue before the end of the first 6 s of effective green time, and derived a model that describes motorcycle behavior at signalized intersections. In particular, an amended first-order macroscopic model was used to represent motorcycle behavior, and multiple regression analysis explained inaccuracies resulting from this technique, which included storage space at the front of the queue. This study, however, did not describe in detail the behavior of motorcycles after the light turned green. Minh et al. (2005a) investigated motorcycle traffic flow characteristics in terms of speed, flow, and headway by adopting the motorcycle equivalent unit (MEU). In this study, the criteria for the motorcycle ratio beyond which the MEU was more suitable than passenger car units were not mentioned. Minh et al. (2005b, 2006) also microscopically investigated motorcycle maneuvers such as passing, paired riding, deceleration, and following. These results must be useful for developing a
microscopic simulation model for mixed traffic flow with motorcycles. To complete the simulation model, the interactions between motorcycles and other transportation modes such as passenger cars, busses, and trucks should be investigated further. Nakatsuji et al. (2001) divided all effects of motorcycles on passenger cars into two types; one was start-up loss time and the other involved the saturation flow rate. The factors influencing these inefficiencies, such as position relative to passenger cars and the number of rows formed by motorcycles lined up behind the stop line, were examined. Moreover, Nguyen et al. (2007) examined the saturation flow rate of mixed traffic flow with motorcycles. It revealed that saturation flow rate varied depending on the width of approach, turning radii and proportion of tuners but remained constant during the saturated time. It is considered that the influential factors are significantly affected by the motorcycle ratio, characteristics of intersections such as signal control and lane configuration. In these studies, however, these factors were not considered. It is also considered that the saturation flow varies depending on traffic situation and the degree of motorization.

2.2 Traffic Operations for Mixed Traffic

Hsu et al. (2003) found that segregation schemes are effective for managing mixed traffic flow on the basis of the comparison among Taiwan, Malaysia, and Vietnam. In particular, schemes for time segregation and spatial segregation, which is further classified into driving space segregation and waiting space segregation at intersections, were introduced. Regarding motorcycle lanes, Minh et al. (2005b) demonstrated through a field survey that the average speed of motorcycles in a motorcycle exclusive lane was higher than that of motorcycles moving in a lane where passenger cars and motorcycles are mixed.

Yoshii et al. (2004) developed a method for estimating the traffic capacity of intersections considering traffic segregation schemes. In that study, intersection configurations are classified into three types: (i) basic, (ii) those that provide a waiting area for motorcycles, and (iii) those that provide a motorcycle exclusive lane. A method of estimating the traffic capacity for each type of intersection was established, and the study concluded that the most efficient intersection configuration varies with the motorcycle ratio. However, traffic flow data were mainly obtained in Bangkok, where the proportion of motorcycles in traffic flow was relatively low, around 0.3–0.4, and motorcycle dominance was not well considered. Moreover, although it was assumed that motorcycle lane width was changeable depending on the proportion of motorcycles, in reality, lane configuration cannot be changed that often, which should be carefully considered in any implementation.

2.3 Viewpoints of This Study

The present study focuses on two types of cities: developed cities such as Taipei and Bangkok, where road infrastructure (e.g., lane markings, motorcycle-oriented intersection configurations) are well provided, and developing cities, such as Hanoi and Phnom Penh, where lane markings on road surfaces are unclear and traffic rules are likely to be broken. It is conjectured that traffic characteristics and efficiency completely differ between these two types of cities, and the most effective traffic operation scheme may also differ according to the traffic situation. Thus, this study will first investigate the factors causing inefficient traffic flow by comparing the two types of cities in terms of traffic efficiency. Next, by establishing a method of estimating traffic capacity at signalized intersections according to the proportion of motorcycles, intersection configuration, and traffic situation, the most suitable traffic operation schemes for each city will be discussed in terms of implementation.
3. DATA COLLECTION

To collect data on saturated conditions in a mixed traffic situation, a survey for measuring traffic flows was conducted. The criteria for selecting intersections are as follows: (i) traffic flow can be measured by a video camera from an elevated place (ii) traffic can be measured in a saturated but not oversaturated condition, (iii) there are no facilities that can block traffic flow, such as bus stops, upstream or downstream of the intersection and (iv) a width of a subject approach is approximately 9 m for 3 lanes. Five intersections in four Asian countries that meet these criteria were selected.

(1) ChengDe Rd. and DunHuang Rd. Intersection (North Approach), Taipei, Taiwan
The intersection of ChengDe Rd. and DunHuang Rd. (hereafter, “Taipei 1”) is located north of the city center of Taipei City, and the subject approach in the intersection comprises four lanes, including a motorcycle exclusive lane that is the second lane counted from the outside. The study focused on the first three lanes counted from the inside as the subject approach. A video camera was set on a pedestrian bridge on the south side of the intersection. Traffic flow was surveyed for about one hour (16:40–17:30) on March 18, 2009. Figure 1 shows a sketch of the intersection and a photograph of the subject approach; the sketch also shows the signal phases and their split time. The motorcycle ratio of the subject approach was around 87.2% during the survey.

(2) Xing Yi Rd. and Jiron Rd. Intersection (East Approach), Taipei, Taiwan
The intersection of Xing Yi Rd. and Jiron Rd. (hereafter, “Taipei 2”) is located on the east side of Taipei City, and the subject approach comprises three lanes; a waiting area for motorcycles appears both in front of and behind the stop line. Motorcycles are stacked in the waiting area during signal phase 1, as shown in Figure 2, according to the guidance of police officers. Traffic flow here was measured for one hour (08:00–09:00) on March 19, 2009. Figure 2 shows a sketch of the intersection, including signal phases and their split time, and a photograph of the subject approach. Motorcycles are clearly waiting in the area in front of the stop line for other vehicles. The motorcycle ratio of the subject approach was around 66.0% during the survey.
(3) Rama I Rd. and Phaya Thai Rd. Intersection (East Approach), Bangkok, Thailand
The intersection of Rama I Rd. and Phaya Thai Rd. (hereafter, “Bangkok”) is located close to the MBK center in the city center of Bangkok. Westbound traffic flow at the intersection was observed on September 16, 2003 from 7:00 a.m. to 9:00 a.m., from 11:00 a.m. to 1:00 p.m., and from 3:00 p.m. to 6:00 p.m. The motorcycle ratio of the subject approach was around 30.8% during the survey. Figure 3 shows a sketch of the intersection, including signal phases and their split time, and a photograph of the subject approach.

(4) Daewoo Intersection (East Approach), Hanoi, Vietnam
The Daewoo Intersection (hereafter, “Hanoi”) is located on the northwestern side of the city center of Hanoi City. In the intersection, the divided lines for each lane were not clearly indicated. A video camera was set on the 16th floor of the Daeha Business Center. Traffic flow was measured for one hour (09:00–10:00) on September 29, 2009. Figure 4 shows a sketch of the intersection, including signal phases and their split time, and a photograph of the subject approach. The motorcycle ratio of the subject approach was around 83.4% during the survey. The lanes for the subject approach were not clearly defined; therefore, this study analyzed the vehicles passing through an area 9 m wide from the outside, corresponding to the width of three lanes.
The intersection of Blvd. Mao Tse Toung and Blvd. Preach Norodom (hereafter, “Phnom Penh”) is located on the southeast side of the city center of Phnom Penh. Traffic flow at the intersection was measured on September 18, 2003 from 8:00 a.m. to 9:00 a.m. The motorcycle ratio of the subject approach was around 71.2% during the survey. The lanes for the subject approach were also not clearly defined; therefore, this study analyzed the vehicles passing through an area 9–10 m wide, corresponding to the width of three lanes. Figure 5 shows a sketch of the intersection, including signal timing and their split time, and a photograph of the subject approach.

4. ANALYSIS OF SATURATION FLOW RATE FOR MIXED TRAFFIC

4.1 Concept
In this section, the saturation flow rate under mixed traffic conditions is analyzed for the five intersections described in the previous section. Generally, the saturation flow rate is defined by the number of representative vehicles. If the representative vehicle is a passenger car, all other types of vehicles are converted to the equivalent number of passenger cars, and the saturation flow rate is measured in passenger car units (PCUs). If the representative vehicle is
a motorcycle, a motorcycle unit (MCU) is used for measuring the saturation flow rate (Minh et al. 2005a). However, it is naturally considered that when motorcycles dominate, the PCU is not a suitable unit, and also when passenger cars dominate, the MCU should be a meaningless unit. Thus, the criteria for using PCU and MCU are unclear, and this way of measuring saturation flow is unsuitable for comparing the efficiency of several types of traffic flow. Therefore, in this study, the saturation flow rate is evaluated by the vector of the number of motorcycles, $s_{mc}$, and the number of passenger cars, $s_{pc}$, crossing a stop line during a certain time period. In this case, when the proportion of motorcycles is the same, the distance from the origin, $\sqrt{s_{mc}^2 + s_{pc}^2}$, indicates the efficiency of the traffic flow. In this way, the saturation flow of the approaches will be compared.

4.2 Definition of Saturation Flow Rate
To obtain the saturation flow rate of each approach, saturation flow is defined as the situation where all the following conditions are satisfied:

(i) To consider the start-up loss time, the traffic flow starting 10 s after the signal turns green is targeted, which can be validated by Hsu (2004).

(ii) All subject lanes in the approach have sufficient traffic demand from the upstream section.

(iii) Traffic flow is not obstructed by vehicles turning left or right, pedestrians, or any other factors.

The number of motorcycles, passenger cars, and large vehicles passing through the stop line every 10 s was counted; a large vehicle is assumed to be equivalent to 1.7 PCU.

4.3 Comparison of Saturation Flow Rate under Mixed Traffic Condition
Figure 6 illustrates the relationship between the number of motorcycles and the number of passenger cars at each approach, Taipei 1, Taipei 2, Bangkok, Hanoi, and Phnom Penh, under saturation flow. The horizontal axis indicates the number of motorcycles and the vertical axis indicates the PCU value for the same time period. As the number of motorcycles increases, the PCU value tends to decrease. In addition, compared with Taipei and Bangkok, the scatter plots for Hanoi and Phnom Penh tend toward lower PCU values. This implies that the saturation flow rate in Hanoi and Phnom Penh can contain far fewer passenger cars than that in Taipei and Bangkok, although the number of motorcycles is almost the same. This tendency is also clearly confirmed by the relationship between the motorcycle ratio, which is defined as the proportion of motorcycles during 10 s, and the number of passenger cars, shown in Figure 7. Focusing on a motorcycle ratio of around 0.6 to 0.8, in Taipei and Bangkok, the number of passenger cars is distributed between 8 and 12 [pcu/10 sec/approach], whereas in Hanoi and Phnom Penh, it is distributed below 8 [pcu/10 sec/approach].

To validate the significance of this tendency, linear discriminant analysis is applied to the data set. All the scatter plots are divided into two groups: Taipei and Bangkok (hereafter, the motorized group), and Hanoi and Phnom Penh (hereafter, the motorizing group), and the Wilks’ lambda and linear discriminant function are estimated, as summarized in Table 1. The Wilks’ lambda turns to be significant, and the hit ratio is sufficiently high, which indicates that the distribution areas of the scatter plots for motorizing and motorized cities are significantly different. In Figure 8, the discriminant function is included in the scatter plots of the motorized and motorizing groups. Assuming a linear relationship between the number of motorcycles and passenger cars in each group, it can be seen that the gradient to the number
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Figure 6 Scatter plot of number of motorcycles passenger cars in saturation flow

Figure 7 Relationship between and motorcycle ratio and number of passenger cars

Table 1 Results of Discriminant Analysis

| (i) Statistics of Wilks’ Lambda |
|---|---|---|---|---|---|
| df1 | df2 | Wilks Lambda | F | P-value | Correct Rate |
| 1 | 322 | 0.277 | 420.8 | 0.00 | 0.945 |

| (ii) Linear Discriminant Function |
|---|---|---|---|---|
| Linear Discriminant Function | Coef. | F | P-value |
| Motorcycles | 0.09 | 12.47 | 0.00 |
| Passenger cars | 1.74 | 554.24 | 0.00 |
| Const. | -17.93 | |

| (iii) Prediction Results |
|---|---|---|---|
| Original | Motorized | Motorizing |
| Motorized | 147 | 14 |
| Motorizing | 4 | 160 |

Hit ratio: 94.5 %
of motorcycles is larger in the motorized group than in the motorizing group. In other words, in the motorizing group, the number of passenger cars does not change as much with increasing number of motorcycles. This implies that passenger car flow in the motorizing situation is so inefficient that sufficient room exists for motorcycles to mix into the passenger car flow.

4.4 Difference in Traffic Flow Characteristics

Negligence of road maintenance may be one reason that traffic flow in motorizing cities becomes severely inefficient. In fact, in both Hanoi and Phnom Penh, the lane markings were almost worn off, and the definition of each lane was unclear. Therefore, traffic flow tends to be disturbed, and as a result, the efficiency of traffic flow may decrease. On the other hand, in motorized cities, lane markings are clearly indicated, and the role of each lane is well defined. Thus, traffic flows uniformly, and as a result traffic efficiency may increase.

To validate this hypothesis, the distribution of vehicle positions when crossing the stop line is analyzed. From the data for Taipei 2 and Hanoi, some signal cycles were chosen to analyze the distribution. The data for 80 passenger cars and 198 motorcycles in Taipei 2 and 49 passenger cars and 234 motorcycles in Hanoi were obtained. The histogram of the position of each vehicle’s left tire is shown in Figure 9. For passenger cars, in both approaches three peaks appear, indicating the existence of three lanes. By comparing the distribution, it can be seen that in Taipei 2, the variance of the distribution within each lane is smaller than that in Hanoi, whereas the distances between each peak is wider than that in Hanoi, or rather, the distances in Hanoi are narrow. This may be caused by the worn-off lane markings and unclear definition of lanes. Namely, because the traffic streams of the lanes are close to each other in Hanoi, traffic flow on a lane is affected negatively by the next lane, which might cause inefficient traffic flow.

![Figure 9 Distribution of vertical position on stop line](image_url)

In Taipei 2, motorcycles are mainly distributed on the outer and middle lanes and tend to pass a point where passenger cars do not pass frequently. On the other hand, in Hanoi, motorcycles are distributed all over the approach. In particular, the proportion using the inner lane is much higher than that in Taipei 2. Figure 10 shows the ratio of motorcycles to other vehicles passing through each position. In Hanoi, the ratio of motorcycles is higher for all positions than in Taipei 2. By appearing all over the approach, motorcycles may disturb the passenger car traffic flow. In Taipei 2, where lane use is mixed, motorcycles and passenger cars are naturally segregated, and consequently efficient traffic flow can be achieved. Although more detailed investigation is required, the results suggest that it is possible to improve the efficiency of traffic flow in motorizing cities by clearly marking the lanes and the purpose of each lane.
5. EVALUATION OF SPATIAL SEGREGATION SCHEMES

This section establishes a method of estimating the capacity of a specific approach in signalized intersections at which spatial segregation schemes are implemented. Then, each scheme is evaluated quantitatively, and an optimal policy for improving traffic efficiency is suggested.

5.1 Establishment of Traffic Capacity Estimation Method

As in Section 4.1, in this study the traffic capacity is evaluated by a vector, $Q$, consisting of the capacity for motorcycles, $q_{mc}$ [veh/approach/hour], and that for passenger cars, $q_{pc}$ [pcu/approach/hour]. Here, traffic capacity is defined as the maximum volume that can cross a stop line during one hour of effective green time, given the signal parameters. Under the definition of traffic capacity, the efficiency of an approach is evaluated by the norm of $Q = (q_{mc}, q_{pc}), \|Q\| = \sqrt{q_{mc}^2 + q_{pc}^2}$, given the motorcycle ratio. The larger $\|Q\|$ is, the more efficient is the approach under the same motorcycle ratio. Based on the results in the previous section, the number of motorcycles and the number of passenger cars in saturated flow are assumed to have a linear relationship in approaches in both motorized and motorizing cities. Supposing that all subject approaches are composed of $N$ straight-through lanes and the total width is $L$ [m], the method of estimating traffic capacity is established in relation to the motorcycle ratio for each intersection configuration: (i) basic type, (ii) that with a motorcycle exclusive lane, and (iii) that with a waiting area for motorcycles. Important variables are defined as follows.

$C$: signal cycle time [sec],
$g$: split of effective green time,
$\rho$: motorcycle ratio ($\rho = q_{mc}/(q_{pc} + q_{mc})$),
$s_{pc}(\rho)$: saturation flow rate of passenger cars given motorcycle ratio $\rho$,
$s_{mc}(\rho)$: saturation flow rate of motorcycles given motorcycle ratio $\rho$,
$p_{\text{max}}^{\text{MED}}$ : maximum flow rate of passenger cars in motorized intersections [pcu/lane/hour],
$p_{\text{max}}^{\text{MING}}$ : maximum flow rate of passenger cars in motorizing intersections [pcu/lane/hour],
$\alpha^{\text{MED}}$ : parameter describing the relationship between $s_{pc}$ and $s_{mc}$ in motorized intersections ($s_{pc} = \alpha^{\text{MED}} s_{mc} + p_{\text{max}}^{\text{MED}}$),
$\alpha^{\text{MING}}$ : parameter describing the relationship between $s_{pc}$ and $s_{mc}$ in motorizing
intersections \( s_{pc} = \alpha^{\text{MING}} s_{mc} + M = M_{\text{max}} \), and
\[ m_{\text{max}} : \text{maximum flow rate of motorcycles [veh/m/hour].} \]

5.1.1 Basic type
In this type of intersection (shown in Figure 11), all motorcycles are assumed to drive mixed with passenger cars. Given a linear relationship between \( s_{pc} \) and \( s_{mc} \), the relationship between \( q_{pc} \) and \( q_{mc} \) can be considered as linear. Thus, the traffic capacity at motorcycle ratio \( \rho \) can be illustrated as an intersection point in Figure 12, where the line representing the linear relationship between the number of motorcycles and the number of passenger cars during the effective green time \( g \) [hour] is crossed by a dotted line indicating the proportion of motorcycles. Thus, the traffic capacity vector of the approach, \( Q_{\text{basic}} \), is expressed as shown in Eq. (1).

\[
Q_{\text{basic}}^i = \left( g \cdot \rho \cdot P_{\text{max}}^i \cdot N, g \cdot \left( 1 - \rho \right) \cdot P_{\text{max}}^i \cdot N \right), \quad i = \{ \text{MED} \text{ or } \text{MING} \}
\]

5.1.2 With a motorcycle segregation lane
All motorcycles are segregated from passenger cars, as illustrated in Figure 13. In this analysis, it is assumed that \( n \) of \( N \) lanes are assigned to motorcycles, and the rest of the lanes are assigned to passenger cars. Once the assignment of lane widths is fixed, the maximum flow rates of passenger cars and motorcycles are also determined regardless of the motorcycle.
ratio. This means that if, for example, the width of the motorcycle lane is set very wide for a given motorcycle ratio, a time period appears when the motorcycle lane does not maintain a saturated flow. Note that in this intersection, lane markings are assumed to be clear, so traffic flow in the case with clear lane markings can be realized. Thus, the traffic capacity $Q_{\text{lane}}$ can be expressed as

$$Q_{\text{lane}} = \begin{cases} \left( n_{\text{MED}} \left( \frac{\rho}{1-\rho} \right), n_{\text{MED}} \right) & (\text{if } \rho \leq \rho^*) \\ \left( g m_{\text{max}} \left( L - (N-n) \cdot l_{pc} \right), g m_{\text{max}} \left( L - (N-n) \cdot l_{pc} \right) \cdot \left( \frac{1-\rho}{\rho} \right) \right) & (\text{otherwise}) \end{cases}$$

(2)

where $l_{pc}$ is the lane width of a passenger car lane [m] and $\rho^* = \frac{m_{\text{max}} \left( L - (N-n) \cdot l_{pc} \right)}{n_{\text{max}} \left( L - (N-n) \cdot l_{pc} \right)}$.

5.1.3 With a waiting area for motorcycles

In this type of intersection (shown in Figure 14), motorcycles are divided into two types; one departs from the motorcycle waiting area, which is segregated from passenger cars, and the other is mixed with passenger cars. This type of intersection can be classified into two cases; in one, the waiting area is located behind the stop line (hereafter, the behind type), and in the other, the waiting area is located in front of the stop line, as in Taipei 2 (hereafter, the front type).

i) Behind type

The number of motorcycles departing from a waiting area when signal turns green, $q_{\text{area}}$ [veh/approach/hour], can be expressed by

$$q_{\text{area}} = \min \left( \left( 1 - g \right) \cdot q_{\text{mc}}, \left( 1 - g \right) \cdot m_{\text{max}} \cdot \left( L - Nw_{pc} \right) \frac{3600 \cdot c_{\text{area}}}{C} \right),$$

(3)

where $w_{pc}$ is the width of a passenger car, and $c_{\text{area}}$ is defined as the capacity of the waiting area and is given by Eq. (4).

$$c_{\text{area}} = \frac{L \cdot l_{\text{area}}}{A_{\text{mc}}},$$

(4)

where $l_{\text{area}}$ [m] indicates the width of the waiting area for motorcycles, and $A_{\text{mc}}$ [m$^2$/veh] indicates the area occupied by one stopped motorcycle. The first term indicates the number of motorcycles generated while the light is red. The second term indicates the maximum number

![Figure 14 Lane configuration of an intersection with a waiting area for motorcycles](image-url)
of motorcycles arriving at the motorcycle waiting area considering obstruction by passenger cars during the red signal. To arrive at the area, motorcycles should percolate through the passenger car queue. In this sense, \( L - NWpc \) shows the minimum available width for motorcycles considering a passenger queue. The last term is related to the capacity of the waiting area.

According to Yoshii et al. (2004), the increase in start-up loss time caused by the motorcycles in the waiting area, \( T_{loss} \) [hour], is assumed to be linearly related to the number of motorcycles and is calculated by Eq. (5),

\[
T_{loss} = \frac{q_{mc} \cdot L}{m_{max}} + \frac{3600}{C} \beta,
\]

where \( \beta \) is a constant value indicating an increase in start-up loss time caused by the stop line for passenger cars shifting upstream. Thus, the traffic capacity vectors of these intersections are shown in Eq. (6),

\[
Q_{area\_behind}^i = \left( \frac{(g - T_{loss}) \cdot \rho' \cdot p_{max} \cdot N_{area}}{1 - \rho' (1 + \alpha')} + q_{mc} \right) \cdot \alpha' \cdot \frac{\left( g - T_{loss} \cdot (1 - \rho') \cdot p_{max} \cdot N_{area} \right)}{1 - \rho' (1 + \alpha')}, i = \{MED, MING\},
\]

where \( \rho' \) is the apparent motorcycle ratio during the effective green time, described as

\[
\rho' = \frac{q_{mc} - q_{mc\_area}}{q_{pc} + q_{mc} - q_{mc\_area}}.
\]

ii) Front type
In this type of intersection, the motorcycles in the waiting area never increase the start-up loss time. Thus, the capacity vector can be rewritten as

\[
Q_{area\_front}^i = \left( g \cdot \rho' \cdot p_{max} \cdot N_{area} + q_{mc} \right) \cdot \alpha' \cdot \frac{g \cdot (1 - \rho') \cdot p_{max} \cdot N_{area}}{1 - \rho' (1 + \alpha')}, i = \{MED, MING\}.
\]

5.2 Parameter Settings
To calculate the traffic capacity for each type of intersection, parameters are set according to the field survey described in Section 4 and the literature, as shown in Table 2.

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<thead>
<tr>
<th>Parameter Settings in the analysis</th>
<th>(i) Parameters obtained from field survey and literature</th>
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<tr>
<td>( p_{max}^{MED} ) [pcu/lane/hour]</td>
<td>1762.8</td>
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<td>( p_{max}^{MING} ) [pcu/lane/hour]</td>
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<td>( m_{max} ) [veh/m/hour]</td>
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<td>( c_{area} ) [veh]</td>
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<table>
<thead>
<tr>
<th>(ii) Parameters set for this case study</th>
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<tr>
<td>( C ) [sec]</td>
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<td>( g ) [m]</td>
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<tr>
<td>( w_{pc} ) [m]</td>
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5.3 Case Study
Based on the parameter settings mentioned above, the traffic capacity vector \( Q \) is calculated for various motorcycle ratios from 0 to 1.0. The relationship between the number of motorcycles and the number of passenger cars that can pass the stop line during one hour is illustrated for each type of intersection. The results are summarized in Figure 15. For motorized cities, the parameter values were obtained from the observation survey in which the
The motorcycle ratio was less than 0.88. Therefore, the obtained parameters are considered to become invalid when the motorcycle ratio exceeds 0.88, and the results shown in Figure 15 are represented by dotted lines at ratios above 0.88.

First, motorized cities are examined. When the number of motorcycles is small, the case of a waiting area (behind) is less efficient than the basic case, but as the number of motorcycles increases, the distance between the two lines shortens, and finally they coincide. This is because when the motorcycle ratio is small, the positive effect of a motorcycle waiting area in which motorcycles and passenger cars are segregated is less than the negative effect of increased start-up loss time. As the motorcycle ratio increases, the positive effect becomes outstanding, and so the distance between two lines decreases. When the motorcycle ratio becomes sufficiently large, the slope of the line for the waiting area (behind) is the same as that of the basic case because of the capacity of the motorcycle waiting area. Although in this case study, it is evident that these two lines finally coincide, whether the negative and positive effects balance depends on the capacity of the waiting area and the parameter $m_{max}$. If its capacity is larger/smaller than that in this case study, the line representing the waiting area (behind) situation may be located above/below that of the basic case. On the other hand, for the waiting area (front), initially the efficiency is the same as in the basic case, but as the motorcycle ratio increases, the distance between the two cases also increases and finally becomes constant. That is because in this type of intersection, the motorcycles departing from the waiting area are assumed not to increase the start-up loss time. Thus, we can conclude that in motorized cities, the implementation of a motorcycle area in front of the stop line, which is already in use at Taipei 2, may improve traffic efficiency. In terms of safety, however, its implementability depends entirely on the intersection configuration, pedestrian usage, signal phases, and other factors. In the case of Taipei 2, the waiting area was managed by police officers, but it can be said that ITS can contribute to improving the efficiency, which is one of the future goals of our work.

In motorizing cities, almost the same results as that for motorized cities were obtained except for the waiting area (behind), whose distance from the line representing the basic case does not shorten even when the proportion of motorcycles increases. This is caused by the parameter settings. Namely, because the value of $m_{max}$ is smaller than the flow rate of

![Figure 15 Estimation of traffic capacity for each intersection configuration](image-url)
motorcycles derived from the linear function shown in Figure 8, the positive effect of the waiting area cannot be realized. Although more detailed investigations of these parameters are required, it can be said that in motorizing cities, the positive effect of implementing a motorcycle waiting area may be limited.

Finally, the effect of a motorcycle lane is analyzed. When a motorcycle lane is implemented in motorized cities, it can be seen that the positive effect is extremely limited by comparison with the basic case. In particular, when the motorcycle ratio is between 0.72 and 0.82, the width of a motorcycle lane offers greater efficiency than that in the basic case. The reason is that if the width of a motorcycle lane is not equivalent to the motorcycle demand, that is, if the lane is designed to be narrower or wider than the demand, useless capacity is generated in passenger car/motorcycle lanes. Thus, the width of a motorcycle lane should be carefully designed according to the motorcycle ratio in motorized cities. On the other hand, if a motorcycle lane is implemented in a motorizing city, the efficiency of traffic flow could be dramatically improved compared to the basic case, though it is assumed that by implementing a motorcycle lane, the definition of traffic lanes becomes clear, and as a result, the traffic situation becomes equivalent to that in a motorized city. Specifically, if one of three lanes is changed into a motorcycle lane and the others are defined as passenger car lanes, the use of the motorcycle lane is more efficient than the basic case at motorcycle ratios of 0 to 0.87. Thus, in motorizing cities, implementing motorcycle lanes and clarifying lane definitions can improve traffic efficiency.

6. CONCLUSION

This research evaluated schemes for spatial motorcycle segregation by analyzing mixed traffic flow situations including motorcycles at five intersections in four Asian countries. The analysis indicated that the efficiency of traffic control in motorizing cities (Hanoi and Phnom Penh) is lower than that for the same motorcycle ratio in motorized cities (Taipei and Bangkok). The reason is considered to be that lanes are not clearly defined in motorizing countries, so mixed traffic consisting of motorcycles and other vehicles becomes more complex with respect to the traffic flow efficiency. On the other hand, the analysis also clarified that in some situations, the capacity of a motorcycle lane is wasted if the motorcycle demand is insufficient. Therefore, before establishing a motorcycle lane on a road, it is important to consider the demand of motorcycles. A comparison of motorizing and motorized countries showed that traffic control at isolated signalized intersections at which a waiting area for motorcycles is provided in front of a stop line of the approach (shown in Taipei 2) can become highly efficient compared to a configuration with a waiting area for motorcycles behind the stop line of the approach. Based on these results, it can be concluded that in motorizing countries establishing a lane for motorcycles should be effective to improve the efficiency of mixed traffic flows, while in motorized countries, the most suitable spatial lane/traffic signal control varies in relation to the actual traffic demand, especially the ratio of motorcycles.

On the other hand, these evaluation results do not clearly consider the impact of road width and the other factors including left and right turn, start-up loss time, and so on. Therefore, the proposed method of evaluating mixed traffic conditions should be applied to roads of different sizes, and standards for implementing spatial motorcycle segregation should be clarified, including safety aspects. By discussing the related topics of efficiency and safety, ITS schemes and the evaluation of their effects on a network-wide, signalized intersection
management scheme for mixed traffic flows should be established as future research.

REFERENCES


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