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Motorcycle crash risk models for urban roads

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This paper presents new models to estimate the potential of rear-end and sideswipe crashes for motorcycles moving in motorcycle-dominated traffic conditions on urban roads based on discrete choice theory and the traffic conflict technique. The proposed models were validated using vehicles' trajectories data collected from an urban road in the city of Danang in Vietnam. The results showed that the models satisfactorily capture the movement characteristics of motorcycles in a motorcycle-dominated traffic environment and provide good estimates of rear-end and sideswipe crash risk for motorcyclists. They therefore have the potential for inclusion in the International Road Assessment Programme (iRAP) star rating system.

Notation

a	maximum braking deceleration of motorcycles
D_{front}	front distance
$D^{\text{F}}_{\text{TSD}}$	threshold safety distance (TSD) for following manoeuvre scenario
$D^{\text{S}}_{\text{TSD}}$	TSD for swerving manoeuvre scenario
Da^m_n	initial lateral gap between motorcycle n and vehicle m
Do^m_n	longitudinal gap between motorcycle n and vehicle m
d	stopping distance
e	base of the natural logarithm
$\ln(y)$	natural logarithm of variable y
v	speed of vehicle
α	swerve angle
β	coefficient of independent variables
μ	mean of the lognormal distribution
σ	standard deviation of the lognormal distribution
τ	reaction time of motorcyclist
Φ	cumulative standard normal distribution

1. Introduction

Motorcyclists' safety is a major concern in a number of cities worldwide, including most Southeast Asian cities where motorcycles are the predominant mode of transport. The World Health Organization reported that motorcyclists account for 23% of the world's road traffic deaths and a third of those occur in the Southeast Asia region (WHO, 2013). Although the number of passenger cars in this region has increased in recent years due to economic growth, the motorcycle is still the dominant mode of urban transport because of its affordability and flexibility in terms of movement and parking. Consequently, crashes involving motorcycles in these cities are still significant. For example, in the city of Danang in Vietnam, motorcycles constitute over 80% of the total traffic and motorcycle crashes account for nearly 70% of total road crashes (DoT, 2013). Similarly, in Indonesia, it has been reported that motorcycles account for 78·3% of the total vehicle population and 75% of fatalities in traffic crashes involved motorcyclists (Indriastuti and Sulistio, 2010). This issue has also been reported in Taiwan (Ming *et al.*, 2013) and Malaysia (Sarani *et al.*, 2011).

In a motorcycle-dominated traffic situation, motorcycles present non-lane-based movement characteristics, which have been found to be the major causes contributing to the crash risk for motorcyclists (Indriastuti and Sulistio, 2010; Long, 2012; Minh, 2007; Shiomi *et al.*, 2013). In Vietnam, for example, crash data reveal that 'changing lanes improperly', 'failing to keep safe following gap' and 'failing to look properly' are the major causes of crashes involving motorcycles, accounting for 19·3%, 16% and 15·9% of crashes, respectively (DoT, 2013). Similarly, these factors have also been found to contribute to a large proportion of motorcycle crashes in Taiwan (Ming *et al.*, 2013).

To examine the effect of this motorcyclist manoeuvring behaviour on crash risk, a methodology was developed for estimating the potential of both rear-end and sideswipe crashes for motorcycles moving in an urban motorcycle-dominated traffic environment. The preliminary results of the proposed models may be used to support traffic engineers in improving urban road safety and developing appropriate countermeasures to mitigate the crash risk for motorcyclists. Furthermore, the proposed methodology is expected to provide a better understanding of the influence of the non-lane-based movement characteristics of motorcycles on crash potential and to trigger further research on road safety assessment for motorcyclists in low-income and middle-income countries where motorcycles are the predominant mode of urban transport systems.

2. Literature review

A number of models for the assessment of motorcyclist safety have already been developed. Most of these models predict crash frequency or crash severity for motorcycles based on historical crash data and statistical methods. However, the key drawbacks of this traditional approach are that the movement characteristics of motorcycles are not considered and it is problematic to obtain reliable historical crash data for model development purposes.

Harnen *et al*. (2006) developed a model to predict motorcycle crashes at junctions on urban roads in Malaysia using the generalised linear modelling approach. Their work revealed that the flow of non-motorcycles on a major road, the approach speed of vehicles, junction geometry, junction control and land use were significant factors contributing to the occurrence of motorcycle crashes. Indriastuti and Sulistio (2010) developed a probability model to predict motorcycle crash occurrence for the city of Malang in Indonesia using a logistic regression model. They found that male riders, an increase in motorcycle ownership, long travel distances and reduced riding knowledge have a significant influence on the occurrence of motorcycle crashes. Manan *et al*. (2013) developed a safety performance function for fatal motorcycle crashes on Malaysian primary roads. They established a relationship between motorcyclist fatalities per kilometre and a set of factors contributing to fatal motorcycle crashes, and suggested that increases in traffic flow and the number of access points per kilometre contribute to an increase in motorcycle crash fatalities.

Similarly, several researchers have applied traditional approaches to investigate the effect of various contributing factors on motorcyclists' crash risk; however, these works are mainly focused on the conventional traffic environment of high-income countries where passenger cars are the predominant vehicle type. Elliott *et al*. (2006) developed a motorcycle rider behaviour questionnaire and used generalised linear modelling to investigate the effect of motorcyclist behaviour on crash risk in the UK. They found five types of motorcycle rider behaviour relating to crash risk (i.e. traffic errors, speed violations, stunts, safety equipment and control errors) and suggested that traffic errors are the main factors in predicting crash risk for motorcyclists. Pai and Saleh (2008) developed models to evaluate factors contributing to the severity of motorcyclist injuries in sideswipe collisions involving motorcycles at T-junctions in the UK and found that motorcyclist injuries were more severe when an overtaking motorcycle collides with a turning vehicle. Haque *et al*. (2009) developed models to investigate the factors contributing to motorcyclist fault in motorcycle crashes by using binary logistic regression. They examined the effect of roadway characteristics, environmental factors, motorcycle descriptions and rider demographics on the fault of motorcyclists involved in crashes at three location types (intersections, expressways and non-intersections). They suggested that the likelihood of at-fault crashes on expressways increases with increased motorcycle speeds and at-fault crashes at non-intersections increase in wet road surface conditions.

In addition, several models have adopted the traffic conflict technique to evaluate motorcyclist safety, but these models only focus on certain types of crashes at intersections or access points on primary roads. Huyen (2009) developed a model for risk analysis of driver behaviour relating to violating traffic regulations at intersections in motorcycle-dominated traffic flow. They adopted the concepts of 'conflict zones' and 'conflict time segments' to determine the hazard that drivers have to face in left-turning movements at intersections. Using mixed effects logistic regression, Manan (2014) examined the contributions of motorcyclist behaviour and road environment attributes to the occurrence of serious conflicts involving motorcycles entering primary roads from access points. They suggested that motorcyclist behaviour is the main factor in predicting conflict occurrence, but also found that traffic volume and speed limit factors contribute significantly to the occurrence of motorcycle conflicts.

The International Road Assessment Programme (iRAP, 2009) developed a star rating protocol to assess the level of safety provided by road design. Star ratings are determined by assigning scores for four road user groups – car occupants, motorcyclists, bicyclists and pedestrians. For motorcyclist safety assessment, the star rating score is calculated for five crash types – run-off, head-on, intersection, property access and along crash. However, it seems that this model does not satisfactorily capture crash types of motorcycles in motorcycle-dominated traffic conditions on urban roads because it was based on research covering more conventional traffic composition and focusing mainly on inter-urban roads.

The literature review therefore seems to suggest that most previous studies on road safety assessment for motorcyclists were based on historical crash data analysis and there is a lack of models focusing on evaluation of the movement characteristics of motorcycles on crash risk in a traffic environment where motorcycles are the predominant vehicles. Furthermore, the key drawback of traditional road safety analysis is the lack of reliable historical crash data for model development (Ismail, 2010; Laureshyn, 2010). There is therefore a need to obtain a surrogate measure to address the limitation of traditional road safety analysis, which is based only on historical crash data, and to develop a methodology capable of capturing crash potentials associated with motorcyclists' manoeuvre behaviour in a motorcycle-dominated traffic environment.

3. Methodology

In this study, the concept of non-lane-based movement of motorcycles in a motorcycle-dominated traffic environment is modelled based on discrete choice models. Its contribution to crash potentials is evaluated using a threshold safety distance (TSD) indicator.

3.1 The concept of non-lane-based movement

Due to their small size and flexible turning radius, motorcycles can be manoeuvred relatively freely in the traffic stream and do not necessarily conform to lane disciplines and lane markings as passenger cars do. They tend to swerve to change directions and speeds frequently. Also, because they occupy a small space, motorcycles are able to travel alongside other vehicles in the same car lane and to filter through the lateral clearance between vehicles. These movement characteristics of motorcycles are distinct from the conventional driving behaviour of passenger cars and are described as non-lane-based movement (Lee, 2007; Long, 2012; Minh, 2007; Shiomi *et al.*, 2013).

3.2 Threshold safety distance indicators

3.2.1 Stopping distance

The stopping distance is defined as the sum of the reaction distance of the driver and the braking distance of the vehicle (Aashto, 2004). The reaction time is the time that drivers need from the instant they recognise a danger ahead to the instant they actually apply the brake. The braking distance of a vehicle is the distance needed to stop the vehicle from the instant that the driver begins applying the brake. The stopping distance may be formulated as

$$1. \quad d = v\tau + \frac{v^2}{2a}$$

where τ, v and a are the reaction time, initial speed and braking deceleration, respectively.

3.2.2 Threshold safety distance

Threshold safety distance indicators are proposed in this study to identify traffic conflicts that potentially lead to crashes. The TSD calculation is based on the critical condition in an emergency situation where it is assumed that a vehicle must stop to avoid a possible collision with the preceding vehicle or swerving motorcycle. Under this assumption, TSD indicators may be defined separately for the cases of a following manoeuvre and a swerving manoeuvre.

In the scenario of a following manoeuvre (Figure 1), it is assumed that the preceding vehicle ($n-1$) suddenly decelerates and the subject motorcycle (n) responds to this urgent situation by applying the brake to avoid a possible collision. The TSD of this scenario may be defined as the distance that the subject motorcycle needs for stopping to avoid a possible collision with the preceding vehicle. This distance may be calculated as

$$2. \quad D^{\mathrm{F}}_{\mathrm{TSD}} = v_n\tau_n + \frac{v_n^2}{2a_n} - \frac{v_{n-1}^2}{2a_{n-1}}$$

where $D^{\mathrm{F}}_{\mathrm{TSD}}$ is the TSD for a following manoeuvre scenario, τ_n, v_n and a_n are the reaction time, initial speed and braking deceleration of the subject motorcycle, respectively, and v_{n-1} and a_{n-1} are, respectively, the initial speed and braking deceleration of the preceding vehicle.

With regard to the swerving manoeuvre scenario, it is assumed that the trajectory of the subject motorcycle (n) is the hypotenuse of a right-angled triangle, as illustrated in Figure 2, and the adjacent following vehicle (m) starts braking while the subject motorcycle starts swerving. The TSD of this movement scenario is defined as the distance that m needs for stopping to avoid a possible collision while motorcycle n executes a swerving manoeuvre. This distance is formulated as

$$3. \quad D^{\mathrm{S}}_{\mathrm{TSD}} = v_m\tau_m + \frac{v_m^2}{2a_m} - \frac{Da_n^m \times \cos\alpha}{\sin\alpha}$$

where $D^{\mathrm{S}}_{\mathrm{TSD}}$ is the TSD for swerving manoeuvre scenario, τ_m, v_m and a_m are, respectively, the reaction time, initial speed and braking deceleration of vehicle m, Da_n^m is the initial lateral gap between motorcycle n and vehicle m, and α is the swerve angle.

3.3 Modelling framework

When travelling on a road, a motorcyclist has three choices for manoeuvre – keep following the preceding vehicle, swerve to the left or swerve to the right to overtake the preceding vehicle. With regard to the following manoeuvre, the subject motorcycle (n) follows the preceding vehicle ($n-1$) with a front distance (D_{front}); a rear-end crash may occur if the front distance is less than the distance needed for motorcycle n to take evasive action to avoid colliding with vehicle $n-1$. With regard to the swerving manoeuvre, the subject motorcycle (n) swerves to the left or to the right to overtake or filter the preceding vehicle, and this behaviour may lead to a side-swipe crash if the longitudinal gap (Do_n^m) is less than the

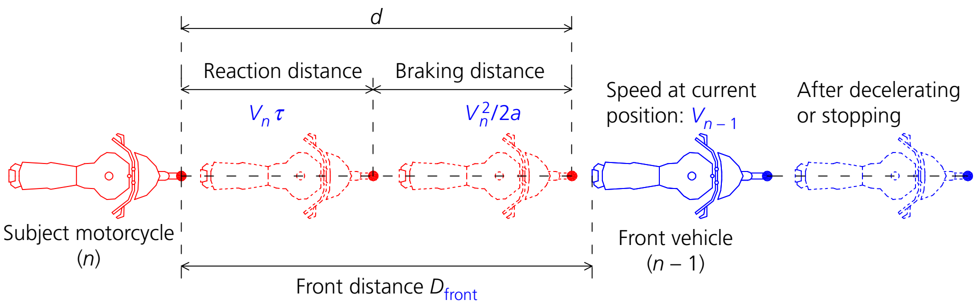

Figure 1. Following manoeuvre scenario

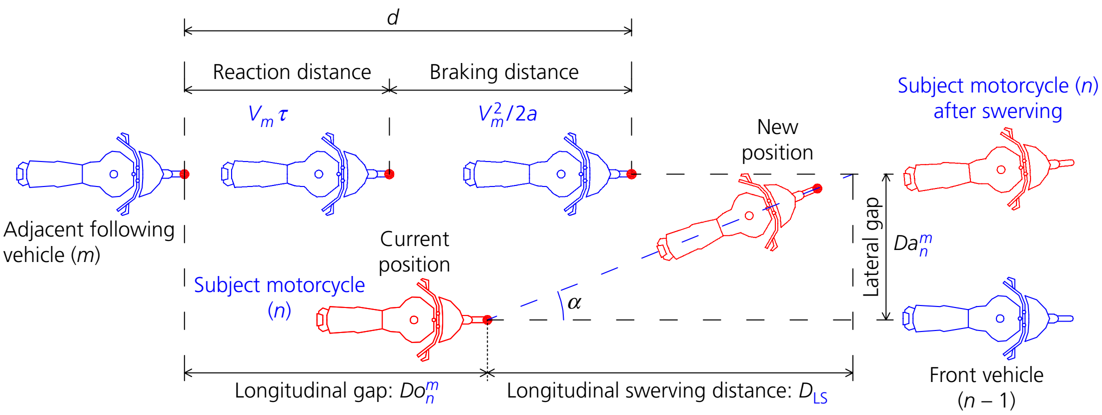

Figure 2. Swerving manoeuvre scenario

distance needed for the adjacent following vehicle (*m*) taking evasive action to avoid colliding with the motorcycle (*n*).

Under these assumptions, two types of conflicts are considered in this study

- a rear-end conflict, occurring due to a motorcycle's following manoeuvre that potentially leads to a rear-end crash
- a sideswipe conflict, occurring due to a motorcycle's swerving manoeuvre that potentially results in a sideswipe crash.

This study defines a conflict as the condition of two consecutively moving motorcycles having inadequate TSD such that the following motorcycle will crash into the preceding motorcycle when it swerves or makes an unexpected stop. The modelling framework is shown in Figure 3.

To develop models for describing rear-end crash and sideswipe crash potentials, this study uses discrete choice theory and the traffic conflict technique. The former is adopted to capture the manoeuvre behaviour of motorcycles resulting in crash potentials and the latter is employed to evaluate crash

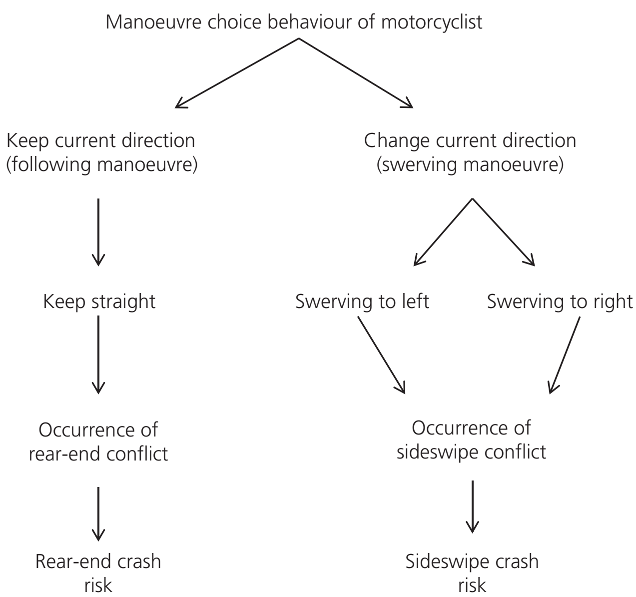

Figure 3. Modelling framework

occurrence probability. The use of discrete choice analysis for modelling the non-lane-based movement characteristic of motorcycles in this context is justified for two reasons. First, manoeuvre behaviour can be regarded as a discrete choice decision made by a motorcyclist for the next movement under given traffic conditions generated by vehicles in surroundings; therefore discrete choice theory may appropriately capture this process decision in a natural way. In addition, discrete choice models are designed to be calibrated on real data and thus the proposed model can be estimated and calibrated from real traffic data collected in the field.

The traffic conflict technique is used in this study as a surrogate approach to identify crash potentials because of the advantages offered by the method. First, traffic conflicts are more frequent than crash events and thus the data needed for road safety analysis based on traffic conflicts can be collected in a short period time without having to wait for actual crash occurrences. In addition, traffic conflicts can be observed in the field and therefore the behaviour of road users and infrastructure attributes that lead to crash potentials can also be studied as all these contributing factors can be obtained together with traffic conflict events (Ismail, 2010; Laureshyn, 2010).

4. Model development

4.1 Rear-end crash risk model

The probability of a rear-end crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation is the result of the following series of events

- the subject motorcycle (n) keeps its current direction to follow the preceding vehicle ($n-1$) with a front distance (D_{front})
- the preceding vehicle suddenly slows down
- the subject motorcycle must decelerate to reduce its speed to avoid a possible rear-end crash with the preceding vehicle
- a rear-end crash potentially occurs if the front distance is less than the TSD ($D^{\text{F}}_{\text{TSD}}$).

Under these assumptions, the potential that a rear-end crash may occur at a point in time t may be estimated using the theory of probability as

4. $$\Pr(\text{RE}_n^{n-1}) = \Pr(\text{KS}_n|X) \times \Pr(\text{KS}_{n-1}|X) \times \Pr(\text{C}_n^{n-1}|D^{\text{F}}_{\text{TSD}})$$

where $\Pr(\text{KS}_n|X)$ is the probability that the subject motorcycle (n) will keep the current direction under a given traffic condition X, $\Pr(\text{KS}_{n-1}|X)$ is the probability that the preceding vehicle ($n-1$) will keep the current direction under a given traffic condition X and $\Pr(\text{C}_n^{n-1}|D^{\text{F}}_{\text{TSD}})$ is the probability that the subject motorcycle (n) potentially collides with the preceding vehicle ($n-1$).

4.2 Sideswipe crash risk model

The probability of a sideswipe crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation is the result of the following series of events

- the subject motorcycle (n) swerves to the left or to the right to overtake the preceding vehicle
- the adjacent following vehicle (m) must decelerate to reduce its speed to avoid a possible sideswipe crash with the subject motorcycle
- a sideswipe crash potentially occurs if the longitudinal gap (Do_n^m) is less than the TSD ($D^{\text{S}}_{\text{TSD}}$).

Under these assumptions, the potential that a sideswipe crash may occur at a point in time t may be estimated as

5. $$\Pr(\text{SW}_n^m) = \Pr(\text{SW}_n|X) \times \Pr(\text{KS}_m|X) \times \Pr(\text{C}_n^m|D^{\text{S}}_{\text{TSD}})$$

where $\Pr(\text{SW}_n|X)$ is the probability that the subject motorcycle (n) will swerve to the left or right under a given traffic condition X, $\Pr(\text{KS}_m|X)$ is the probability that the adjacent following vehicle (m) will keep the current direction under a given traffic condition X and $\Pr(\text{C}_n^m|D^{\text{S}}_{\text{TSD}})$ is the probability that the subject motorcycle (n) potentially collides with the adjacent following vehicle (m).

4.3 Model components

To obtain the crash risk from the proposed models presented in Equations 4 and 5, two probabilities need to be calculated

- the probability that the subject motorcycle chooses either a swerving manoeuvre or a following manoeuvre
- the probability that the subject motorcycle potentially collides with the preceding vehicle or the adjacent following vehicle by using the TSD indicators.

For the first component, a swerving manoeuvre choice model is developed based on the discrete choice model in which the decision of a motorcyclist for manoeuvre behaviour is a binary discrete choice process: following or swerving. Therefore, the binary logistic regression model may be used in this study to capture whether the subject motorcycle chooses either a swerving manoeuvre or a following manoeuvre. The form of logistic regression model represents the probability that a motorcyclist chooses swerving manoeuvre behaviour as follows (Ben-Akiva and Lerman, 1985)

6. $$\Pr(\text{SW}_n|X) = \frac{\text{e}^{V(x_i)}}{1 + \text{e}^{V(x_i)}}$$

The probability that a motorcyclist chooses following manoeuvre behaviour is given by

7. $$\Pr(\mathrm{KS}_n|X) = 1 - \Pr(\mathrm{SW}_n|X) = 1 - \frac{\mathrm{e}^{V(x_i)}}{1+\mathrm{e}^{V(x_i)}} = \frac{1}{1+\mathrm{e}^{V(x_i)}}$$

where $V(x)$ is the logit of the logistic regression model. If the outcome variable stands for the manoeuvre choice of the motorcyclist (which is coded with a value of one to indicate the subject motorcyclist choosing a swerving manoeuvre or zero for a following manoeuvre), then the logit of the logistic regression model for a collection of n independent variables $x_i = (x_1, x_2,\dots, x_n)$ is given by

$$V(x) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n$$

in which x_i are factors (independent variables) affecting the choice of swerving manoeuvre behaviour of the subject motorcyclist and β_0, $\beta_1,\dots$, β_n are unknown parameters to be estimated.

In a motorcycle-dominated traffic environment, the relations between the subject motorcycle and the surrounding vehicles affect the motorcyclist's manoeuvre choice. The choice of a swerving manoeuvre depends on the relative positions and speeds of the subject motorcycle with respect to the surrounding vehicles. Motorcyclists are assumed to evaluate the available conditions to decide whether to swerve or not. If they are satisfied with the speed of the preceding vehicle, they will keep their direction and follow the preceding vehicle. Conversely, they will decide to change direction by swerving left or right in order to overtake preceding vehicles. In addition, if they feel the front distance to the preceding vehicle is too short but the lateral clearance space beside the preceding vehicle is safe enough, they will choose to swerve; otherwise, they will keep their direction and wait for a chance to swerve. It is therefore reasonable to assume that a motorcyclist's swerving manoeuvre choice depends on the following independent variables: the difference in speed with preceding vehicle (S_n^{n-1}), the difference in speed with adjacent following vehicles (S_n^m), the front distances to preceding vehicles (D_{front}), the lateral clearance spaces beside preceding vehicles (C) and the longitudinal gap (Do_n^m), as shown in Figure 4. Using this assumption, the logit of the logistic regression model for a collection of these five independent variables affecting the decision of motorcyclists in choosing their manoeuvre behaviour is formulated as

8. $$V(x) = \beta_0 + \beta_1 D_{\text{front}} + \beta_2 Do_n^m + \beta_3 C + \beta_4 S_n^{n-1} + \beta_5 S_n^m$$

where S_n^{n-1} is the relative speed between the subject motorcycle and its preceding vehicle ($S_n^{n-1} = S_n - S_{n-1}$), S_n^m is the relative speed between the subject motorcycle and the adjacent following vehicle ($S_n^m = S_n - S_m$), D_{front} is the front distance between the subject motorcycle and its preceding vehicle, clearance is the lateral clearance space beside the preceding vehicle, Do_n^m is the longitudinal gap between the adjacent following vehicle (m) and the subject motorcycle (n) and β_0, β_1, β_2, β_3, β_4 and β_5 are unknown coefficients to be estimated from real data.

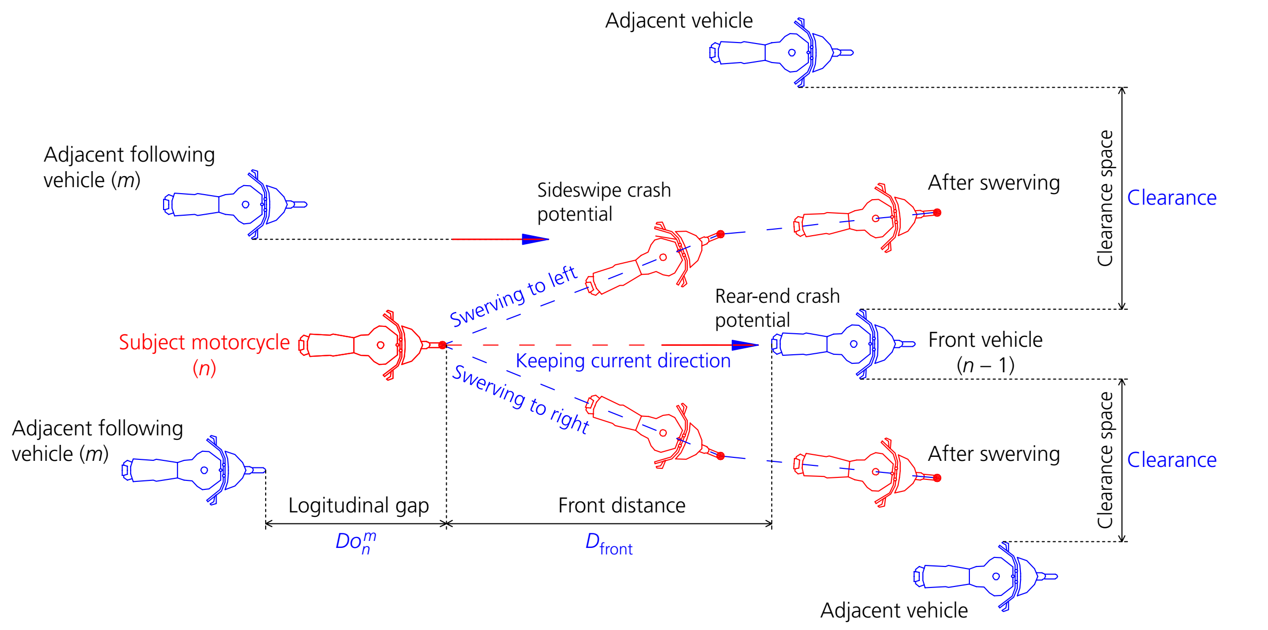

Figure 4. Parameters of the swerving manoeuvre model

With regard to the probability of a collision potentially occurring on a road segment, a probability distribution function may be used. It is assumed that when a random variable Y ($0 < Y < \infty$) follows a lognormal distribution with mean μ and standard deviation (SD) σ, the probability that variable Y is less than the value of y is given by (Aitchison and Brown, 1957)

$$\text{9.} \quad \Pr(Y \leq y) = \Phi\left[\frac{\ln(y) - \mu}{\sigma}\right]$$

where $\Phi[\cdot]$ is the cumulative standard normal distribution

Under the assumption that the front distances follow a lognormal distribution (Lee, 2007; Minh, 2007), the probability that the subject motorcycle potentially collides with the preceding vehicle is given by

$$\text{10.} \quad \begin{aligned} \Pr(\text{C}_n^{n-1}|D_{\text{TSD}}^{\text{F}}) &= \Pr(D_{\text{front}} \leq D_{\text{TSD}}^{\text{F}}) \\ &= \Phi\left[\frac{\ln(D_{\text{TSD}}^{\text{F}}) - \mu^{D_{\text{front}}}}{\sigma^{D_{\text{front}}}}\right] \end{aligned}$$

where $\mu^{D_{\text{front}}}$ and $\sigma^{D_{\text{front}}}$ are, respectively, the mean and SD of the logarithm of front distances.

Similarly, the probability that the subject motorcycle potentially collides with adjacent following vehicles while swerving is given by

$$\text{11.} \quad \begin{aligned} \Pr(\text{C}_n^{m}|D_{\text{TSD}}^{\text{S}}) &= \Pr(Do_{\text{n}}^{\text{m}} \leq D_{\text{TSD}}^{\text{S}}) \\ &= \Phi\left[\frac{\ln(D_{\text{TSD}}^{\text{S}}) - \mu^{Do_n^m}}{\sigma^{Do_n^m}}\right] \end{aligned}$$

where $\mu^{Do_n^m}$ and $\sigma^{Do_n^m}$ are the mean and SD of the logarithm of longitudinal gaps, respectively.

5. Model estimation and verification

5.1 Data collection

To estimate and verify the proposed models, a traffic survey was conducted on a road segment in the city of Danang in Vietnam. Vehicle trajectory data were collected using video recording. A representative road segment of length 35 m and width 8 m on Nguyen Van Linh Street was chosen that could be captured by the video camera (Figure 5). The traffic survey was conducted on 20 and 21 February 2014, from 7.00 to 11.00 a.m. and 2.00 to 6.00 p.m.

5.2 Data extraction

The trajectories of vehicles were manually extracted from the recorded video file using SEV (speed estimation from video data) computer software (Minh, 2007), which converts video screen coordinates into roadway coordinates. As a result, a dataset containing 541 observations of the trajectories of 108 subject motorcycles and 1047 observations of 212 influential vehicles was used to estimate the unknown coefficients of the proposed models. The dataset included flow density, relative positions, speeds, accelerations and decelerations of each vehicle.

5.3 Results and discussion

5.3.1 Parameter estimation

The statistical software R was used to analyse the vehicle trajectory data and to estimate the unknown parameters of the developed models. It was found that the speed variable S_n^m did not significantly affect the swerving manoeuvre decision of motorcyclists and it was thus removed from the model. The final estimate results are summarised in Table 1 together with further statistical tests. The swerving manoeuvre probability model developed in this study was thus

$$\text{12.} \quad \Pr(\text{SW}_n|X) = \frac{\text{e}^{-1{\cdot}575+0{\cdot}698C+0{\cdot}561Do_n^m+0{\cdot}125S_n^{n-1}-0{\cdot}277D_{\text{front}}}}{1+\text{e}^{-1{\cdot}575+0{\cdot}698C+0{\cdot}561Do_n^m+0{\cdot}125S_n^{n-1}-0{\cdot}277D_{\text{front}}}}$$

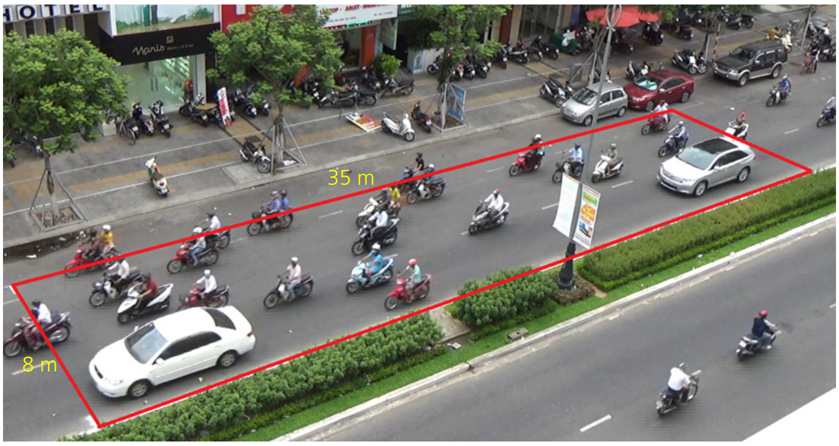

Figure 5. Road segment selection for traffic observation

Considering the statistical tests shown in Table 1, it may be seen that the estimate coefficients of independent variables are statistically significant; this means that the proposed model satisfactorily captures the swerving manoeuvre behaviour of motorcyclists in a motorcycle-dominated traffic situation. As shown in the results, the clearance space is a significant factor contributing to the decision of motorcyclists in choosing a swerving manoeuvre. The coefficient of this variable is positive, illustrating that motorcyclists are more likely to swerve to change their current moving direction if higher clearance spaces are available and vice versa.

Similarly, the estimated coefficients of the longitudinal gap and relative speed variables are both positive, indicating that the probability of a motorcyclist choosing a swerving manoeuvre will increase with an increasing longitudinal gap and relative speed. Conversely, the coefficient of the front distance factor is negative, as expected; this implies that motorcycles tend to choose a swerving manoeuvre when the front distances to preceding vehicles become shorter.

5.3.2 Front distance and longitudinal gap distribution

The statistical properties of the longitudinal gaps and front distances from the dataset are summarised in Table 2. The Kolmogorov–Smirnov test (KS test) measure was applied to verify the assumption of the distribution for the longitudinal gaps and front distances and the results illustrate that they follow a lognormal distribution.

With the parameters of the longitudinal gaps distribution, the probability that the subject motorcycle potentially collides with an adjacent following vehicle while swerving using the TSD indicator is given by

$$\text{13.}\quad \Pr(C_n^m | D_{\text{TSD}}^{\text{S}}) = \Phi\left[\frac{\ln(D_{\text{TSD}}^{\text{S}}) - 1{\cdot}29}{0{\cdot}3}\right]$$

Similarly, the probability that the subject motorcycle potentially collides with a preceding vehicle using the TSD indicator is given by

$$\text{14.}\quad \Pr(C_n^{n-1} | D_{\text{TSD}}^{\text{F}}) = \Phi\left[\frac{\ln(D_{\text{TSD}}^{\text{F}}) - 1{\cdot}23}{0{\cdot}52}\right]$$

To investigate the effect of speed and lateral gap on the occurrence of a sideswipe collision, the probabilities were estimated for different speed levels of the adjacent following motorcycle for five scenarios with a lateral gap of 0·5 m, 1·0 m, 1·5 m, 2·0 m and 2·5 m. To simplify the calculation process, several parameters were assumed to be constant: the reaction time (τ) of motorcyclists was assumed to be 0·5 s (Minh, 2007), the braking deceleration of a motorcycle in an emergency situation was assumed to be 6·02 m/s (Seyed and Hussain, 2013) and the swerving angle was assumed to be 10° (the mean calculated from the collected dataset). As shown in Figure 6, the probability of a sideswipe collision increases with the value of speed but decreases with an increase in lateral gap.

Variable	Coefficient	Coefficient estimate	Standard error	z test	Significance
Intercept	β_0	−1·575	0·443	−3·552	***
Front distance, D_{front}	β_1	−0·277	0·057	−4·840	***
Longitudinal gap, Do_n^m	β_2	0·561	0·103	4·981	***
Lateral clearance space, C	β_3	0·698	0·091	7·670	***
Relative speed, S_n^{n-1}	β_4	0·125	0·120	1·061	

***$p < 0{\cdot}001$

Table 1. Results of logistic regression analysis

	Number of observations	Observation data		Lognormal distribution		KS test for lognormal distribution
		Mean	SD	Mean	SD	Confidence
Longitudinal gap	184	3·79	1·19	1·29	0·30	0·948
Front distance	139	3·93	2·32	1·23	0·52	0·509

Table 2. Statistical properties of longitudinal gaps and front distances

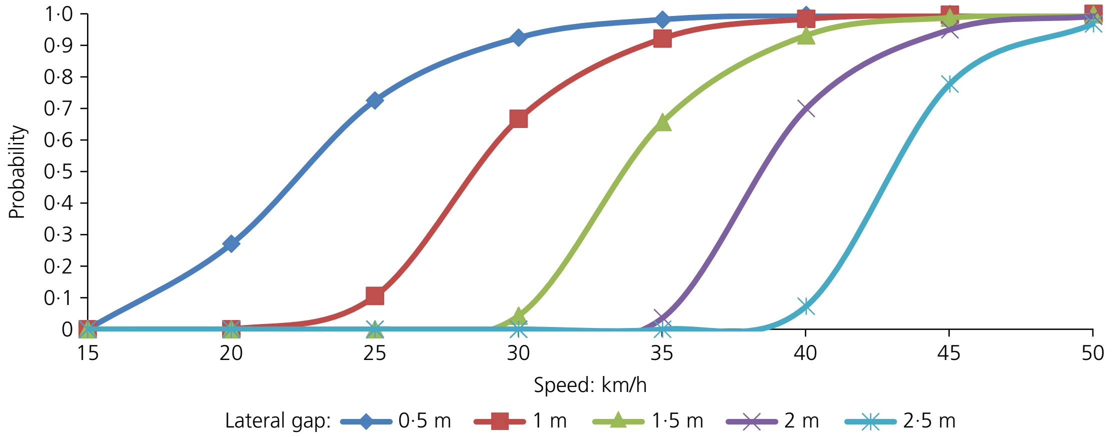

Figure 6. Probability of sideswipe collisions occurring

Similarly, to investigate the influence of speed on the occurrence of a rear-end collision, the probabilities were estimated for different speed levels of the subject motorcycle with four values of the relative speed between the subject motorcycle with its preceding vehicle. The results shown in Figure 7 illustrate that rear-end collisions are more likely to occur with increases in speed and relative speed with the preceding vehicle.

5.3.3 Model verification

This study proposed a methodology to estimate the crash potential in real time based on determining the occurrence of near crashes (i.e. conflicts that have the characteristics of crashes, but no actual crash results). To verify the proposed methodology, field observations of conflicts were compared with the results estimated by the proposed models. The verification process was conducted in two steps. First, rear-end conflicts and sideswipe conflicts were observed in real time in the field. Second, the occurrences of rear-end conflicts and sideswipe conflicts were identified by the proposed models and then the estimated results were compared with the real observations.

To collect the data for the model verification process, a traffic survey was conducted on a road segment of length 35·0 m and width 7·5 m on Le Duan Street in the city of Danang in Vietnam, on 23 February 2014, from 7.00 to 11.00 a.m. The methods of data collection and extraction were similar to those used in the model calibration. As a result, a dataset was obtained containing observations of 3887 motorcycle swerving manoeuvres and 9855 motorcycle following manoeuvres in which 91 sideswipe conflicts and 79 rear-end conflicts were noted. Individual vehicle positions, speeds, accelerations, decelerations and spacing of vehicles were also extracted and used as inputs to the proposed models.

The dataset consisting of 170 observations of 79 rear-end conflicts and 91 sideswipe conflicts was used to compare the

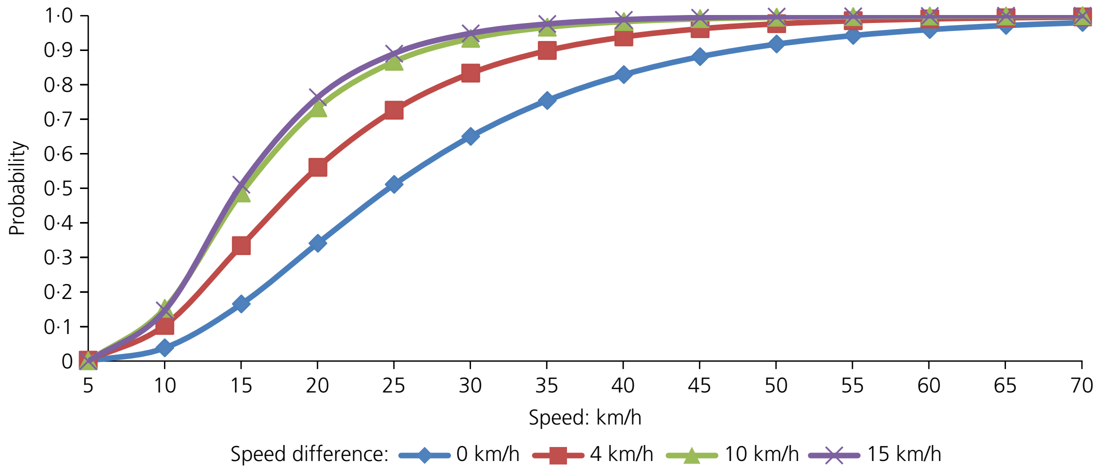

Figure 7. Probability of rear-end collisions occurring

Crash type	Number of observations	t	p-value	95% confidence interval	Mean of difference
Rear-end	79	10·58	< 0·05	0·05 and 0·08	0·06
Sideswipe	91	6·28	< 0·05	0·02 and 0·05	0·04

Table 3. Paired *t*-test results for verification of crash risk models

results estimated by the proposed models. A value of 1·0 was assigned to an observed conflict and a value of 0·0 was assigned otherwise. The results are summarised in Table 3. The *p*-values of the two cases are less than 0·05, implying that the relationship between the estimated results and the observations is strong. The differences between estimated and observed values were relatively small: the mean of the difference was only 0·06 and 0·04 for rear-end and sideswipe conflicts, respectively, which means that the estimated values of the model are sufficiently close to the observed data. In other words, the models developed in this study provide reasonable estimates for rear-end and sideswipe crash potentials for motorcyclists in motorcycle-dominated traffic situations on urban roads.

6. Conclusions

A new methodology to estimate rear-end and sideswipe crash risk for motorcyclists in motorcycle-dominated traffic conditions on urban roads using vehicle trajectory data in real time was presented in this paper. The innovative feature of the methodology is that non-lane-based movement, characteristic of motorcycles, is captured to evaluate its contribution to the risk of rear-end and sideswipe crashes. The developed models were verified using data collected from an urban road segment in the city of Danang in Vietnam.

The following conclusions can be drawn from the findings of this study.

- The proposed methodology provides a good estimate of the potential of rear-end and sideswipe crashes for motorcyclists in motorcycle-dominated traffic situations on urban roads.
- The potential of both rear-end and sideswipe crashes increases significantly with an increase in motorcycle speeds.
- The front distance, the longitudinal gap, the lateral gap, the lateral clearance and speed difference between vehicles were also found to have a significant effect on the risk of rear-end and sideswipe crashes. The higher the relative speed with the preceding vehicle the higher the rear-end crash risk, and the lower the lateral gap with the adjacent following vehicle the higher the sideswipe crash risk.
- The models developed could be invaluable tools for detecting hazardous traffic conditions associated with higher potential crash occurrence and countermeasures may therefore be subsequently identified to prevent them.
- The estimates of rear-end and sideswipe crash risks for motorcyclists obtained in this study may be integrated and enhanced with the International Road Assessment Programme (iRAP) star rating system methodology.

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