Crash Risk Models For A Motorcycle - Dominated Traffic Environment

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Abstract

This paper presents a methodology to estimate the potentials of rear-end and sideswipe crashes for motorcycles moving in a motorcycle-dominated traffic environment on urban roads and examines their integration in the International Road Assessment Programme (iRAP) star rating system. The crash risk models developed are based on discrete choice models and traffic conflict techniques. The proposed methodology was validated using data collected on road segments from the city of Danang in Vietnam. The models' field validation shows that the proposed methodology produces a good estimate of rear-end and sideswipe crash risk for motorcyclists and the enhanced iRAP star rating methodology produces most satisfactory results. It was found that risk factors such as front distance, longitudinal gap, lateral gap, lateral clearance, speed difference, and operating speed have a significant contribution to motorcycle crash risk and therefore they should be considered in the selection of appropriate countermeasures aimed at improving motorcyclist safety.

Introduction

The motorcycle is the predominant mode of urban transport in a number of low-income and middle-income countries worldwide, particularly in most Southeast Asian cities due to its affordability and flexibility in terms of movement and parking. As a result, crashes resulting in deaths and serious injuries involving motorcycles in these countries are significant. In certain countries, motorcycles' crashes may reach about 70% of the total road crashes. For example, in the city of Danang in Vietnam, motorcycles constitute over 80% of total traffic and motorcycles' crashes account for nearly 70% of the total road crashes (DoT, 2013). Similarly, in Indonesia, the number of motorcycles reached 78.3% of the total vehicle population and 75% fatalities of traffic crashes involved motorcyclists (Amelia and Harnen, 2010). In Taiwan, the motorcycles' crashes were about 88% of the total traffic crashes in 2011 (Ming et al, 2013) and in Malaysia in 2009, accident statistic data revealed that the ratio of other road users to motorcyclist fatalities was 1:1.52 (MIROS, 2011).

In motorcycle-dominated traffic conditions, it is found that non-lane based movements of motorcycles are the major contributors to motorcycle crash risk (Minh, 2007; Amelia and Harnen, 2010; Long, 2012; Shiomi et al., 2013). In Danang of Vietnam for example, crash data revealed that "changing lanes improperly" and "failed to keep safe following gap" are two major causes of motorcycle crashes, accounting for 19.3%, 31.9% respectively (DoT, 2013). Those causations were also found to contribute to a large proportion of motorcycles' crashes in Taiwan (Ming et al., 2013).

Although the movement characteristics of motorcycles are found to be a significant factor contributing to motorcycle crashes, it seems that to date there are no models taking into account explicitly these risk factors. To this end and to examine the effect of such manoeuvre behaviour of motorcyclists on crash risk, this study develops models to estimate the potentials of both rear-end and sideswipe crashes between motorcycles in a motorcycle-dominated traffic environment.

Literature Review

Several researchers have examined the risk factors affecting the motorcycles' crash frequency in the traffic environment of low-income and middle-income countries by developing crash prediction models based on historical data and statistical methods. For example, Harnen et al. (2006) developed a model to estimate the frequency of motorcycle crashes at junctions of urban roads in Malaysia. They suggested that the flow of non-motorcycle on a major road, the approach speed of vehicles, the junction geometry, the junction control and the land use are significant factors contributing to the occurrence of motorcycle crashes at junctions. Amelia and Harnen (2010) built a probability model to predict the motorcycle crash occurrence for the city of Malang in Indonesia and they suggested that gender (i.e. male riders), the increase of motorcycle ownership, long travel distances and little riding knowledge are factors that have a significant impact on the occurrence of motorcycle crashes. Manan et al. (2013) developed a safety performance function for fatal motorcycle crashes for primary roads and they suggested that an increase of traffic flow and number of access points per kilometer lead to an increase in motorcycle crash fatalities. However, it appears that to date there are no models developed to assess the effect of non-lane-based movement of motorcycle on crash occurrence. In addition, as most of the above models were built based on historical crash data, they inherit the drawback of poor data quality which is a major issue in most low-income and middle-income countries (Ismail, 2010; Laureshyn, 2010).

Although several researchers focused on investigating the effect of manoeuvre behaviour of motorcyclists on crash risk, they mainly focused on the conventional traffic environment of high-income countries where the passenger cars are the predominant vehicle types. For example, Elliot et al. (2006) using a questionnaire found that traffic errors, speed violations, stunts, safety equipment and control errors are significant factors relating to crash risk for motorcyclists. Pai and Saleh (2008) evaluated factors contributing to the severity level of motorcyclist injuries in sideswipe collisions between motorcycles and other motorised vehicles at T-junctions in the United Kingdom and they suggested that motorcyclist injuries are more severe when an overtaking motorcycle collides with a turning vehicle. Haque et al. (2009) examined the effect of roadway characteristics, environmental factors, motorcycle descriptions, and rider demographics on the fault of motorcyclists involved in crashes at intersections, expressways, and non-intersections and found that the higher the speed of motorcycles the higher likelihood of at-fault crashes on expressways.

Moreover, the International Road Assessment Programme (2009) developed a star rating protocol to assess the safety level for four road user groups including car occupants, motorcyclists, bicyclists and pedestrians. For motorcyclists, the star rating score is calculated for five crash types including run-off, head-on, intersection, property access and along crash. Due to the range of paths that motorcycles can take within traffic streams, those five crash types are likely to capture less of the total motorcycles' crashes (Lynam, 2012). Sideswipe crashes and rear-end crashes away from intersections are found to account for a large proportion of total motorcycles' crashes in urban environments (AASHTO, 2009; Davoodi et al., 2011; DoT, 2013; Ming et al., 2013). However, these two crash types are not taken into account by the existing iRAP star rating score system (iRAP, 2013) which is based on research covering more conventional traffic composition and focusing mainly on inter-urban roads.

Therefore, the literature review seems to suggest that there is a lack of models focusing on evaluating the movement characteristics of motorcycles contributing to the risk of crashes in the traffic environment where the motorcycle is the predominant mode of transport. In addition there is a need therefore to obtain a surrogate measure to address the limitation of historical crash data analysis approach and to develop a methodology to capture crash potentials associated with motorcyclists' manoeuvre behaviour in the above conditions. The preliminary results of the developed models may be used to support traffic engineers in improving urban road safety and developing appropriate countermeasures to mitigate the crash risk for motorcyclists.

Model Development

Model Formulation

Due to their small size and flexible turning radius, motorcycles can manoeuvre relatively freely in the traffic stream. In a motorcycle-dominated traffic environment, motorcycles do not conform to lane disciplines and lane markings as passenger cars do. They tend to swerve to change their directions and speeds frequently. Also, because they occupy a small space when travelling, motorcycles are able to travel alongside other vehicles in the same lane as well as filter through the lateral clearance between vehicles. These movement characteristics are described to be as the non-lane-based movement characteristics of motorcycles (Minh, 2007; Lee, 2007; Long, 2012; Shiomi et al., 2013). Such non-lane-based movement characteristics are found to be the major causes contributing to the crash risk for motorcyclists (Hsu et al, 2003; Minh, 2007; Amelia and Harnen, 2010; Long, 2012; Manan, 2014). The manoeuvre behaviour of motorcyclists in a motorcycle-dominated traffic environment may be illustrated as in Figure 1. The crash risk is defined as a traffic conflict event potentially leading to a crash if there are no evasive actions taken by road users involved. Under this assumption, two types of conflicts may be considered. One is the rear-end conflict occurring due to motorcycles' following manoeuvre that potentially lead to a rear-end crash. The other one is the sideswipe conflict occurring due to motorcycles' swerving manoeuvre that results potentially in a sideswipe crash.

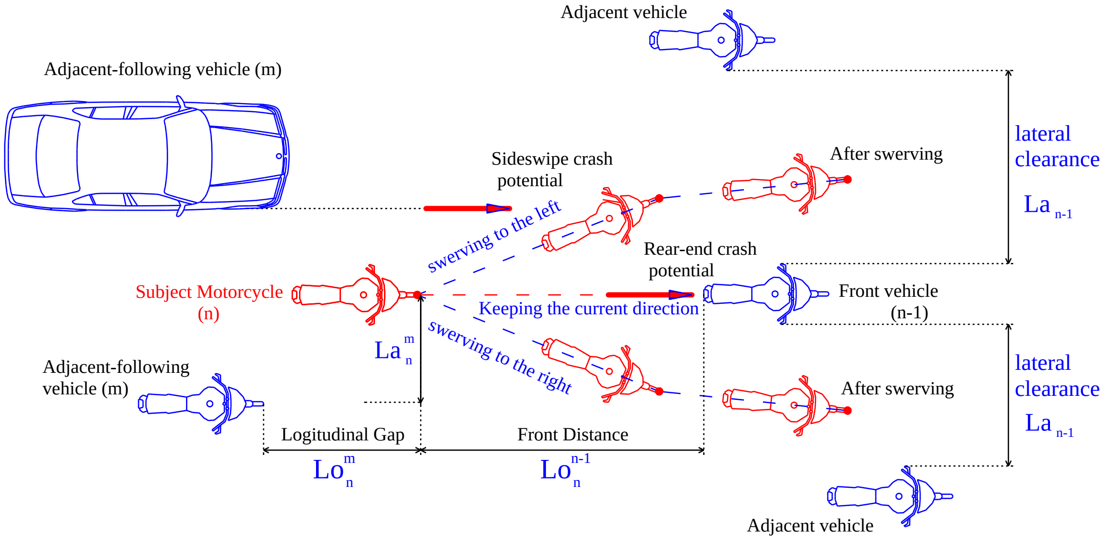

Figure 1. Manouevre behaviour of motorcycles in a motorcycle-dominated traffic situation

Rear-end crash risk model

The potential of a rear-end crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation may be defined as the result of a series of events: (i) the subject motorcycle (n) keeps its current direction to follow the front vehicle (n-1) with a front distance (Lo_n^{n-1}); (ii) the front vehicle suddenly slows down; (iii) the subject motorcycle must decelerate to reduce its speed to avoid a possible rear-end crash with the front vehicle and (iv) a rear-end conflict occurs if the front distance is less than the threshold safety distance (D_{TSD}^{FM}) and it potentially leads to a rear-end crash if no proper evasive actions taken by road users involved. Under the assumption that these events are independent, the probability that a rear-end crash may occur at a point of time t under a given traffic condition may be estimated by the joint probabilities of these events as follows:

$$Pr(RE_{n-1}^{n}) = Pr(FM_n|X) \times Pr(FM_{n-1}|X) \times Pr(C_n^{n-1}|D_{TSD}^{FM}) \quad (1)$$

where,

- $Pr(FM_n|X)$: is the probability that the subject motorcycle (n) will keep its current direction under a given traffic condition X.
- $Pr(FM_{n-1}|X)$: is the probability that the preceding vehicle (n-1) will keep its current direction under a given traffic condition X.
- $Pr(C_n^{n-1}|D_{TSD}^{FM})$: is the probability of occurring a rear-end conflict between the subject motorcycle (n) and the front vehicle (n-1).

Sideswipe crash risk model

The potential of a sideswipe crash for a motorcycle (n) moving in a motorcycle-dominated traffic situation may be defined as the result of a series of events: (i) the subject motorcycle (n) swerves to the left or right to overtake the front vehicle; (ii) the adjacent-following vehicle (m) must decelerate to reduce its speed to avoid a possible sideswipe crash with the subject motorcycle and (iii) a sideswipe conflict occurs if the longitudinal gap (Lo_n^m) is less than the threshold safety distance (D_{TSD}^{SM}) and it potentially results in a sideswipe crash if no proper evasive actions taken by road users involved. Under the assumption that these events are independent, the possibility that a sideswipe crash may occur at a point of time t under a given traffic condition may be estimated by the joint probabilities of these events as follow:

$$Pr(SW_n^m) = Pr(SM_n|X) \times Pr(FM_m|X) \times Pr(C_n^m \middle| D_{TSD}^{SM}) \quad (2)$$

where,

- $Pr(SM_n|X)$: is the probability that the subject motorcycle (n) will swerve to the left and right under a given traffic condition X.
- $Pr(FM_m|X)$: is probability that the adjacent-following vehicle (m) will keep its current direction under a given traffic condition X.
- $Pr(C_n^m \middle| D_{TSD}^{SM})$: is the probability of occurring a sideswipe conflict between the subject motorcycle and the adjacent-following vehicle (m).

Model components

To fully implement the proposed estimation methodology in Equation (1) and (2), two probabilities should be calculated: (i) the probabilities that the motorcycle chooses either a swerving manoeuvre or a following manoeuvre to perform in a given traffic condition, and (ii) the probabilities of the conflicts to occur.

To capture the probability that the subject motorcycle chooses either swerving manoeuvre or following manoeuvre to perform in a given traffic condition, a manoeuvre choice model is developed based on the discrete choice analysis using the binary logistic regression model. The form of binary logistic regression model represents the probability that a motorcycle choose a swerving manoeuvre behaviour as follows (Ben-Akiva and Lerman, 1985):

$$Pr(SW_n|X) = \frac{e^{g(x_i)}}{1 + e^{g(x_i)}} \qquad (3)$$

The probability that a motorcycle chooses a following manoeuvre behaviour is given by:

$$Pr(KS_n|X) = 1 - Pr(SW_n|X) = 1 - \frac{e^{g(x_i)}}{1 + e^{g(x_i)}} = \frac{1}{1 + e^{g(x_i)}} \qquad (4)$$

where, g(x) is the logit of the logistic regression model, x_i are independent variables affecting the choice of swerving manoeuvre behaviour of the subject motorcyclist.

It is felt that before deciding to choose a path to travel in a traffic stream, drivers normally evaluate the current driving conditions with respect to the relation with surrounding vehicles. In other words, the presence of neighbouring vehicles on the road directly affects the subject drivers' decisions for their movement choices. It therefore seems reasonable to suggest that the movement behaviour of the subject motorcyclist depends on the relative positions and relative speeds of the subject motorcycle with respect to its surrounding vehicles including: the relative speeds with the front vehicle ($V_{\mathrm{n}}^{\mathrm{n-1}}$), the relative distance with the front vehicle ($Lo_{\mathrm{n}}^{\mathrm{n-1}}$), the lateral clearance beside the front vehicle (La_{n-1}), the relative speeds with the adjacent-following vehicle ($V_{\mathrm{n}}^{\mathrm{m}}$), the longitudinal gaps with the adjacent-following vehicle *(Lo_n^m)*, the type of front vehicle (Te_{n-1}) and the type of adjacent-following vehicle (Te_m). In a motorcycle dominated traffic environment, the type of front vehicle and adjacent-following vehicle may be a motorcycle or a passenger car. Heavier vehicles such as buses or trucks were not considered in this study. These variables are illustrated in Figure 1.

Therefore, the logit of the logistic regression model *$g(x_i)$* for the seven independent variables x_i = ($Lo_{\mathrm{n}}^{\mathrm{n-1}}$, $V_{\mathrm{n}}^{\mathrm{n-1}}$, Lo_n^m, $V_{\mathrm{n}}^{\mathrm{m}}$, La_{n-1}, Te_{n-1}, Te_m) may be formulated as follows:

$$g(x_i) = \beta_0 + \beta_1 Lo_n^{n-1} + \beta_2 V_n^{n-1} + \beta_3 Lo_n^m + \beta_4 V_n^m + \beta_5 La_{n-1} + \beta_6 Te_{n-1} + \beta_7 Te_m \quad (5)$$

where, β_0, β_1, β_2, β_3, β_4, β_5, β_6, β_7 are unknown coefficients of independent variables to be estimated from the real data.

This paper defines traffic conflict as a condition of two consecutively moving motorcycles having inadequate threshold-safety-distance (TSD) such that the following motorcycle will crash into the preceding motorcycle when it swerves or makes an unexpected stop. The TSD indicators are calculated based on the stopping distance of a vehicle and identified separately for the rear-end conflict scenario (D_{TSD}^{FM}) and the sideswipe conflict scenario (D_{TSD}^{SM}) (see Appendix A). In a real traffic stream, the front distances (Lo_n^{n-1}) and the longitudinal gaps (Lo_n^m) are likely to follow a lognormal distribution (Minh, 2007; Lee, 2009). Therefore, the probability that the rear-end conflicts occur on a road segment may be predicted based on a lognormal distribution function as follows:

$$Pr(C_n^{n-1} | D_{TSD}^{FM}) = Pr(Lo_n^{n-1} \leq D_{TSD}^{FM}) = \Phi\left[\frac{ln(D_{TSD}^{FM}) - \mu^{Lo_n^{n-1}}}{\sigma^{Lo_n^{n-1}}}\right] \quad (6)$$

where, $\Phi[\cdot]$ denotes the cumulative standard normal distribution, $\mu^{Lo_n^{n-1}}$ and $\sigma^{Lo_n^{n-1}}$ are the mean and standard deviation of the logarithm of front distances respectively.

Similarly, the probability that the sideswipe conflicts occur on a road segment is expressed by:

$$Pr(C_n^m \middle| D_{TSD}^{SM}) = \Pr(Lo_n^m \leq D_{TSD}^{SM}) = \Phi\left[\frac{\ln(D_{TSD}^{SM}) - \mu^{Lo_n^m}}{\sigma^{Lo_n^m}}\right] \quad (7)$$

where, $\Phi[\cdot]$ denotes the cumulative standard normal distribution, mean $\mu^{Lo_n^m}$ and $\sigma^{Lo_n^m}$ are the mean and standard deviation of the logarithm of longitudinal gaps respectively.

Model Specification

To specify the proposed model, a traffic survey was conducted on a road segment in the city of Danang in Vietnam. Vehicles' trajectory data was collected using video recording. A representative road segment of length 40 m and of width 7.0 m on the Nguyen Tri Phuong street was chosen that could be captured by the video camera (see Appendix B). The traffic survey was conducted on 20 August, 2014, from 6:00 am to 09:00 am and 3:00 pm to 6:00 pm. The trajectories of vehicles were manually extracted from the recorded video file using the SEV (Speed Estimation from Video Data) computer software (Minh, 2007) which converts video screen coordinates into roadway coordinates. As a result, a data set containing 535 observations of the trajectories of 115 subject motorcycles and 2675 observations of 575 influential vehicles was used to estimate the unknown coefficients of the proposed models. The data set included flow density, relative positions, speeds, accelerations and decelerations of each vehicle.

The statistical software SPSS was used to analyze the vehicle trajectory data and to estimate the unknown coefficients of independent variables. The Wald test revealed that the (Te_{n-1}) variable does not affect significantly on the swerving manoeuvre decision of motorcyclists and thus it was removed from the model. The final estimate results are summarized in Table 1 together with further statistical tests. As a result, the best fitting model capturing the probability that the motorcyclist chooses a swerving manoeuvre is expressed:

$$Pr(SM_n|X) = \frac{e^{-0.524-\ 1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}}{1+e^{-0.524-\ 1.677Lo_n^{n-1}+1.452V_n^{n-1}+0.139Lo_n^m+0.224V_n^m+1.445La_{n-1}-0.642Te_m}} \quad (8)$$

By considering the statistical tests shown in Table 1, it may be seen that the estimated coefficients of independent variables are statistically significant which means that the proposed model satisfactorily captures the swerving manoeuvre choice behaviour of motorcyclists in a motorcycle-dominated traffic situation.

Table 1. Estimated coefficients for the best fitting manoeuvre choice model

Variables	Estimated Parameters	Standard Error	Wald test	p-value
Lo_n^{n-1}	-1.677	0.234	51.246	< 0.001
V_n^{n-1}	1.452	0.283	26.379	< 0.001
Lo_n^m	0.139	0.056	6.161	0.013
V_n^m	0.224	0.109	4.196	0.041
La_{n-1}	1.445	0.193	56.020	< 0.001
Te_m	-0.642	0.096	44.652	< 0.001
constant	-0.524	0.591	0.785	0.376

The statistical characteristics of the longitudinal gaps and the front distances from the data set were investigated and it was found that these distances are correlated with the traffic density condition and may be fitted with a polynomial function as shown in Table 2. The Kolmogorov-Smirnov test (K-S test) measure was also applied to verify the assumption of the distribution for these distances and the results illustrate that they follow a lognormal distribution.

Table 2. The statistical properties of longitudinal gaps and front distances

Factor	Lognormal distribution			K-S test
	Mean	R-squared value	Standard Deviation	Confidence
Front distance	$7*10^{-5}\,Den^2-0.019Den+2.108$	0.75	0.52	0.51
Longitudinal gap	$4*10^{-5}\,Den^2-0.013Den+1.823$	0.62	0.30	0.95

where, *Den:* is the traffic density defined as the number of motorcycles travelling on a road segment of length 100 m and width 10 m.

Therefore, Equation (6) and (7) become:

$$Pr(C_n^{n-1}|D_{TSD}^{FM}) = \Phi\left[\frac{ln(D_{TSD}^{FM}) - (7 * 10^{-5}\ Den^2 - 0.019Den + 2.108)}{0.52}\right] \quad (9)$$

$$Pr(C_n^{m}|D_{TSD}^{SM}) = \Phi\left[\frac{ln(D_{TSD}^{SM}) - (4 * 10^{-5}\ Den^2 - 0.013Den + 1.823)}{0.3}\right] \quad (10)$$

Model verification

The main purpose of the field validation task was to verify the performance of the proposed models in the real-world by comparing the predictive conflict frequency produced by the proposed models with the actual conflict frequency observed in the field. This verification task is conducted in two steps. First, rear-end conflict and sideswipe conflict frequencies are observed in the field for different time periods in a day in order to fully capture conflict frequencies for both peak hours and non-peak hours. Second, the frequencies of rear-end and sideswipe conflicts are predicted using the proposed models for those same time periods and then the estimate results are compared with the real observed conflict frequencies in the field by determining the percentage correct of estimate with observed values. The data used for this field verification was collected on a road segment of length 40.0 m and of width 7.5 m on Truong Chinh street. The comparison results for each hour of six hours from 6:00 am to 9:00 am and from 3:00 pm to 6:00 pm are presented in Table 3 and show a good degree of accuracy between predicted and observed conditions. It is appreciated however that a more extensive trial programme could lead to a calibrated model.

Table 3. The comparison results between predicted and observed conflict frequency

Time periods	**Predicted conflicts**			**Observed conflicts**			**Percentage correct (+/- %)**
	Rear-end	**Sideswipe**	**Total**	**Rear-end**	**Sideswipe**	**Total**	
6:00am-7:00am	7.4	3.6	11.0	9	5	14	78.5
7:00am-8:00am	32.7	8.1	40.8	27	10	37	89.8
8:00am-9:00am	19.6	11.8	31.4	24	14	38	82.6
3:00pm-4:00pm	4.1	1.7	5.8	5	2	7	83.0
4:00pm-5:00pm	18.6	8.8	27.3	22	12	34	80.4
5:00pm-6:00pm	57.3	12.9	70.2	46	15	61	84.9

Sensitivity Analysis

The effect of input variables on the outputs of the proposed models was tested. To simplify the process, several input variables were assumed to be a constant. The reaction time (τ) of the motorcyclists is 0.5 second (Minh, 2007), the braking deceleration of motorcycles in emergency situation is 6.02 m/s/s (Davoodi and Hamid, 2013), the swerving angle is 12.5 degree (the mean determined from the collected data set). Therefore, the effects of the following input data on the model was tested: Front distance; Longitudinal gap; Speed; Speed difference; Traffic density and Lateral clearance (see Appendix C).

Model Application

The Development of Conflict Modification Factor (CoMF)

To address specific safety concerns of a specific location on road networks, a treatment should be determined and implemented. To estimate the effectiveness of a treatment, Crash Modification Factor (CMF) is used as a tool to support this effort. CMF is used to estimate crash frequency or the change in crashes due to the implementation of a given countermeasure at a specific location by multiplying a CMF with the number of crashes before applying a treatment to estimate the number of crashes after applying a treatment (AASHTO, 2009; Gross et al., 2010).

In low-income and middle-income countries, obtaining reliable crash data to define CMFs is a difficult task due to the under-reporting of accidents and the poor quality of historical crash data (Lynam, 2012). Therefore, this study proposes a concept of Conflict Modification Factor (CoMF) and as potential surrogate measure to CMF in road safety assessment due to the following reasons:

- The causal mechanism for conflicts and crashes are similar (Hyden, 1987; Svensson, 1998; Guo et al., 2010).
- There is a strong relationship between the frequency of conflicts and crashes (Hyden, 1987; Svensson, 1998; Archer, 2004; Guo et al., 2010).
- The contributing factors and risk factors are not significantly different for crashes and near-crashes (Guo et al., 2010).

CoMFs are defined as the ratio of the likelihood of conflicts for a specific location under a specific condition to the likelihood of conflicts for the same location under a base condition. According to this definition, CoMFs of risk factors may be used as the relative risk values presenting the changes in crash potentials due to the change in values of those risk factors.

To this end, CoMFs are developed in this study as follows. The likelihood of the occurrence of an event (e.g. conflict) may be expressed (Guo et al., 2010) as follows:

$$likelyhood\ of\ conflict = \frac{probability\ of\ event\ occurrence}{probability\ of\ event\ nonoccurrence} \qquad (11)$$

Subsequently, the CoMFs may be calculated as follows:

$$Conflict\ Modification\ Factor = \frac{likelyhood\ of\ conflict_{certain\ traffic\ conditions}}{likelyhood\ of\ conflict_{baseline\ traffic\ condition}} \qquad (12)$$

The baseline traffic condition is defined as the normal driving condition in which motorcyclists can move freely in the traffic stream with a low crash risk level. As a result, for the proposed crash risk models, CoMFs are developed for its variables (i.e. traffic density, operating speed, speed difference, front distance, longitudinal gap, lateral clearance, lateral gap, road surface condition, separate motorcycle lane, presence of heavier vehicles) based on the sensitivity analysis of section 3.4. The relative risk values (CoMFs) of these variables are presented in Appendix D.

Enhancing the existing iRAP star rating system for motorcyclists

Methodology

The International Road Assessment Programme (iRAP) has developed a Star Rating methodology to assess and improve the safety of roads in the low-income and middle-income countries (iRAP methodology, 2013). It is based on the assessment of infrastructure attributes to identify the likelihood of a crash and its severity. For motorcyclists, the star rating score is based on assessing five crash types including run-off crash, head-on crash, intersection crash, property access crash, and along crash. These are likely to capture less of the total motorcycles' crashes in urban environments (Lynam, 2012). The existing star rating score (SRS) is calculated as follows:

$$\text{Motorcyclist SRS} = (\text{Run-off} + \text{Head-on} + \text{Intersection} + \text{Property} + \text{Along}\ )\ \text{Crash Scores}$$

Therefore, to provide an enhanced tool for assessing the motorcyclist safety in a motorcycle-dominated traffic environment, the existing star rating score system may be enhanced by taking into account the risk of rear-end and sideswipe crashes as follows:

$$\begin{aligned}\text{Enhanced Motorcyclist SRS} = (&\text{Run-off} + \text{Head-on} + \text{Intersection} + \text{Property} + \text{Along} \\ &+ \text{Rear-end} + \text{Sideswipe})\ \text{Crash Scores}\end{aligned} \tag{13}$$

The scores of rear-end and sideswipe crashes are calculated as follows:

$$\begin{aligned}(\text{Rear-end / Sideswipe})\ \text{Crash Score} = &\ \text{Likelihood} \times \text{Severity} \times \text{Operating speed} \\ &\times \text{External flow influence}\end{aligned} \tag{14}$$

where,

- Likelihood refers to attribute risk factors that account for the chance that a crash will be initiated
- Severity refers to attribute risk factors that account for the severity of a crash
- Operating speed refers to factors that account for the degree to which risk changes with speed
- External flow influence factors account for the degree to which a person's risk of being involved in a crash is a function of another person's use of the road

The risk factors that contribute to the likelihood and severity of rear-end and sideswipe crashes are shown in Table 4.

Table 4. Risk factors of Likelihood and Severity for rear-end and sideswipe crash type

Crash type	Risk factors attribute the Likelihood	Risk factors attribute the Severity
Rear-end	• Front distance • Road surface condition • Separate motorcycle lane	• Speed • Presence of heavier vehicles • Separate motorcycle lane
Sideswipe	• Longitudinal gap • Lateral gap • Road surface condition • Separate motorcycle lane	• Speed • Presence of heavier vehicles • Separate motorcycle lane

In the iRAP methodology, the relative risk values of the above factors are known as Crash Modification Factors (CMFs) (iRAP methodology, 2013). In a similar and simplified manner, the scores of rear-end crash type and sideswipe crashes are associated with the CoMF which are based on potential conflicts instead of actual crashes. In other words, CMF represents the relative change in the crash frequency due to the change in one specific risk factor and CoMF represents the relative change in the conflict frequency due to the change in one specific risk factor.

Comparison

To compare the outputs between the existing iRAP star rating system and the enhanced iRAP star rating system, real data was collected from five homogeneous road sections chosen randomly from five divided roads in the city of Danang in Vietnam and then analyzed (see Appendix E). The results (see Table 5) show that the existing iRAP star rating system produces the same Star Rating Score (SRS) for all locations, implying that all these locations have the same risk. However, the actual historical crash data of these locations are different and they present the same trend with the SRS produced by the enhanced iRAP star rating methodology.

Table 5. Comparison results between existing and enhanced iRAP star rating system

Location	**Existing iRAP Star Rating system**		**Enhanced iRAP Star Rating system**	
	SRS	**Rating star**	**SRS**	**Rating star**
1	0.76	5-star	2.9	4-star
2	0.76	5-star	2.2	5-star
3	0.76	5-star	2.6	4-star
4	0.76	5-star	3.3	4-star
5	0.76	5-star	3.5	4-star

The above was tested further first by calculating the average yearly crash frequency for each road segment as proposed by AASHTO’s Highway Safety Manual (HSM) (2009). These locations were then ranked based on the predicted average yearly crash frequency in descending order. The same locations were ranked based on the enhanced iRAP star ratings and based on the average yearly actual crash frequency (real crash data collected over the period from 2008 to 2015) and then by using the Spearman rank correlation coefficient the three rankings were compared.

The outputs of methodologies and the corresponding rankings for locations are shown in Table 6 and the Spearman correlation coefficients are shown in Table 7. The comparison results reveal that there is a strong correlation between the outputs of the enhanced iRAP star rating methodology with the actual historical crash data, implying that the enhanced iRAP methodology produce most satisfactory results.

Table 6. Outputs of methodologies and rankings for road segments

Location	**Enhance iRAP methodology**		**HSM methodology**		**Actual historical crash**	
	SRS	**Ranking**	**Crash frequency**	**Ranking**	**Crash frequency**	**Ranking**
1	2.9	3	0.6	2	3.3	3
2	2.2	5	0.4	4	1.4	5
3	2.6	4	0.5	3	2.5	4
4	3.3	2	0.6	2	4.2	2
5	3.5	1	0.8	1	5.5	1

Table 7. Spearman rank correlation coefficient

Methodology	Average actual historical crash
Enhanced iRAP SRS	1.00**
HSM methodology	0.97**

** Correlation is significant at the 0.01 level

Conclusion

The paper presented a methodology to estimate the rear-end and sideswipe crash risk for motorcyclists in a motorcycle-dominated traffic environment of urban roads. The innovative feature of the methodology is the non-lane-based movement of motorcycle is captured to evaluate its contribution to the crash risk. In addition, a new concept of Conflict Modification Factor was proposed as a potential surrogate measure to Crash Modification Factor in road safety assessment and a methodology to integrate the developed models with the existing iRAP star rating system was also presented in the paper. Furthermore, the study focused on the contribution of infrastructure factors and traffic conditions to the potential of motorcycle crashes. Other contributing factors that may affect motorcyclists' crash risk may include their knowledge and experience, alcohol or drugs consumption, and motorcycle capabilities but these were not included in the proposed models as in most cases this information cannot be directly measured from vehicles' trajectory data in real time.

In conclusion:

a) The developed methodology provides a good estimate of both the rear-end crash and sideswipe crash risks for motorcyclists in a motorcycle-dominated traffic environment of urban roads.

b) The front distance, the longitudinal gap, the lateral gap, the lateral clearance, speed difference, and the speed of motorcycles were found to be the predominant factors contributing to the rear-end and sideswipe crash risk.

c) The models may estimate the rear-end and sideswipe crash risk for motorcyclists using real time data; this could be an invaluable tool in detecting hazardous roads in traffic conditions were motorcycles is the predominant mode of transport.

d) A Conflict Modification Factor (CoMF) was proposed in this study as a surrogate measure to Crash Modification Factor for road safety assessment in order to overcome the under-reporting or unavailability of historical crash data in low-income and middle-income countries.

e) The proposed methodology to enhance the current iRAP star rating system seems to produce reliable results and subject to more testing, may be considered for full implementation.

f) The proposed models may assist traffic engineers in detecting hazardous locations associated with higher motorcycles' crash risk and developing appropriate countermeasures to improve motorcyclist safety.

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Appendix A

Threshold-safety-distance calculation

With regard to rear-end conflict scenario as illustrated in Figure A1, it is assumed that the front vehicle (n-1) suddenly decelerates to slow down and the subject motorcycle (n) responds to this urgent situation by applying the brake to avoid a possible crash. The threshold-safety-distance of this scenario is defined as the distance that the subject motorcycle needs to stop to avoid a possible crash with the front vehicle. This distance may be calculated as:

$$D_{TSD}^{FM} = v_n \tau_n + \frac{v_n^2}{2a_n} - \frac{v_{n-1}^2}{2a_{n-1}} \quad (A.1)$$

where, D_{TSD}^{FM} is the threshold-safety-distance for rear-end conflict scenario; τ_n, v_n and a_n are the reaction time, initial speed and braking deceleration of the subject motorcycle respectively; v_{n-1} and a_{n-1} are initial speed and braking deceleration of the front vehicle respectively.

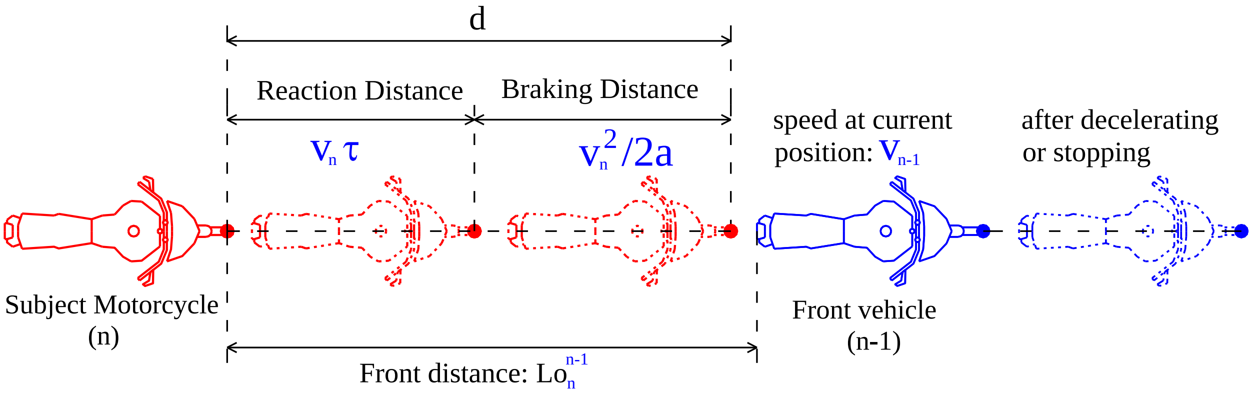


Figure A1. Rear-end conflict scenario

With regard to sideswipe conflict scenario, it is assumed that the trajectory of the subject motorcycle (n) is the hypotenuse of a right triangle as illustrated in Figure A2 and the adjacent-following vehicle (m) starts braking while the subject motorcycle starts swerving. The threshold-safety-distance of this scenario is defined as the distance that the vehicle (m) needs to stop to avoid a possible collision while the motorcycle (n) executes a swerving manoeuvre. This distance may be calculated as:

$$D_{TSD}^{SM} = v_m \tau_m + \frac{v_m^2}{2a_m} - \frac{La_n^m \times cos\alpha_n}{sin\alpha_n} \quad (A.2)$$

where, D_{TSD}^{SM} is the threshold-safety-distance for sideswipe conflict scenario; τ_m, v_m and a_m are the reaction time, initial speed and braking deceleration of vehicle (m) respectively, La_n^m is the initial lateral gap between motorcycle (n) and vehicle (m), and α_n is the swerving angle of motorcycle (n).

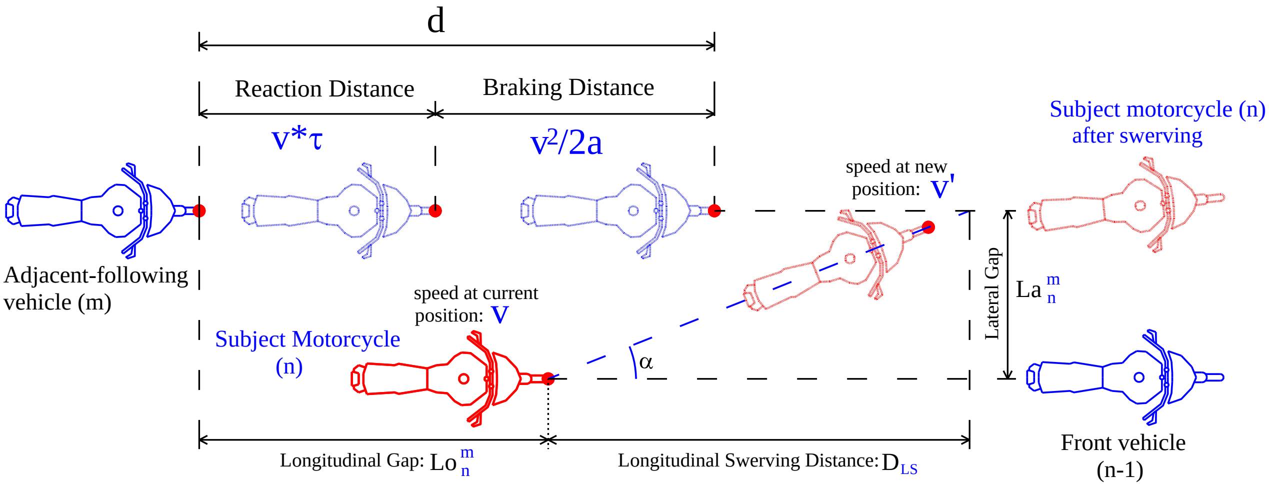


Figure A2. Sideswipe conflict scenario

Appendix B

The selected road segment for traffic survey

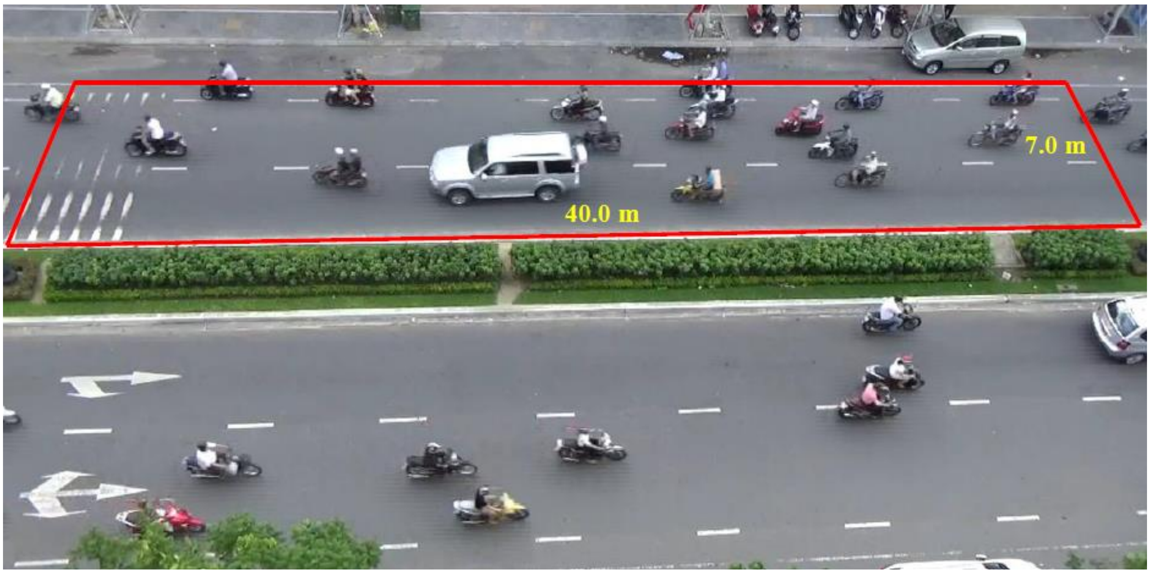


Figure B. The selected road segment for traffic survey

Appendix C

Sensitivity analysis results

Figure C.1. Effect of front distance on crash risk

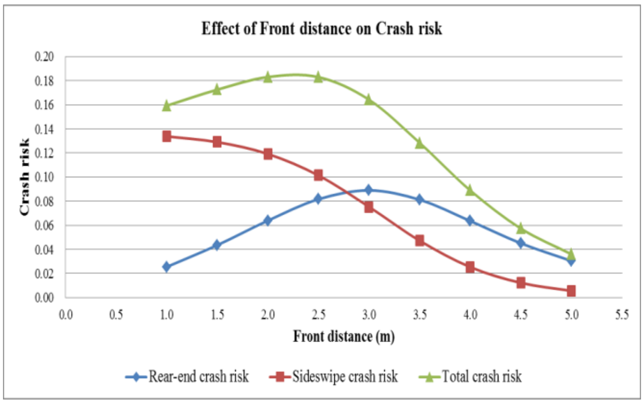


Figure C.2. Effect of longitudinal gap on crash risk

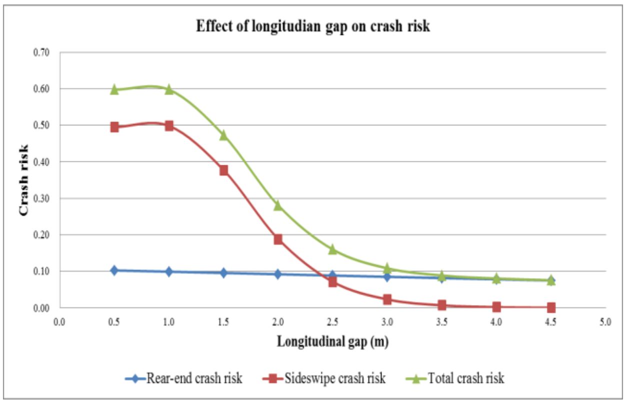


Figure C.3. Effect of speed on crash risk

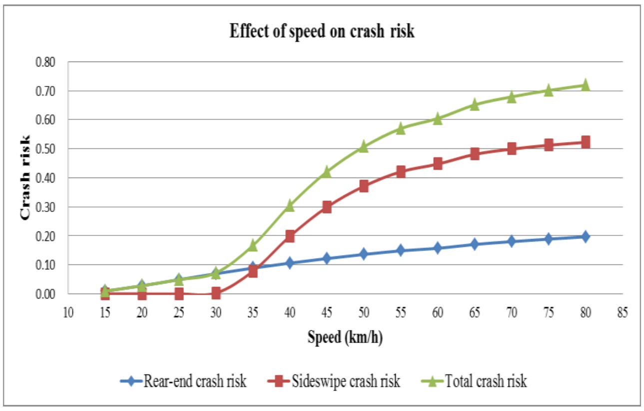


Figure C.4. Effect of speed difference on crash risk

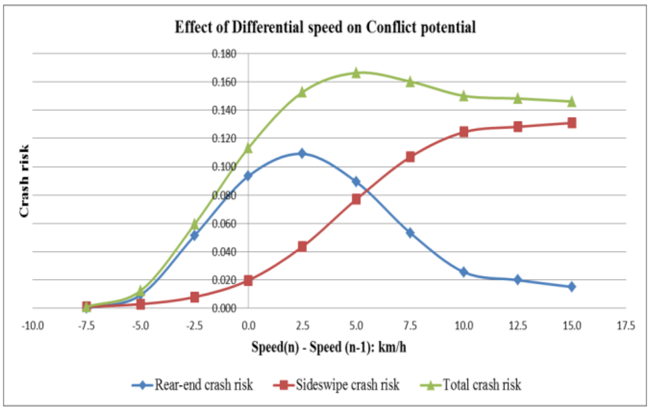


Figure C.5. Effect of traffic density on crash risk

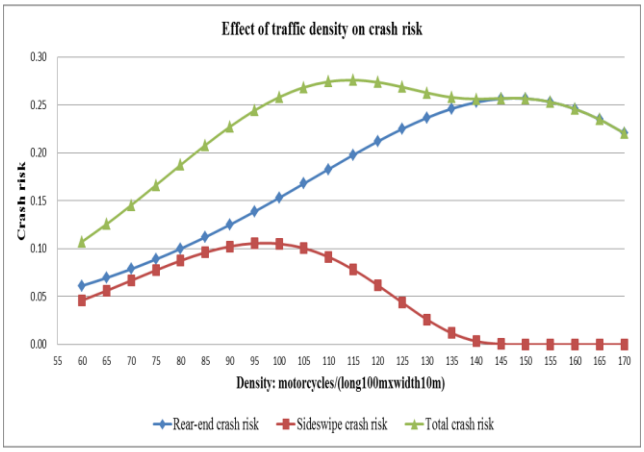
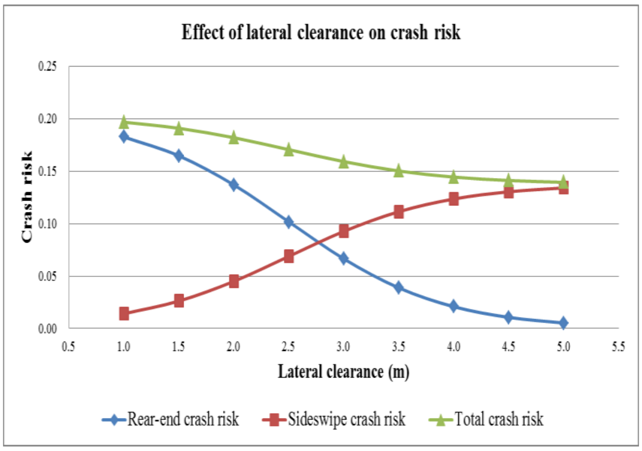


Figure C.6. Effect of lateral clearance on crash risk



Appendix D

Relative risk values of risk factors

Table D1. Relative risk values of front distance factor

Front distance (m)	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**
Rear-end crash	0.5	0.8	1.0	1.1	1.0	0.8	0.5	0.4
Sideswipe crash	3.0	2.7	2.3	1.6	1.0	0.5	0.2	0.1

Table D2. Relative risk values of speed difference factor

Speed difference (km/h)	**-7.5**	**-5.0**	**-2.5**	**0.0**	**2.5**	**5.0**	**7.5**	**10.0**	**12.5**	**15.0**
Rear-end crash	0.01	0.1	0.5	1.0	1.2	1.0	0.5	0.3	0.2	0.1
Sideswipe crash	0.1	0.1	0.4	1.0	2.2	4.1	5.9	7.0	7.3	7.4

Table D3. Relative risk values of longitudinal gap factor

Longitudinal gap (m)	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**
Rear-end crash	1.1	1.1	1.0	1.0	1.0	0.9	0.9	0.8
Sideswipe crash	12.9	7.9	3.0	1.0	0.3	0.1	0.01	0.01

Table D4. Relative risk values of lateral clearance factor

Lateral clearance (m)	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**
Rear-end crash	2.8	2.2	1.6	1.0	0.6	0.3	0.2
Sideswipe crash	0.3	0.5	0.7	1.0	1.2	1.4	1.5

Table D5. Relative risk values of speed factor

Speed (km/h)	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**65**	**70**
Rear-end crash	0.5	0.8	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3
Sideswipe crash	0.0	0.1	1.0	2.9	5.0	7.0	8.6	9.6	10.9	11.8

Table D6. Relative risk values of traffic density factor

Traffic density	**Free flow**	**Few restriction**	**Low restriction**	**Moderate restriction**	**High restriction**	**Very high restriction**
Rear-end crash	0.75	1.0	2.0	3.0	3.5	2.5
Sideswipe crash	0.75	1.25	1.5	0.5	0.25	0.1

Table D7. Relative risk values of lateral gap factor

Lateral gap (m)	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**
Rear-end crash	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Sideswipe crash	2.4	1.0	0.1	0.0	0.0	0.01	0.01	0.01

Table D8. Relative risk values for road surface condition factor

Road surface condition	**Dry Pavement**	**Wet Pavement**

Rear-end crash	1.00	1.1
Sideswipe crash	1.00	1.7

Table D9. Relative risk values of vehicle factor

Vehicle factor	**Motorcycle**	**Heavier vehicle**
Rear-end crash	1.00	1.5
Sideswipe crash	1.00	2.3

Table D10. Relative risk values of motorcycle lane presence

Separate motorcycle lane	**Absence**	**Presence**
Rear-end crash	1.00	0.66
Sideswipe crash	1.00	0.43

Appendix E

Traffic characteristics of road segments and historical crash data

Table E. Traffic characteristics of road segments and historical crash data

Location	**Volume (vehicles/day)**	**Density (vehicles/1000m^2)**	**Average speed (m/s)**	**Crash records (2008-2015)**	
				Rear-end	**Sideswipe**
1	59704	89	9.68	21	5
2	41621	68	9.99	9	2
3	49706	72	9.83	16	4
4	61402	94	9.48	27	7
5	78945	76	9.19	35	9

- Historical crash data collection source: Danang Department of Transport

Appendix F

Non-lane based movement characteristics of motorcycles

Due to their small size and flexible turning radius, motorcycles can manoeuvre relatively freely in the traffic stream. In a motorcycle-dominated traffic environment, motorcycles do not conform to lane disciplines and lane markings as passenger cars do. They tend to swerve to change their directions and speeds frequently. Also, because they occupy a small space when travelling, motorcycles are able to travel alongside with other vehicles in the same lane as well as filter through the lateral clearance between vehicles. These movement characteristics are described to be as the non-lane-based movement characteristics of motorcycles (Minh, 2007; Lee, 2007; Long, 2012; Shiomi et al., 2013). Such non-lane-based movement characteristics (e.g. Alongside manoeuvre, Oblique following manoeuvre, Filtering manoeuvre, Swerving/Weaving manoeuvre) were discussed in a number of previous studies as follows:

Alongside manoeuvre

Due to small size with the average width of 0.75 m which accounts for only 25 per cent of an average car-lane of 3.0 m, motorcycles occupy a small space while moving on roads and they are therefore capable of travelling alongside with other motorcycles in the same car-lane (Hsu et al., 2003; Minh, 2007; Lee, 2007; Long, 2012). Minh (2007) also described this behaviour as a pair-riding manoeuvre of motorcycles and it is commonly observable in a motorcycle-dominated traffic environment.

Oblique following maneuver

Due to a flexible movement characteristic, motorcycles can follow the preceding vehicle at an oblique position (Lee, 2007; Long, 2012). For this manoeuvre behaviour, motorcyclists can achieve a better view in front of and a better chance to overtake the front vehicle.

Filtering maneuver

Due to a small size and a flexible turning radius, motorcycles can move freely in the traffic stream. The filtering manoeuvre refers to the behaviour that a motorcycle moves through the lateral clearance between vehicles to achieve a desired speed and a better condition (Elliott et al., 2003; Minh, 2007; Lee, 2007; Long 2012). Minh (2007) described this behaviour as a zigzag movement of motorcycles and they tend to perform this manoeuvre frequently in a motorcycle-dominated traffic environment.

Swerving/weaving manoeuvre

Due to a small turning radius, motorcycles can make turns easily. The swerving manoeuvre refers to the behaviour that a motorcycle changes its current direction to move to the left or right beside the front vehicle. It may be sometimes followed by an overtaking or filtering movement. This is the typical behaviour that represents the none-lane-based movement characteristic of motorcycles and can be frequently observable in motorcycle-dominated traffic environments (Minh, 2007; Lee, 2007; Long, 2012).