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# Safe Following Distances for Motorcycle to Prevent Rear-end Collision

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**Abstract** – *Rear-end collision is one of the top accidents for the motorcycle in ASEAN countries because the motorcyclists always keep their following distances too short. There are no specific safe distances suggested for motorcycle especially in an emergency braking situation. This study proposed a model based on the piecewise linear model of motorcycle braking deceleration profile and kinematic equations for calculating the stopping distances in a worst-case scenario. The calculated results were compared to the braking experiment and test results from other studies. The information from this study can be useful to relevant authorities such as driving institutes and enforcement agencies in order to setup a safety measure for the motorcyclists.*

**Keywords:** Motorcycle, following distance, deceleration profile, Piecewise linear model



## 1.0 INTRODUCTION

The use of motorcycles is very high amongst ASEAN countries. The number of motorcycle sales in 2018 is more than 13 million units in the ASEAN market (ASEAN Automotive Federation, 2018) and the number is increasing every year. Motorcyclists are very much prone to accidents on the road due to various reasons. Many factors such as chaotic manner of drivers, road traffic infrastructure, and education cause traffic congestion and accidents (Kitamura et al., 2018). Figure 1 shows traffic accident fatalities from two- and three-wheelers among ASEAN countries in 2018. It is clearly shown that motorcycle is the major cause of death comparing to other types of vehicles.

There are many types of motorcycle crashes which can be classified into rear-end collision, head-on collision, sideswipe, fixed object collision, pedestrian and animal collision, out of control, etc. (Ishak, 2018). The rear-end collision is one of the top motorcycle accidents in many ASEAN countries (Larbwisuthisaroj, 2016; Kitamura et al., 2018; Ishak, 2018; Ponboon et al., 2019). Some main causes of the rear-end collision include driver's errors, e.g.

inadequate surveillance, distraction, false assumption, too-close following distance (Larbwisuthisaroj, 2016). Some studies observed riding behavior of motorcycles behind the vehicles by using a video recorder and then the data were analysed by statistical methods. The results from various countries show that most of the motorcyclists kept their time headway only around 1.5 to 2 s (Minh et al., 2005; Wedagama, 2017; Lee et al., 2012). Thus, maintaining a minimum safe following distance would lead to the elimination of major collisions with the leading vehicle in situations where braking is immediately applied.

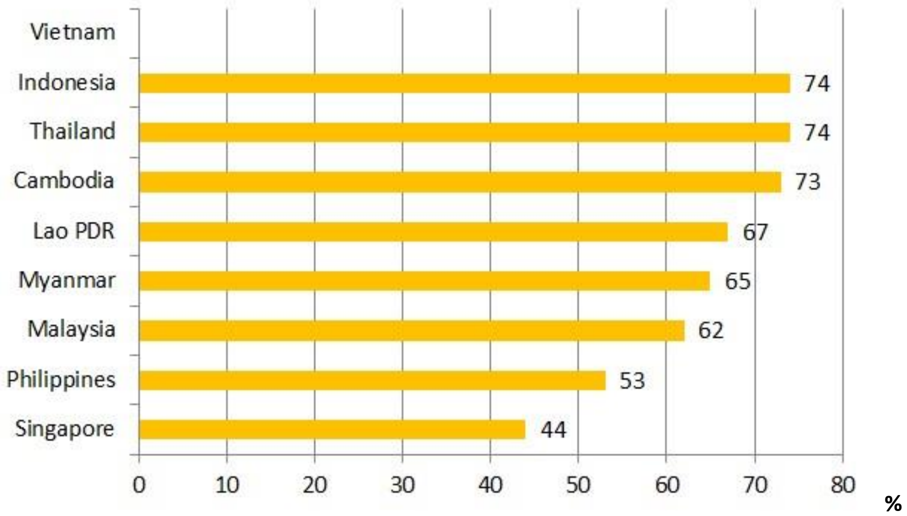


**Figure 1**: Percentages of traffic accident fatalities in ASEAN countries caused by motorized two- and three-wheelers in 2018 (WHO, 2018) except the Philippines, Malaysia, and Lao PDR (WHO, 2015)

For travelling behind a vehicle, it falls generally into a 'two-second rule' (SWOV, 2012; Shinar, 2017; UK Government, 2019). The two-second rule came from a study on the brake reaction time of drivers dated back in 1999. Although this rule can provide a safe distance in general for all passenger cars on motorways under uncomplicated traffic situation, it still does not safe at all especially from mid to high-speed ranges because the stopping distance is affected by the driver's reaction, vehicle speed, vehicle mass, and road condition. Rule 126 of the UK Highway Code (UK Government, 2019) provides the typical stopping distances at typical speeds for passenger cars which are the minimum safe following distances as shown in Figure 2. Large vehicles and motorcycles are needed to keep a greater distance according to the suggested. Nevertheless, the distances have not been specified.

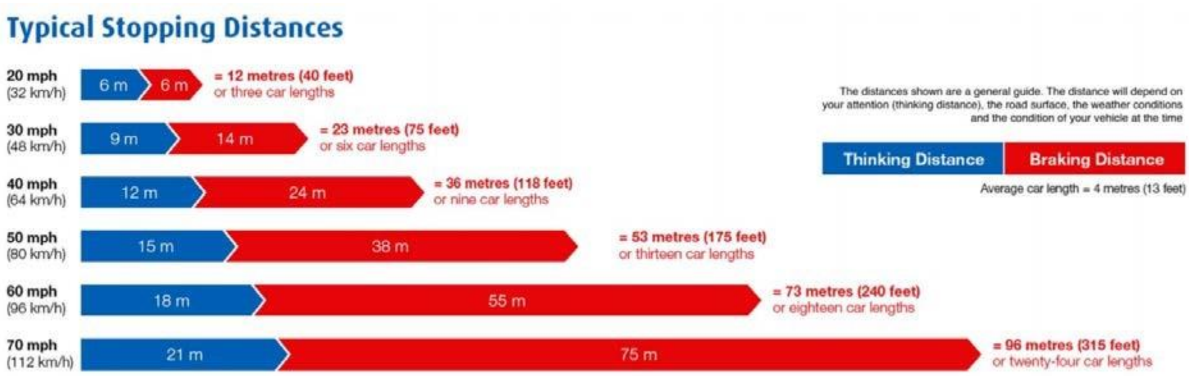


**Figure 2**: Typical stopping distances (UK Government, 2019)

Although there were numbers of study on motorcycle braking performance and deceleration, only a few had done on motorcycle stopping distance especially in the worst-case scenario. Green (2006) compared the stopping distance performance among total six motorcycles which were equipped with conventional brake systems, combined brake systems (CBS) and anti-lock brake systems (ABS) at some specific speeds. Ariffin et al. (2017) compared the braking performance of common motorcycles in the Malaysia market under emergencies. The results from these studies are still not enough to construct the recommended safe stopping distance for a motorcycle which covers all speed range.

In the case of stopping distance model, Lee et al. (2012) proposed mathematical models of the distance between a motorcycle and a leading vehicle both swerving and unswerving in everyday tailgating situation. The models formulated from kinematic equations. Many assumptions were made on parameters that could not be obtained from the video recording. Average safety gaps were presented. However, they reflected only the real behaviours of the motorcyclists, not for the safety aspect.

In this paper, the analytical model of motorcycle stopping distance is proposed which is based on kinematic equations. A piecewise linear model of deceleration profile is presented including values of parameters under emergency braking condition. The calculated results from the model are compared with the experiment and test results from other studies and the proposed following distances are expressed in the same manner of UK Highway Code Rule 126 for a comparison purpose.

## 2.0 MOTORCYCLE BRAKING CHARACTERISTICS

### 2.1 Motorcycle Braking Deceleration Profile

Dunn et al. (2012) conducted a motorcycle straight-line braking test on sport, sport-touring and cruiser motorcycles with three initial speeds. The deceleration profiles from the test were recorded as shown in Figure 3. The braking process can be simplified into three intervals: (1) reaction; (2) building up deceleration; and (3) fully developed deceleration (Greibe, 2007). These figures illustrate that motorcycle cannot achieve fully developed deceleration immediately after applying the brake. It needs some time to develop until reaching the desired value.

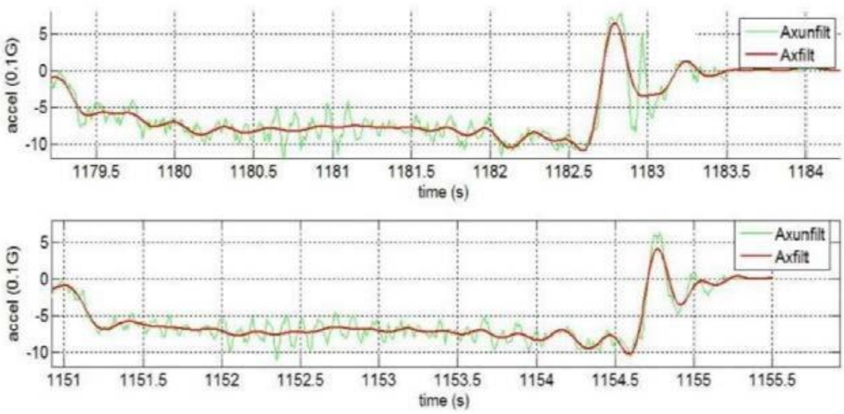


**Figure 3**: Motorcycle straight-line braking acceleration profile test data; front brake only (top) and combined front-and-rear (bottom) (Dunn et al., 2012)

Markkula et al. (2016) proposed a piecewise linear model of acceleration profile which is shown in Figure 4 for studying brake reaction time. This model can fit very well with the profile in Figure 3 and the described braking process. The model assumes that a vehicle starts with an initial constant acceleration $a_0$ which can be any numbers or zero. The brake is applied at $t_B$ which decreases acceleration at a constant rate so-called 'brake jerk' $j_B$. Then deceleration $a_1$ is fully developed at a constant value. The model of the piecewise linear model and values of the related parameter is going to be explained in sections 2.2 and 2.3 respectively.

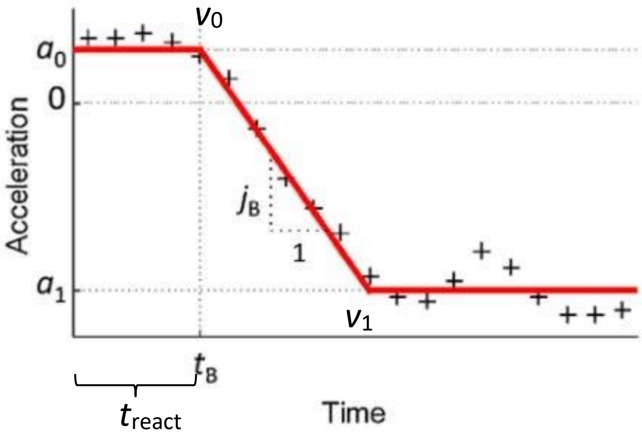


**Figure 4**: Piecewise linear model of the deceleration profile (Markkula et al., 2016)

### 2.2 The Piecewise Linear Model of Deceleration Profile

As mentioned in section 2.1, the piecewise linear model of the deceleration profile can be divided into three intervals according to the breaking process. The worst-case emergency braking situation of the motorcycle is defined as the following assumptions. The motorcycle is an ordinary motorcycle without ABS. It is travelling behind a vehicle at constant speed $v_0$ and no acceleration ($v_0$ = constant and $a_0 = 0$). The leading vehicle brakes and stops immediately (car braking time is almost zero). The motorcycle then stuns for a period of time $t_{react}$ and starts to apply the brake. The deceleration is decreased at a critical jerk rate until reaching the minimum constant fully developed deceleration before stopping safely at some marginal distance. The general idea of the motorcycle stopping distance $S$ can be expressed as follows:

$$S = S_{\text{react}} + S_{\text{jerk}} + S_{\text{brake}} + S_{\text{margin}} \tag{1}$$

where $S_{\text{react}}$ = distance used for reaction time,
$S_{\text{jerk}}$ = distance used during jerk,
$S_{\text{brake}}$ = distance used for braking at the minimum fully develop deceleration, and
$S_{\text{margin}}$ = marginal distance

By kinematic equations, distance used in terms above can be expressed as follows:

$$S_{\text{react}} = v_0 t_{react} \tag{2}$$

$$S_{jerk} = \frac{1}{6}\frac{a_1^3}{j_B^2} + \frac{v_0 a_1}{j_B} \tag{3}$$

$$S_{brake} = -\frac{1}{2}\frac{v_2^2}{a_1} \tag{4}$$

$S_{margin}$ is a distance between the motorcycle and the leading vehicle after completely stop in order to prevent the motorcycle from hitting the bumper. It is kept at 1 meter in front of the motorcycle based on the hypothesis and safety factor. $v_1$ in Equation (4) is needed to change into $v_0$ as the other distance terms. So, the relationship between $v_0$ and $v_1$ is shown in Equation (5).

$$v_1 = v_0 + \frac{1}{2}\frac{a_1^2}{j} \tag{5}$$

## 2.3 Related Parameters under Emergency Braking Situation

The parameters that relate to the braking process such as reaction time, brake jerk and fully developed deceleration including assumptions and constraints are explained as the following.

### *2.3.1 Reaction time*

Driver's reaction time usually represents the time duration from when a driver detects a potential hazard, for example, a leading vehicle applies brake suddenly, until the same driver initiates some responses such as evasive or braking (Markkula et al., 2016). There are many factors influencing the reaction time such as age, gender, cognitive load, situation urgency, number of stimuli for a driver to be considered, etc. Expectancy plays a major factor in the reaction time (Green, 2000). The driver reacts faster under a fully aware situation than the unexpected or surprise situation.

Davoodi et al. (2012) conducted a study on motorcyclist perception response time in stopping the situation under expected and unexpected scenarios. The numbers of participants were 89 and 16, respectively. The reaction time was measured after detecting an object until the brake is applied. The results in the expected scenario were 0.68 s on average and 85 percent of participants achieved at 1.01 s, whilst the results from unexpected scenarios were 1.29 s on average and 85 percent of participants achieved at 2.12 s. However, the maximum reaction time in this scenario was 2.5 s which could cover all the test subjects. In this study, the reaction time is chosen at 2.5 s as the worst case.

### *2.3.2 Brake jerk*

Jerk is the rate of change of acceleration. In everyday driving, averaged jerk is around -3.6 m/s$^3$ and the lowest value is -8 m/s$^3$, while it can go further down to -9.9 to -12.6 m/s$^3$ in the near-accident situation (Nygård, 1999). It is a wide range of the jerk value that can be selected. However, the jerk at -8 m/s$^3$ is chosen as a maximum threshold to express the critical situation and to prevent biologically infeasible deceleration ramp up (Markkula et al., 2016; Tageldin and Sayed, 2016).

### *2.3.3 Fully developed deceleration*

There are several factors influencing the motorcycle brake capabilities e.g. friction between road and tire, brake system, motorcycle dimension and configuration, loads (rider and/or passenger weight), rider braking skills, etc. which can be categorized into two main aspects i.e.

machine and rider. In the first aspect of the motorcycle as a machine, it has a regulation mandating the brake performance of the motorcycle. UN Regulation No. 78 (United Nations, 2018) requires motorcycle (category L) passing the minimum braking performance in order to assure the machine capability and providing some level of safety to users. The most popular motorcycle in the ASEAN market is underbone and scooter types with engines less than 150cc which fall into category L3. This category of motorcycle has to produce deceleration at least -2.9 m/s$^2$ from rear brake only and stop within specific distances.

Another aspect is the rider. Most motorcyclists were deficient in braking skills and could not make full use of the motorcycle braking system (Ecker et al., 2001). In addition, the motorcyclists performed rear braking more than front braking twice (Kasantikul, 2001) during collision avoidance. Rose (2017) reviewed braking capability tests of motorcyclists from studies between 1989-2017. The summarized information is shown in Table 1. It is clearly shown that rear brake using alone produces the lowest braking performance among other brake systems. The lowest deceleration from those pieces of literature in Table 1 is 0.31g or 3.04 m/s$^2$ which is quite similar to the regulation at 2.9 m/s$^2$. Weight transfer during braking is the main cause of low braking performance in the rear braking.

**Table 1**: Summary of braking deceleration rates from various studies on dry pavement (Rose, 2017)

| | **Best Effort Braking Deceleration Rates on Dry Asphalt (g)** | | | |
|---|---|---|---|---|
| **Study** | **Rear Brake Only (No ABS)** | **Front Brake Only (No ABS)** | **Front and Rear Combined (No ABS)** | **Front and Rear with ABS** |
| Fries, Smith, and Cronrath [1989] | 0.31 to 0.52 | | 0.54 to 0.88 | |
| Hunter [1990] | 0.35 to 0.36 | 0.64 to 0.74 | 0.63 to 0.96 | |
| Hugemann and Lange [1993] | | | | |
| Bartlett [2000] | 0.38 to 0.46 | 0.88 to 0.89 | 0.96 | |
| Ecker [2001] | | | 0.63 ± 0.12 | |
| Vavryn [2004] | | | 0.67 | 0.8 |
| Bartlett, Baxter, Robar [2007] | 0.37 ± 0.06 | 0.60 ± 0.16 | 0.74 ± 0.15 | |
| Dunn, et al., [2012] | 0.345 to 0.386 | 0.518 to 0.709 | 0.612 to 0.708 | 0.642 to 0.842 |
| Peck and Deyerl [2017] | 0.321 to 0.341 | | | |

There is a piece of evidence that supports very low motorcycle deceleration. Bartlett et al. (2007) collected data from motorcycle braking demonstration tests under accident reconstruction courses at the Institute of Police Technology and Management (IPTM) over the years. The results are shown in Figure 5. There was around 16 percent of the rear brake case achieving the deceleration lower than 0.3g which were unacceptable according to the regulation. Thus, the deceleration of -2.9 m/s$^2$ is reasonable for using as the worst case.

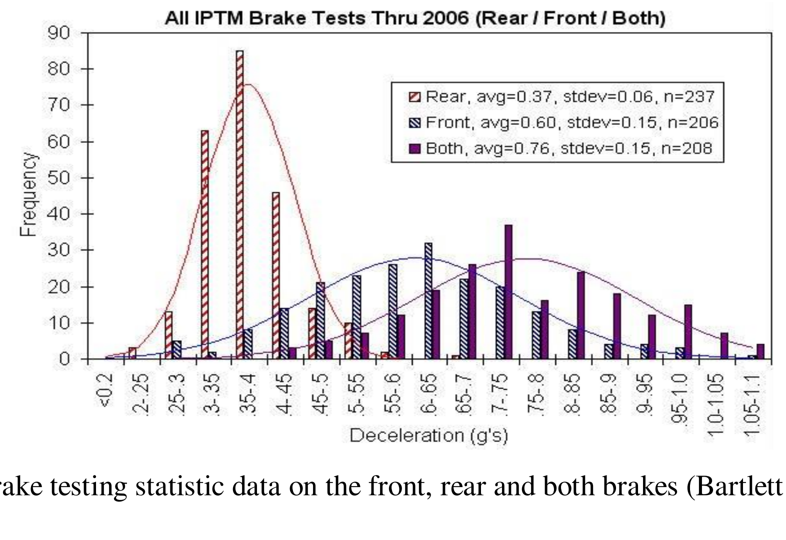


**Figure 5**: Brake testing statistic data on the front, rear and both brakes (Bartlett et al., 2007)

## 3.0 TEST PROCEDURE FOR BRAKING PERFORMANCE EVALUATION

The test was performed in an expected braking situation without the influence of reaction time in order to compare with the distances calculated from the proposed piecewise linear model. Honda Click 125cc with CBS model year 2018 was used with a 60-kg rider in the test. The adjustable stopper was installed to keep the consistent brake application at the rear wheel as shown in Figure 6 (a). The road was dry asphalt and the test was conducted on two speeds which were 40 and 60 km/h. On the test lane, cones were put at every 5 m distance from the starting point as shown in Figure 6 (b). The rider used only the rear brakes with the adjusted stopper to stop the motorcycle without rear wheel locking condition. And the exact stopping distance was measured by using a tape meter as shown in Figure 6 (c). The trials were done to adjust the range of stopper for maximal stoke of hand brake lever without wheel locking condition. Then, the tests with six times were repeatedly conducted for each speed and the maximum stopping distances were selected. The consistency reaction time of the motorcyclist was not measured but the expected brake scenario and perception were recognized by the rider.

(a) (b) (c)

**Figure 6**: The test ground; (a) a stopper at handbrake lever, (b) test lane, and (c) motorcycle completely stop

## 4.0 RESULTS AND DISCUSSION

### 4.1 Model Evaluation with Test Results

The brake distances from each test speed from the dry surface were shown in Table 2 including results from other works of literature. The underbone motorcycles were tested by Ariffin et al. (2017) and this study, while high-performance motorcycles were tested by Dinges and Hoover (2018), Dunn et al. (2012) and Green (2006). When compared between the underbone and the high-performance motorcycles, it was clear that the high-performance motorcycles achieved higher decelerations. It could imply the high-performance motorcycles are safer in the braking aspect. However, these data were averaged or even the best values which did not reflect the possibility of the lowest deceleration in the worst case. So, the rear brake application testing of the high-performance motorcycle for finding out the maximum stopping distance is recommended.

**Table 2**: Rear brake only test results on the dry surface

| Literatures | Test Speed | Model Brake Distance [m] | Test Brake Distance [m] | Test Deceleration [m/s$^2$] | Notes |
|---|---|---|---|---|---|
| **This study** | 40 | 24 | 18.2 | -3.39 | Max |
| | 60 | 52 | 40.7 | -3.41 | |
| **Ariffin et al. (2017)** | 50 | 37 | 30.6 | -3.15 | Max Average |
| **Dinges & Hoover (2018)** | 64.4 | 59 | 42.3 | -3.78 | Average |
| | 72.4 | 74 | 55.3 | -3.65 | |
| | 80.4 | 90 | 68.2 | -3.65 | |
| | 88.5 | 110 | 81.2 | -3.72 | |
| | 96.5 | 128 | 94.2 | -3.81 | |
| | 104.6 | 152 | 107.1 | -3.94 | |
| **Dunn et al. (2012)** | 40 | 24 | 18.4 | -3.35 | Max Average |
| | 72.4 | 74 | 55.9 | -3.61 | Max Average |
| | 96.5 | 128 | 88.0 | -4.08 | Average |
| **Green (2006)** | 48.3 | 37 | 25.7 | -3.5 | Min (Best) |
| | 117.8 | 192 | 113.3 | -4.72 | |
| | 128.8 | 232 | 160.2 | -3.99 | |

When considering the underbone motorcycle data, they were plotted against the calculated values as illustrated in Figure 7. The brake distances from underbone motorcycle tests were averagely around 80 percent of the model calculated values. The interesting point was the distance differences between the model and test results were 0.52, 0.46 and 0.68 s according to the speed of 40, 50 and 60 km/h respectively when converted into time unit. This means the motorcyclists have a very short time for taking some reactions. So, the motorcyclists should keep additional time headway of around 2 s from the actual braking distance when the reaction time is considered.

With only a few data available, the effectiveness of the calculated distances from the model could not be evaluated properly. The full-scale test on the rear brake of the underbone motorcycle is necessary for determining the maximum brake distances through the speed range.

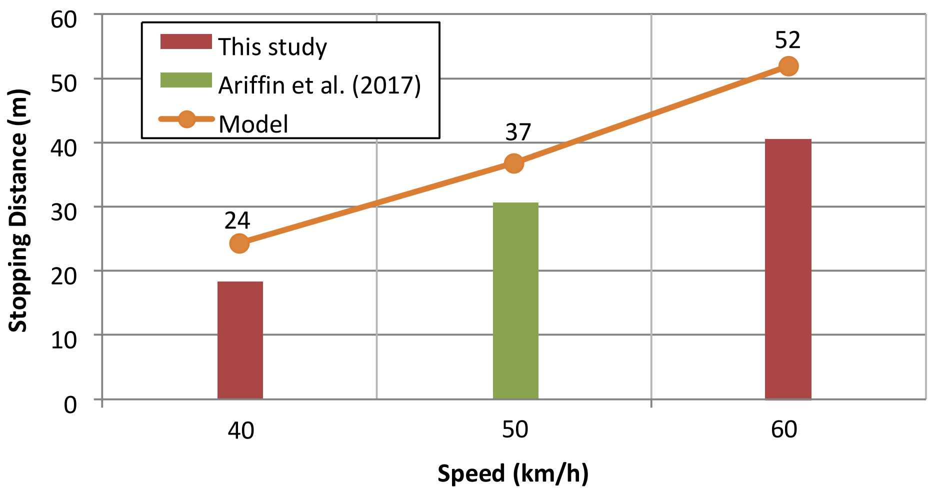


**Figure 7**: Comparison between test results from Table 2 and the model

### 4.2 Proposed Safe Following Distance for Motorcycle

The proposed stopping distances for motorcycle are shown in Figure 8. These data came from the calculation based on deceleration of -2.9 m/s$^2$, jerk of -8 m/s$^3$ and reaction time of 2.5 s. The motorcycle should keep its headway distance at least equal to the stopping distance depicted in red arrows. For the reaction distances, it is not compulsory. However, it is recommended to keep distance in about half of the reaction distance, for example, 27 m at 32 km/h. These data give some ideas for motorcycle following distances in comparison to the passenger car following distances provided by the UK Highway Code in Figure 2.

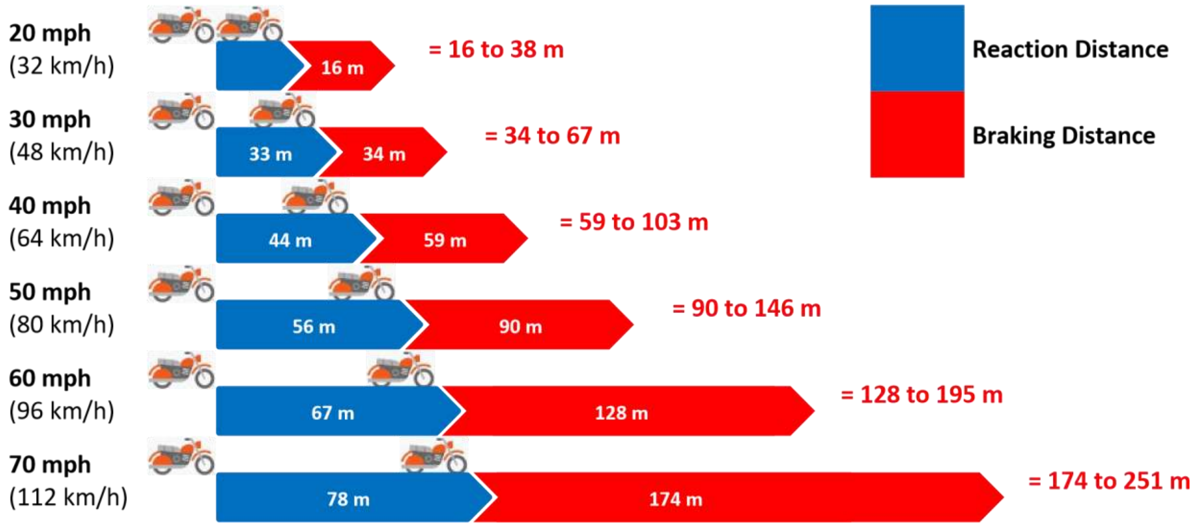


**Figure 8**: Proposed stopping distances for motorcycle

## 5.0 CONCLUSION

This study proposes the safe following distances for a motorcycle under the worst-case scenario using the piecewise linear model of the acceleration profile. The calculated distances from the model are introduced as a suggestion for motorcyclists in order to prevent the rear-end collision in case of following any vehicle. The distances were compared to the test results from this study and other literature. However, due to the different aspects of testing, the distances could not evaluation properly. It is recommended to make the full-scale test on the maximum brake distance on both underbone and high-performance motorcycles using rear brake application only for evaluating the model. However, this study provides useful information on the safe following distances to relevant authorities in order to setup a safety measure for the motorcyclists. This information will also be used in the preliminary study on the rear-view mirror visibility assessment.

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