International Journal of Road Safety

Journal homepage: www.miros.gov.my/journal

Motorcycle Crash Causation Study (MCCS) Along Malaysian Expressways

Muhammad Marizwan Abdul Manan[1,*], Nora Sheda Mohd Zulkiffli[1] & Hawa Mohamed Jamil[1]

*Corresponding author: marizwan@miros.gov.my

[1]*Road Safety Engineering & Environment Research Centre, Malaysian Institute of Road Safety Research, 43000 Kajang, Selangor, Malaysia*

ABSTRACT

Expressways are well known for its high fatality risk for motorcycles. Despite the various risk factors being identified in previous findings, we have yet to address the causality of these motorcycle crashes, specifically along expressways. Thus, the objective of this study is to determine the most common cause and contributing factors of motorcycle crash along Malaysian expressways. This study uses motorcycle crash data from 2016 – 2018 were obtained from the Malaysian Highway Authority (MHA). It was found that the three highest factors of motorcycle fatal crash causality are loss of control, poor visibility (no lighting) and incompetence (poor driving skills). The mixed-effects logistic regression (MELR) indicates that motorcyclists are four times safer riding on the emergency lane than on other lanes along the expressway section. Motorcyclists are approximately two times more likely to be involved in a fatal-multiple vehicle crash than a fatal single-vehicle crash and they tend to be involved in fatal crashes during low light conditions twice as compared to daytime. The MELR model also indicates that different types of expressway governed by different concessionaire have at least 16 – 18% variation effects towards motorcycle fatal outcome, which may need further study. It is recommended that motorcycles are allowed to utilize the emergency lanes as their travel path along the expressway as it is proven statistically safer and low probability to be involved in a fatal outcome.

ARTICLE INFO

Article History:
Received 15 Feb 2019
Received in revised form
12 Mac 2020
Accepted
25 Mac 2020
Available online
01 May 2020

Keywords:
Motorcycle
Crash causation
Mixed Effect Logistic Regression

1. Introduction

The majority of motorcycle fatalities occurring on primary roads is as shown in Figure 1 (Abdul Manan & Várhelyi, 2012). However, Malaysian expressways are also risky for motorcycles due to the road length, the fatality rate per 100 km is much higher than the secondary road, local street and minor road (see Figure 1). Additionally, more than 50% of motorcyclists do not comply with the speed limit and ride above the 85th percentile speed along expressways with 80 km/h limit (Abdul Manan et al., 2017).

Malaysian expressways have more multiple fatal crashes involving motorcycles than another road hierarchy and it is proven significant (Abdul Manan et al., 2018). Abdul Manan et al. (2018) shows that factors such as expressway, primary and secondary roads, speed limit over 70 km/h, roads with double lines and daylight condition, may increase the probability of occurrence of multiple-vehicle crash involving motorcycles. The same study also shows that the probability of a motorcycle fatal crash involving two (2) or more vehicle crashes increases by 6.2% along expressways.

Moreover, crash data have shown that motorcycle crashes involving two (2) or more other vehicles in Malaysia are more likely to end in a fatal outcome compared to a motorcycle single-vehicle crash (Abdul Manan et al., 2018). These findings were supported by the fact that high-speed roads are associated with higher injury-severity levels while roads with speed limits exceeding 70 km/h have a 132% higher likelihood of a fatal injury (Savolainen & Mannering, 2007).

Motor vehicle crashes are complex events whereby they involve two or more vehicles and the elements that influence the occurrence of a crash may take place hours, days, or months before the crash. This includes driver training and experience (Åberg, 2008), vehicle design and manufacture, highway condition and traffic signaling, and weather conditions (Theofilatos & Yannis, 2014). Other elements may take place immediately before a crash (Blows et al., 2005), such as decision to turn in traffic, tire blowout, or heavy rain (Theofilatos & Yannis, 2014). Crash reconstruction experts rarely conclude that crashes are the result of a single factor (AASHTO, 2010). Overall, fatigue, drinking alcohol, and speeding are major factors in motor vehicle crashes (DOT, 2006).

In not an orderly manner, the top 10 factors that associated with motorcyclist fatalities in Malaysia along various road types based on previous findings as seen in Abdul Manan & Várhelyi (2012), Abdul Manan (2014), Abdul Manan & Várhelyi, (2015) and Abdul Manan et al. (2017) were straight road sections, access points, primary or secondary road, 00 am to 6 am, male, 21 – 30 years old, speeding, rutting or corrugation or sandy surface, wet surface or water ponding and double line marking. Although their presence does not always result in a crash, these factors, as well as other drivers, vehicle, and environmental factors, can increase the risk of crash occurrence.

Despite the various risk factors being identified in previous findings, we have yet to address the causality of these motorcycle crashes, specifically along expressways. Thus, the objective of this study is to determine the most common cause and contributing factors of motorcycle crash along Malaysian expressways.

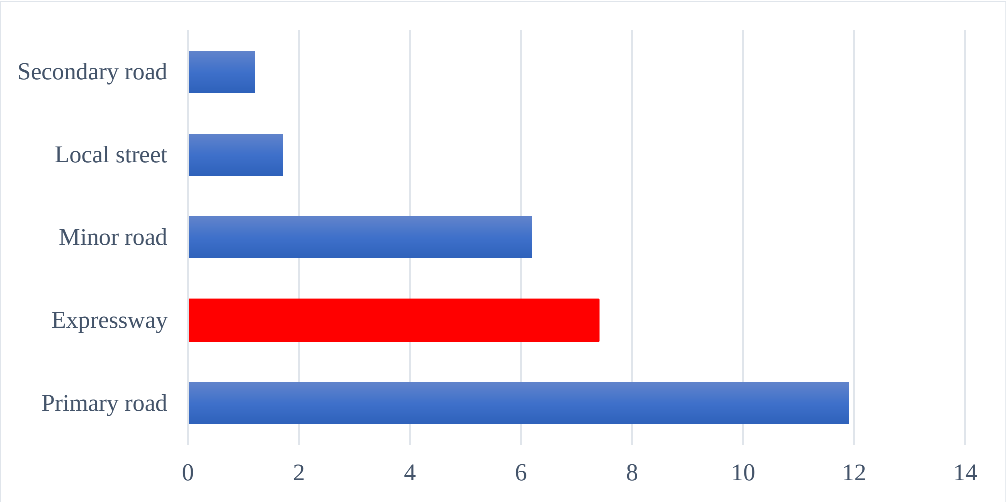

Figure 1: Motorcycle fatalities per 100 km based on a road hierarchy (Abdul Manan & Várhelyi, 2012).

2. Method

In this motorcycle crash causation study (MCCS), 'causation' is defined as the factors that are most likely to increase the risk of motorcycles will be involved in serious crashes (see Penumaka et al., (2014), Kasantikul (2001), Starnes (2006), DOT (2006)). Expressway is in the focus because the crash data are more comprehensive and accurate than the conventional police records, as reported in Abdul Manan and Várhelyi (2012).

2.1. Coding Crash Causation Variables

Based on DOT (2006), crash causation can be determined by examining each crash data and coded into three (3) key variables, i.e. critical event, critical reason and associated factors (following DOT (2006)):

Critical Event (CE): The action or event that put the vehicle(s) on a course that made the collision unavoidable. The critical event is assigned to the vehicle that took the action that made the crash inevitable. For example, there are three (3) major types of critical events assigned to motorcycle:

1. Running out of travel lane, either into another lane or off the road
2. Motorcycle loss of control due to traveling too fast for conditions, motorcycle mechanical failure, poor road conditions, or other reasons
3. Colliding with the rear end of another vehicle

Critical Reason (CR): The immediate reason for the critical event (i.e., the failure leading to the critical event). The critical reason is assigned to the vehicle coded with the critical event in the crash. It can be coded as driver error, vehicle failure, or environmental condition (roadway or weather). Motorcyclist critical reasons are coded into four (4) categories:

1. Non-Performance: The driver fell asleep, disabled by a heart attack or seizure, or physically impaired for another reason.
2. Recognition: The driver was inattentive, distracted by something inside or outside the vehicle, or failed to observe the situation adequately for some other reason.
3. Decision: E.g. the driver was driving too fast for conditions, misjudged the speed of other vehicles, or followed other vehicles too closely.
4. Performance: E.g. the driver panicked, overcompensated, or exercised poor directional control.

Associated Factors (AF): The person, vehicle, and environmental conditions present at the time of the crash. No judgment is made as to whether any factor is related to the reason for a particular crash, just whether the factor was present. The list of the many factors that can be coded provides enough information to describe the circumstances of the crash. Hundreds of associated factors were collected for each vehicle in each crash.

2.2. Site Verification

Site verification was commenced after data coded by visiting the locations that are considered an anomaly, i.e. same location but different road geometry characteristics or road section with high crash history. The site verification process helps in updating the crash data.

2.3. Multilevel Regression

A multilevel regression allows for the possibility that the effects of variables (i.e. motorists' behaviour, road environment attributes and vehicle characteristics), which influence the occurrence of crash outcome, may vary across the observations and circumvent all of the problems with traditional generalized linear model techniques. Additional heterogeneity across observations, e.g. motorcyclists' inherent attitude to the road environment or safety, could be introduced (in addition to the expected unobserved heterogeneity, relating to the roadway, vehicle, and rider factors) since our data were collected from roadside observations where the underlying factors to the behaviour of the motorcyclists cannot be determined.

These behavioural-specific details can include factors such as motorcyclists' socioeconomic status (income or education level), risk perception (risky lifestyle, aggressive behaviour), perceived usefulness of helmet and level of enforcement, all of which have been shown to affect the occurrence of accidents (see Crundall et al. (2008), Nordqvist & Gregersen (2010)). Thus, bias from unobserved heterogeneity is particularly important to consider, because estimates of the effect of independent variables will be biased even if the unobserved heterogeneity is not correlated with the observed independent variables (Washington et al., 2003). Unobserved heterogeneity is typically dealt with either by conditioning through random effects, or by transforming the data to eliminate individual-specific fixed effects (Revelt & Train, 1998).

MELR is logistic regression containing both fixed effects and random effects. It allows for not just one, but many levels of nested clusters of random effects (see Jones & Jørgensen (2003), Dupont et al. (2013), Abdul Manan (2014)). For example, in a four-level model, we are proposing the random effects be specified for different 'Expressway concessionaire' on the fourth level, and then for 'Expressway zone' nested within 'speed limit' are the third and the second level respectively, while the variable 'motorcyclist' involved in a crash comprises at the first level.

To understand further, we first consider a two-level model for binary outcomes with a single explanatory variable (1). Conceptually, this model is equivalent to a linear model except for the outcome variable. In applying Model (1) in this study, data consisting of motorcyclists (Level 1) grouped into location characteristics (Level 2) e.g. speed limit, duration category, etc. We observe y_{ij}, a binary response for motorcyclists involved in a fatal crash (i) in a location (j) and x_{ij}, an explanatory variable at the motorcyclist level. We define the probability of the response equal to one (involve in a fatal crash) as $p_{ij} = P_r (y_{ij} = 1)$ and let p_{ij} be modelled using a logit link function. The standard assumption is that y_{ij} has a Bernoulli distribution. Then the two-level model can be written based on research by Guo & Zhao (2000), as follows:

$$y_{i}j = \log [p_{ij}/(1 - p_{ij})] = \beta_0 + \beta_{1xij} + u_j \quad \text{(combined model)} \qquad (1)$$

where u_j is the random effect at Level 2. Without u_j, (1) would be a standard logistic regression model. Conditional on u_j, y_{ij} s are assumed to be independent. As in the case of multilevel linear models, u_j is assumed to be normally distributed, with the expected value 0 and the variance σ^2_u. Model 1 is often described alternatively as (see Guo & Zhao (2000)):

$$\log [p_{ij}/(1 - p_{ij})] = \beta_{0j} + \beta_1 x_{ij} \quad \text{(Level 1 model)} \qquad (2)$$

$$\beta_{0j} = \beta_0 + u_j \quad \text{(Level 2 model)} \qquad (3)$$

The multilevel model for binary outcomes can also be derived through a latent variable conceptualization (Guo & Zhao, 2000; Dupont et al., 2013). We assume that there exists a latent continuous variable y^*_{ij} underlying y_{ij}. We observed only the binary response variable y_{ij} directly, but not y^*_{ij} (Guo & Zhao, 2000). We know, however, $y^*_{ij} > 0$ if $y_{ij} = 1$ and $y^*_{ij} \leq 0$ if $y_{ij} = 1$. A multilevel model for y^*_{ij} equivalent to (1) can be written as:

$$y^*_{ij} = \beta_0 + \beta_{1xi}j + u_j + e_{ij} \qquad (4)$$

Model (1) is almost the simplest possible multilevel model for binary data. However, in this study, we propose a four-level model with a single explanatory variable that has both fixed effect and random effect (Model 5):

$$\log [p_{ijk} /(1 - p_{ijk})] = \beta_0 + \beta_1 x_{ijkl} + u_{1jkl}\, x_{ijkl} + v_{0l} + u_{0kl} + w_{0jkl} \quad \text{(combined model)} \qquad (5)$$

where i, j, k and l are index, Levels 1, 2, 3 and 4, v_{0l}, u_{0kl} and w_{0jkl} are the random intercepts for Level 2, Level 3 and Level 4, respectively, and u_{1jkl} is the random coefficient for the explanatory variables x_{ijkl}. Thus, to incorporate this model into our study, we could let the Levels 1, 2, 3 and 4 represent motorcyclists, speed limit, expressway zone and expressway concessionaire respectively.

$$\log [p_{ijk}/(1 - p_{ijk})] = \beta_{0jkl} + \beta_{1j}\, x_{ij} \quad \text{(Level 1 model)}$$

$$\beta_{0l} = \beta_0 + v_{0l} \quad \text{(Level 2 model)}$$

$$\beta_{0kl} = \beta_{0k} + u_{0kl} \quad \text{(Level 3 model)}$$

$$\beta_{0jkl} = \beta_{0l} + w_{0jkl} \quad \text{(Level 4 model)}$$

The conditional density for (2) is still identical to that for the logistic regression; but with four (4) random effects in the model, the unconditional density is a high-dimensional integral (Guo & Zhao, 2000; Dupont et al., 2013). In Model (2), both u_j, v_k and w_l are random quantities, whose means are equal to zero; they form the random part of the model. The assumption is that, being at different levels, these variables are uncorrelated, and that they follow normal distribution so that it is sufficient to estimate their variances $\sigma^2_{u0} = \text{var}\ (u_{0kl})$, $\sigma^2_{v0} = \text{var}\ (v_{0l})$ and $\sigma^2_{w0} = \text{var}\ (w_{0jkl})$ respectively (Jones & Jørgensen, 2003; Rasbash et al., 2009).

It is the existence of the two (2) random variables that marks it out as a multilevel model. The variances σ^2_{u0}, σ^2_{v0} and σ^2_{w0} are referred to as random parameters of the model, whereas the quantities β_0 and β_1 are known as fixed parameters. A multilevel model of this simple type, where the only random parameters are the intercept variances at each level, is known as a variance components model. However, in a more complex model, the random parameter may have either a random intercept or a random slope (or both) associated with the level (see Abdul Manan, 2014).

The MELR model proposed in this study will not only indicate the significant motorcyclist behaviour or road environment factors that are associated with motorcyclists crash outcome, but it will also indicate the percentage of variation in each level, e.g. expressway speed limit (Level 2), expressway zone (Level 3), and expressway concessionaire (Level 4) with relation to the fatal crash outcome involving motorcycle. In order to ensure the robustness of this model, several mixed-effect logistic regression models were developed. Each model's goodness-of-fit for this study is measured in terms of Akaike's Information Criterion (AIC), which was used extensively by Jones and Jørgensen (2003), Dupont et al. (2013) and Abdul Manan (2014). The smaller the value, the better and more preferred the model would be, i.e. the best-fitted model (Abdel-Aty & Radwan, 2000; Ayati & Abbasi, 2011).

The models are also compared in terms of their random parameters' residual variance at each level. To estimate the proportion of overall residual variability that is associated with each level, it is normal to calculate the ratio of each of the two-variance terms to total variance (Jones & Jørgensen, 2003). The result is known as the intra-unit correlation coefficient (ICC), ρ and it can be calculated using the formula:

$$\text{ICC Level 1, } \rho_1 = (\sigma^2_{e0}) / (\sigma^2_{u0} + \sigma^2_{e0} + \sigma^2_{v0} + \sigma^2_{w0}) \qquad (6)$$

$$\text{ICC Level 2, } \rho_2 = (\sigma^2_{u0}) / (\sigma^2_{u0} + \sigma^2_{e0} + \sigma^2_{v0} + \sigma^2_{w0}) \qquad (7)$$

$$\text{ICC Level 3, } \rho_3 = (\sigma^2_{v0}) / (\sigma^2_{u0} + \sigma^2_{e0} + \sigma^2_{v0} + \sigma^2_{w0}) \qquad (8)$$

$$\text{ICC Level 4, } \rho_4 = (\sigma^2_{w0}) / (\sigma^2_{u0} + \sigma^2_{e0} + \sigma^2_{v0} + \sigma^2_{w0}) \qquad (9)$$

where σ^2_{e0}, σ^2_{u0}, σ^2_{v0} and σ^2_{w0} are the variances for Levels 1, 2, 3 and 4 residuals, respectively. As a guide, if the ICC Level 2 (ρ_2), approaches zero, then the random parameter effect would be considered useless and simple regression would suffice. On the other hand, if the ρ_2, approaches one, then there is no variance to be explained at level one, or in other words: all motorcyclists on the roads are the same.

3. Results

3.1. Motorcycle Crash Demographic

Overall, there were 45,094 crash cases recorded by the MHA during the year 2016 – 2018, in which a total of 67,687 victims were involved. Table 1 shows that motorcycles have a higher rate of single-vehicle crash (68%) than any known type of vehicles. It was also found that the ratio of SVC/MVC for motorcycles is much higher (2.2) than other types of vehicle class. Thus, motorcycles are likely to be involved in a crash by themselves rather than being involved in a crash with many vehicles along the expressways.

Table 1: Number of cases by collision type and vehicle class.

Type of Vehicle Class	Collision Type by Case					
	MVC – Multiple Vehicle Crash		SVC – Single Vehicle Crash		Total	Ratios of SVC to MVC Crash
Motorcycle	2,390	31.2%	5,263	68.8%	7,653	2.2
Private passenger cars	11,086	35.5%	20,120	64.5%	31,206	1.8
Small trucks*	776	45.1%	946	54.9%	1,722	1.2
Large trucks**	1,576	48.0%	1,710	52.0%	3,286	1.1
Taxi	84	44.9%	103	55.1%	187	1.2
Bus	158	50.2%	157	49.8%	315	1.0
Unknown	54	7.4%	671	92.6%	725	12.4

Note: * - Vehicle with 2 axles with 3 or 4 tires; ** - Vehicle with 3 or more axles; Unknown: The data and the crash description did not mention specifically the type of vehicle; MVC: Vehicle crash involving more than 2 vehicles and involving at least 1 motorcycle; SVC: Vehicle crash involving only 1 motorcycle

Table 2 shows that, despite the higher number of motorcycles involved in single-vehicle crashes, multiple-vehicle crashes have a higher fatality rate (10.7%). In other words, a motorcycle has a higher probability to be fatally involved in a crash involving multiple vehicles.

Table 3 and Table 4 demonstrate that fatal crash cases involving motorcyclists are along the main carriageway (n = 557), and along the slow lane (n = 204). Moreover, crash cases along the emergency lane (i.e. paved road shoulder) have a high number of severe, light and damage only cases involving motorcyclists.

Table 2: Number of crash case by collision type and severity involving motorcycle.

Motorcycle Collision Type by Case	Fatal		Severe		Light		Damage Only	
MVC – Multiple vehicle crash	255	10.7%	1157	48.4%	770	32.2%	208	8.7%
SVC – Single vehicle crash*	344	6.5%	2363	44.9%	2044	38.8%	512	9.7%
Total (n = 7,653)	599		3,520		2,814		720	

Note: MVC: Vehicle crash involving more than 2 vehicles and involving at least 1 motorcycle; SVC: Vehicle crash involving only 1 motorcycle; * Reference variables used in the mixed-effects logistic regression

Table 3: Number of crash cases by expressway’s zone and severity involving motorcycle.

Expressway's Geometry	Fatal		Severe		Light		Damage Only	
Main carriageway	557	93.0%	3,046	86.5%	2377	84.5%	609	84.6%
Interchange	21	3.5%	201	5.7%	175	6.2%	49	6.8%
Intersection	6	1.0%	192	5.5%	187	6.6%	39	5.4%
Toll plaza	8	1.3%	42	1.2%	26	0.9%	9	1.3%
Rest area	4	0.7%	17	0.5%	20	0.7%	7	1.0%
Tunnel	1	0.2%	8	0.2%	22	0.8%	4	0.6%
Rest stop	2	0.3%	8	0.2%	3	0.1%	3	0.4%
Lane closure working zone	-	0.0%	6	0.2%	4	0.1%	-	0.0%
Total (n = 7,653)	599		3,520		2,814		720	

Table 4: Number of crash cases by expressway section and severity involving motorcycle.

Expressway Section	Fatal		Severe		Light		Damage Only	
Slow lane	204	34.1%	807	22.9%	425	15.1%	107	14.9%
Emergency lane*	178	29.7%	1,409	40.0%	1392	49.5%	324	45.0%
Fast lane	106	17.7%	655	18.6%	463	16.5%	140	19.4%
Middle lane	87	14.5%	349	9.9%	164	5.8%	73	10.1%
Exclusive motorcycle lane	14	2.3%	219	6.2%	320	11.4%	41	5.7%
Road median	5	0.8%	40	1.1%	25	0.9%	22	3.1%
Overall road section	4	0.7%	28	0.8%	20	0.7%	11	1.5%
On the opposite lane	1	0.2%	4	0.1%	2	0.1%	1	0.1%
On lane closure	-	-	9	0.3%	3	0.1%	1	0.1%
Total (n = 7,653)	599		3,520		2,814		720	

Note: *Reference variables used in the mixed-effects logistic regression

3.2. Motorcycle Crash Causality

The crash causality can be assessed in three (3) aspects which are critical events, associated factors and critical reasons. Table 5 shows the crash cases by type of critical events and severity involving motorcycles. It was found that loss of control of vehicles (i.e. motorcycle) is the critical event that has the highest number of fatalities involving motorcycles, followed by rear end collision between vehicles. Meanwhile, Table 6 shows that the type of Associated Factors, factors such as poor visibility with no lighting and slippery pavement has the highest number of fatalities involving motorcycles.

The crash description in each data was analysed and re-categorized into possible causality of the crash, i.e. ‘Critical Reason’. After analysing each 7,653-crash descriptions, 5 main Critical Reason category were narrowed down, i.e. Incompetence, Reckless, Negligent, Non-performance and Not at fault. Table 7 shows that poor driving skill (Incompetence) and speeding (Reckless) are the two main critical reasons that contributed to the high number of fatal crash cases involving motorcyclists.

Table 5: Number of crash cases by type of critical events and severity involving motorcycle.

Expressway's Section	Fatal		Severe		Light		Damage Only	
LC of vehicle*	312	52.1%	1,893	53.8%	1,625	57.7%	366	50.8%
Rear end collision between vehicles	84	14.0%	423	12.0%	249	8.8%	78	10.8%
Side swipe between vehicles	47	7.8%	337	9.6%	295	10.5%	47	6.5%
LC of vehicle and hit rear end of vehicle	70	11.7%	265	7.5%	117	4.2%	30	4.2%
LC of vehicle and run out of travel way	23	3.8%	180	5.1%	153	5.4%	55	7.6%
Hit and run by unknown vehicle	16	2.7%	18	0.5%	8	0.3%	-	-
LC of vehicle and sideswipe with vehicle	14	2.3%	82	2.3%	50	1.8%	15	2.1%
Head on collision	10	1.7%	28	0.8%	12	0.4%	-	-
Side collision between vehicles	8	1.3%	42	1.2%	45	1.6%	7	1.0%
Hit and run	3	0.5%	11	0.3%	-	-	9	1.3%
Hit object on road	2	0.3%	95	2.7%	121	4.3%	76	10.6%
Squeezed by vehicle	2	0.3%	21	0.6%	14	0.5%	2	0.3%
Hit by object on road	2	0.3%	12	0.3%	11	0.4%	4	0.6%
LC of vehicle after hitting object / animal	1	0.2%	52	1.5%	44	1.6%	7	1.0%
Hit pedestrian on road	1	0.2%	29	0.8%	12	0.4%		0.0%
Hit road infra	1	0.2%	11	0.3%	11	0.4%	7	1.0%
Vehicle on fire	1	0.2%	1	0.0%	2	0.1%	12	1.7%
LC of vehicle after passing pavement defect	1	0.2%	-	-	3	0.1%	1	0.1%
Hit crash victim on road	1	0.2%	-	-	-	-	-	-
LC of vehicle after being hit by object/animal	-	-	1	0.0%	1	0.0%	-	-
Hit animal or carcass on road	-	-	19	0.5%	41	1.5%	4	0.6%
Total (n = 7,653)	599		3,520		2,814		720	

Note: LC: Loss of control; *Reference variables used in the mixed-effects logistic regression

Table 6: Number of crash cases by type of associate factors and severity involving motorcycle.

Associate Factors	Fatal		Severe		Light		Damage Only	
Poor visibility – no lighting	102	58.0%	321	31.9%	184	20.9%	56	18.8%
Pavement deficiencies – slippery	51	29.0%	362	36.0%	304	34.6%	112	37.6%
Poor visibility – limited distance	7	4.0%	18	1.8%	16	1.8%	8	2.7%
Mechanical failure – tire burst	6	3.4%	62	6.2%	88	10.0%	8	2.7%
Mechanical failure – vehicle component	3	1.7%	16	1.6%	9	1.0%	10	3.4%
Presence of debris – long shaft	2	1.1%	6	0.6%	2	0.2%	1	0.3%
Presence of debris – tire	1	0.6%	34	3.4%	44	5.0%	5	1.7%
Mechanical failure – flat tire	1	0.6%	31	3.1%	37	4.2%	6	2.0%
Presence of animal	-	-	26	2.6%	43	4.9%	4	1.3%
Presence of debris – misc. objects	-	-	24	2.4%	26	3.0%	21	7.0%
Presence of debris – steel	1	0.6%	19	1.9%	27	3.1%	18	6.0%
Presence of debris – wood	-	-	20	2.0%	23	2.6%	13	4.4%
Constricting infrastructure	-	-	14	1.4%	19	2.2%	8	2.7%
Presence of pedestrian	1	0.6%	16	1.6%	5	0.6%	-	-
Presence of debris – rock	-	-	6	0.6%	9	1.0%	7	2.3%
Mechanical failure – brake failure	-	-	11	1.1%	8	0.9%	2	0.7%
Pavement deficiencies – pothole	1	0.6%	2	0.2%	9	1.0%	9	3.0%
Pavement deficiencies – bad/adulating surface	-	-	1	0.1%	10	1.1%	2	0.7%
Mechanical failure – engine	-	-	6	0.6%	3	0.3%	1	0.3%
Presence of debris – vehicle component	-	-	3	0.3%	4	0.5%	1	0.3%
Presence of debris – oil slick	-	-	3	0.3%	5	0.6%	-	-
Mechanical failure – Engine on fire	-	-	1	0.1%	1	0.1%	4	1.3%
Presence of debris – fallen goods	-	-	3	0.3%	1	0.1%	1	0.3%
Mechanical failure – dislodge tire	-	-	-	-	2	0.2%	-	-
Pavement deficiencies – water ponding	-	-	1	0.1%	-	-	-	-
Mechanical failure – engine on fire	-	-	-	-	-	-	1	0.3%
Total (n = 2,359)	176		1006		879		298	

Note: A total of 5,294 crash cases was excluded because they were unidentifiable

Regardless of various types of severity, only two (2) types of crash outcome were used as a binary outcome, i.e. fatal injury motorcyclists (code = 1) and non-fatal injury (code = 0). Table 8 and Table 9 shows the results of the model estimations utilizing the MELR. The result is divided into three (3) sections: Fixed and random effects parameters or Hierarchical effects, Goodness-of-fit test, and the Intra-unit correlation analysis. We have regressed the data up to four (4) hierarchical levels due to a large number of observations (n = 11,201). Only two (2) statistically significant models were considered after exhaustive attempts; both statistically significant at the fixed and random parameters ($p<0.05$). The two (2) models hold the same fixed parameters and have almost similar odds ratios but with different levels of statistically significant. The only difference between these models are the random parameters in Level 2 (see Table 3). In order to evaluate these models, each table has to be examined and discussed.

The fixed effects parameters can be interpreted as a normal logistic regression. From Table 8, in Model 1, shows that all the expressway sections (e.g. fast lane, middle lane, slow lane, etc.) are more likely to have approximately four (4) times fatally injured motorcyclists as compared to the emergency lane. This indicates that motorcyclists are safer riding on the emergency lane, i.e. paved road shoulder, than on any other expressway section.

Table 7: Number of crash cases by type of critical reason and severity involving motorcycle.

Associate Factors	Fatal		Severe		Light		Damage Only	
Incompetence – Poor driving skills	227	38.5%	1,496	42.9%	1,379	49.6%	344	49.1%
Reckless – Speeding	177	30.0%	896	25.7%	523	18.8%	140	20.0%
Non-performance – Tired or sleepy	41	6.9%	253	7.2%	217	7.8%	28	4.0%
Not at fault – Hit by vehicle	32	5.4%	83	2.4%	42	1.5%	8	1.1%
Negligent – Driving with close proximity	30	5.1%	173	5.0%	145	5.2%	28	4.0%
Negligent – Tailgating	26	4.4%	227	6.5%	122	4.4%	52	7.4%
Incompetence – Failure to see/notice	13	2.2%	41	1.2%	42	1.5%	15	2.1%
Reckless – Risky driving	8	1.4%	32	0.9%	33	1.2%	5	0.7%
Reckless – Driving on the wrong lane - EL	8	1.4%	47	1.3%	35	1.3%	6	0.9%
Reckless – Driving under influence (DUI)	7	1.2%	24	0.7%	20	0.7%	4	0.6%
Reckless – Driving on the wrong lane *	6	1.0%	20	0.6%	6	0.2%	-	-
Reckless – Abrupt lane change	4	0.7%	15	0.4%	22	0.8%	2	0.3%
Incompetence – Poor hazard detection	3	0.5%	60	1.7%	89	3.2%	41	5.9%
Reckless – Dangerous overtaking	2	0.3%	22	0.6%	20	0.7%	2	0.3%
Non-performance – Heart attack/stroke	2	0.3%	-	-	-	-	-	-
Incompetence – Abrupt braking	1	0.2%	13	0.4%	11	0.4%	3	0.4%
Incompetence – Failure to negotiate curve	1	0.2%	12	0.3%	5	0.2%	1	0.1%
Not at fault – Hit by object	1	0.2%	4	0.1%	3	0.1%	1	0.1%
Reckless – Red light running	1	0.2%	3	0.1%	3	0.1%	-	-
Not at fault – Hit unexpected hazard	-	-	44	1.3%	40	1.4%	14	2.0%
Reckless – Driving on the wrong lane – Toll	-	-	14	0.4%	8	0.3%	3	0.4%
Negligent – Poor vehicle & equipment condition	-	-	5	0.1%	6	0.2%	1	0.1%
Non-performance – Misc. health problem	-	-	1	0.0%	2	0.1%	2	0.3%
Non-performance – Loss of awareness	-	-	1	0.0%	3	0.1%	-	-
Reckless – Driving while using phone	-	-	1	0.0%	3	0.1%	-	-
Non-performance – Vehicle mechanical failure	-	-	1	0.0%	3	0.1%	-	-
Incompetence – Failure to judge	-	-	1	0.0%	-	-	-	-
Reckless – Vehicle overloaded/over limit	-	-	1	0.0%	-	-	-	-
Total (n = 7,562)	590		3,490		2,782		700	

Note: *or riding on the opposite lane, a total of 92 crash cases was excluded because they were unidentifiable

As for collision type, motorcyclists involved in a fatal-multiple vehicle crash (ORModel 1 = 1.623, 95% CI = 1.364 – 1.932) are approximately two (2) times more likely than a fatal single vehicle crash. Also, motorcyclists are two (2) times more likely to be involved in a fatal crash during the low light condition (i.e. night with or without lighting, dusk or dawn) than during daytime (see Table 8). Furthermore, motorcyclists riding during the weekends (ORModel 1 = 1.534, 95% CI = 1.306 – 1.800) are more likely to be involved in a fatal crash than during the weekdays.

For the Critical Event, the model indicates that a motorcycle being Hit and Run by unknown vehicles (ORModel 1 = 4.639, 95% CI = 2.289 – 9.399) are four (4) times likely to suffer fatal injuries than in a situation where the motorcyclists lost control of their motorcycles. Moreover, motorcycles being involved in a Head-on Collision (ORModel 1 = 1.919, 95% CI = 1.092 – 3.373) are twice likely to suffer fatal injuries compared to situations where motorcyclists lost control of their motorcycle.

As for the motorcyclists' characteristics, motorcyclists aged more than 60-year-old motorcyclists (ORModel 1 = 9.316, 95% CI = 5.060 – 17.150) have the highest probability of being fatally injured, followed by those aged 10 – 15 years old. In addition to this, motorcyclists with different races other than the Malaysian, are more likely to be involved in a fatal crash than the Malays, Chinese, Indian and Bumiputra Sabah/Sarawak.

Table 8: Mixed-effects logistic regression for fixed effects variables.

Fixed Effects Variables	Model 1		Model 2	
	O.R.	95% C.I.	O.R.	95% C.I.
1. Intercept	0.009 (0.003) **	0.005 – 0.016	0.010 (0.003) **	0.006 – 0.018
2. Expressway section				
On the opposite lane	4.533(5.305)	0.457 – 44.926	4.085 (4.715)	0.425 – 39.242
On lane closure	3.639 (3.064)	0.699 – 18.949	3.185 (2.595)	0.645 – 15.726
Overall expressway section	3.208 (1.287) **	1.461 – 7.041	3.161 (1.259) **	1.449 – 6.898
Exclusive motorcycle lane	0.726 (0.196)	0.427 – 1.234	0.655 (0.170)	0.394 – 1.090
Fast lane	2.071 (0.238) **	1.653 – 2.594	1.979 (0.224) **	1.585 – 2.471
Slow lane	3.258 (0.338) **	2.659 – 3.993	3.165 (0.324) **	2.589 – 3.868
Middle lane	3.595 (0.458) **	2.800 – 4.615	3.539 (0.446) **	2.764 – 4.531
Road median	1.158 (0.578)	0.435 – 3.082	1.094 (0.540)	0.416 – 2.877
3. Collision type				
MVC – Multiple vehicle crash	1.623 (0.144) **	1.364 – 1.932	1.619 (0.143) **	1.362 – 1.925
4. Lighting				
Night with lighting	1.825 (0.173) **	1.517 – 2.197	1.866 (0.174) **	1.555 – 2.240
Night without lighting	2.101 (0.235) **	1.688 - 2.615	2.107 (0.231) **	1.699 – 2.612
Dusk/Dawn	2.067 (0.313) **	1.536 – 2.783	2.085 (0.313) **	1.554 – 2.798
5. Day type				
Public holiday	1.161 (0.200)	0.829 – 1.627	1.155 (0.197)	0.827 – 1.612
Weekend	1.534 (0.125) **	1.306 – 1.800	1.543 (0.125) **	1.317 – 1.809

Continued on next page.

Table 8 – *Continued from previous page.*

Fixed Effects Variables	Model 1		Model 2	
	O.R.	**95% C.I.**	**O.R.**	**95% C.I.**
6. Critical events				
Head-on collision	1.919 (0.552) **	1.092 – 3.373	1.804 (0.513) **	1.033 – 3.148
Hit and run	2.521 (1.738)	0.653 – 9.734	2.451 (1.683)	0.638 – 9.417
Hit and run by unknown vehicle	4.639 (1.671) **	2.289 – 9.399	4.436 (1.575) **	2.211 – 8.898
Hit by object on road	0.097 (0.070) **	0.023 – 0.402	0.098 (0.071) **	0.024 – 0.409
Hit object on road	0.057 (0.029) **	0.021 – 0.154	0.057 (0.029) **	0.021 – 0.154
Hit pedestrian on road	0.393 (0.298)	0.089 – 1.733	0.384 (0.291)	0.087 – 1.693
Hit road infra	0.272 (0.308)	0.029 – 2.507	0.276 (0.307)	0.031 – 2.445
LC of vehicle after hitting object/defect	0.181 (0.108) **	0.056 – 0.585	0.186 (0.111) **	0.058 – 0.599
Rear end collision between vehicles	0.867 (0.094)	0.700 – 1.072	0.870 (0.094)	0.705 – 1.075
Side collision between vehicles	0.738 (0.206)	0.428 – 1.275	0.764 (0.210)	0.446 – 1.308
Side swipe between vehicles	0.762 (0.099) **	0.591 – 0.983	0.768 (0.099) **	0.597 – 0.988
Squeezed by vehicle	0.611 (0.378)	0.182 – 2.053	0.623 (0.383)	0.187 – 2.079
Vehicle on fire	0.878 (0.968)	0.101 – 7.622	0.904 (0.990)	0.105 – 7.740
7. Motorcyclist's age range				
10 – 15	8.500 (4.171) **	3.249 – 22.237	8.291 (4.035) **	3.194 – 21.522
16 – 20	5.717 (0.761) **	4.404 – 7.422	5.486 (0.721) **	4.240 – 7.097
21 – 30	5.686 (0.617) **	4.597 – 7.032	5.500 (0.588) **	4.460 – 6.781
31 – 40	5.742 (0.814) **	4.349 – 7.582	5.551 (0.778) **	4.218 – 7.304
41 – 50	6.681 (1.233) **	4.653 – 9.592	6.350 (1.159) **	4.440 – 9.082
51 – 60	7.763 (1.622) **	5.155 – 11.691	7.248 (1.495) **	4.838 – 10.859
> 60	9.316 (2.901) **	5.060 – 17.150	8.505 (2.621) **	4.649 – 15.558
8. Race				
Other race	1.940 (0.523) **	1.144 – 3.291	1.909 (0.511) **	1.129 – 3.227
Bumiputra Sabah/Sarawak	1.001 (0.474)	0.396 – 2.532	0.970 (0.455)	0.387 – 2.431
Chinese	1.000 (0.238)	0.627 – 1.594	0.997 (0.236)	0.626 – 1.586
Indian	1.049 (0.235)	0.675 – 1.628	1.065 (0.238)	0.688 – 1.650
Malay	0.833 (0.165)	0.565 – 1.227	0.844 (0.166)	0.574 – 1.242

Note: OR: Odds ratio; ( ): Standard error; ** >95% level of significance based on the likelihood ratio test versus ordinary logistic regression (fixed effect parameters)

Fitting a multilevel model here is to determine if, after controlling for the variables in the fixed part of the model, there is any statistically significant variation in the motorcycle fatal crash outcomes within a certain type of expressway concessionaire, expressway zones, speed limit. The variance between the four levels of each model may be neatly summarised by the four parameters σ^2_{e0}, σ^2_{u0}, σ^2_{v0} and σ^2_{w0} (see Table 10). They are known as variance parameters, as they measure the variance in the parameters at Levels 1, 2, 3 and 4. In this case, they show the relative variability in the model residuals that may be attributed to the fatal crash outcome of each rider (at Level 1) and the variation of speed limit (at Level 2), expressway zones (at Level 3) and the different expressway concessionaire (at Level 4).

In these models, the Level 1 variance parameter is constrained to the value 1 to correspond to a binomially distributed response, as stipulated by Jones & Jørgensen (2003), and this value is multiplied by $\pi^2 / 3$, which is extensively described in Jones & Jørgensen (2003) and also in Rasbash et al. (2009). The random intercepts in the output in Table 10, exhibit significant variation, judging by a likelihood- ratio test versus an ordinary logistic regression ($p_{model\ 2} = 0.000$), or by the all of its intercept variance of random intercepts (Level 2 = 0.258) being more than its standard error (S.E. at Level 2 $_{model\ 2}$ = 0.122) (see Hamilton (2006) for more detail).

To estimate the proportion of overall residual variability which is associated with each level, equation 6, 7, 8 and 9 are used (see Table 10). All models show that 71.7% to 73.8% of the variations come from Level 1, i.e. each motorcycle rider involved in a crash. As for Level 2, the different type of speed limit for Model 1 has a variation of 5.6% while for Level 3, different expressway zones in Model 1 has the lower variation with 6.5% compared to Model 2 (8.4%). Lastly, at Level 4, the different type of expressway concessionaire has the variation ranges from 16.2% to 17.8%, with Model 2 having the highest variation. This shows that different types of expressways governed by different concessionaires may have at least 16% to 18% effects towards the motorcycle fatal outcome, which may need further study.

The goodness-of-fit test is used to choose the best model, in which shows that Model 1 has a better fit than all models based on the Akaike's Information Criterion (AIC) i.e. $AIC_{Model\ 1}$, < $AIC_{Model\ 2}$ (see Table 10). Thus, Model 1 is better in explaining the factors and their variations in association with the fatal and non-fatal outcome of motorcyclists along Malaysian expressway. Model 1 is represented by the relative variability of the residuals that may be attributed to the fatal or non-fatal outcome of each rider at Level 1, and the variation of speed limit at Level 2, expressway zone at Level 3 and different expressway concessionaire at Level 4.

Table 9: Mixed-effects logistic regression for random effects variables.

Hierarchical Levels/Random Effects	Model 1			Model 1		
	Intercept Variance	**N**	**95% C.I.**	**Intercept Variance**	**N**	**95% C.I.**
Level 1						
Motorcyclists, σ^2_{e0}	1.000			1.000		
Level 2						
Speed limit of the expressway, σ^2_{w0}	0.258 (0.122)	491	0.102 – 0.654	–	–	–
Level 3						
Expressway zones, σ^{2u}_0	0.300 (0.198)	162	0.082 – 1.097	0.374 (0.183)	162	0.143 – 0.976
Level 4						
Expressway concessionaires, σ^2_{v0}	0.742 (0.310)	33	0.327 – 1.683	0.795 (0.312)	33	0.369 – 1.714

Note: N = Number of groups in each Hierarchical level; OR: Odds ratio; ( ): Standard error, SE

Table 10: Goodness-of-fit for all models and intra-unit correlation.

	Model 1	Model 2
Goodness-of-fit		
Number of observations	11,201	11,201
ll(model)	-2,701.31	-2,710.25
df	39	39
AIC	5,488.614	5,504.498
BIC	5,803.535	5,812.096
Integration method: mvaghermite		
Integration points	7	7
Wald chi^2(39)	747.92	755.55
Prob > chi2	0.000	0.000
Log likelihood	-2,701.31	-2,710.25
LR test vs. logistic regression:		
chi^2(3)	244.90	227.01
Prob>=chibar^2	0.000	0.000
Intra-unit correlation (%)		
ICC Level 1, ρ_1	71.7%	73.8%
ICC Level 2, ρ_2	5.6%	-
ICC Level 3, ρ_3	6.5%	8.4%
ICC Level 4, ρ_4	16.2%	17.8%

4. Discussion and Conclusion

This research aims to determine the cause of motorcycle crashes along the expressway. This is done by identifying most common Critical Events, Critical Risk and Associated Factors, and other contributing factors of motorcycles fatal crashes. It was found that loss of control of vehicles (i.e. motorcycle) is the Critical Event that has the highest number of fatalities involving motorcycles, followed by rear-end collision between vehicles. Meanwhile, poor driving skill (incompetence) and speeding (reckless) are the two (2) main Critical Reasons that contributed to the high number of fatal crash cases involving motorcyclists. As for the type of Associated Factors, factors such as poor visibility with no lighting and the slippery pavement has the highest number of fatalities involving motorcycles. Motorcycle crash data acquisition was from MHA from the year 2016 to 2018, with 7,653 crash cases recorded from a total of 11,201 victims involved.

The MELR indicated significant factors associated with motorcyclists crash outcome, and also indicate the percentage of variation in each level, e.g. expressway speed limit (Level 2), expressway zone (Level 3), and expressway concessionaire (Level 4) with relation to the fatal crash outcome involving motorcycle. Findings show that motorcycles are likely to initiate the crash rather than being the victim of the crash, motorcycles are likely to be involved in a crash by themselves rather than being involved in a crash with many vehicles along the expressways and despite the higher number of motorcycles involved in single-vehicle crash, multiple-vehicle crash has a higher fatality rate. The MELR indicates that motorcyclists are four (4) times safer riding on the emergency lane than on fast, middle or slow lanes along the expressway section. Motorcyclists involved in a fatal-multiple vehicle crash are almost two (2) times more likely than a fatal single vehicle crash. Motorcyclists are also two (2) times more likely to be involved in a fatal crash during low light conditions than during daytime. Motorcyclists riding during the weekend have the tendency to be involved in a fatal crash than during the weekdays.

Based on the findings, motorcycles are likely to be involved in a crash by themselves rather than involved in a crash with many vehicles along the expressways. This supported study by (Hurt & Dupont, 1977) stated that the crash involved motorcycle rider generally demonstrates a high level of primary control failure in the pre-crash circumstances. Frequently the hazard is detected, but the rider is not capable of making the vehicle respond as wanted. Many single-vehicle motorcycle crashes demonstrate the sensitivity of the motorcycle equilibrium and the result of rider errors of braking. If the rider applies too much front brake torque, the front wheel will lock up and skid. Since the side force capability of the tire vanishes as the wheel lock-up occurs, the skidding front wheel will quickly slide out to one side or the other and a fall will occur.

In addition to this, crash cases along the emergency lane (i.e. Paved road shoulder) have a high number of severe, light and damage only cases involving motorcyclists. Research by (Braimaister, 1999) concluded that travel on the emergency lane contains its additional elements of crash risk, however, their findings also show crashes of single-vehicle have a less serious effect than multiple-vehicle crashes on emergency lanes. It is worth to note, there are obstacles found on the emergency lanes such as vehicle breakdowns, thus the same study recommended a minimal width of the emergency lane is recommended more than 3.5 m. In order to prevent improper use of emergency lanes and to reduce the number of stopped vehicles, the typical facilities must proper provide such as rest areas with parking and toilet's (every 20 kilometres); service areas (every 50 to 100 kilometres); service and accommodation areas (every 200 kilometres). However, the best countermeasure is providing exclusive motorcycle lane in reducing road fatalities involving motorcycles along the Malaysian expressways.

5. Recommendation

It is recommended that motorcycles are allowed to utilize the emergency lanes as their travel path along the highway as it is proven statistically safer and low probability to be involved in fatal outcomes. However, further study needs to be conducted regarding motorcycles feasibility on the emergency lane. Exclusive motorcycle lanes are also recommended to be built as a long-term effort in curbing road fatalities involving motorcycles along the Malaysian expressways.

Acknowledgements

The authors would like to express their appreciation to the MHA for providing the crash data for three (3) years. The authors would also like to express special thanks to the team members and research assistants for their help and contribution in completing the research.

References

AASHTO (2010). *Highway safety manual* (Vol. 3, 1st ed.). Washington, D.C.: American Association of State Highway and Transportation Officials (AASHTO).

Abdel-Aty, M. A., & Radwan, A. E. (2000). Modeling traffic accident occurrence and involvement. *Accident Analysis & Prevention, 32*(5), 633-642.

Abdul Manan, M. M., & Várhelyi, A. (2012). Motorcycle fatalities in Malaysia. *IATSS Research, 36*(1), 30-39.

Abdul Manan, M. M. (2014). Motorcycles entering from access points and merging with traffic on primary roads in Malaysia: Behavioral and road environment influence on the occurrence of traffic conflicts. *Accident Analysis & Prevention, 70*(0), 301-313.

Abdul Manan, M. M., & Várhelyi, A. (2015). Motorcyclists' road safety-related behavior at access points on primary roads in Malaysia – A case study. *Safety Science, 77*(0), 80-94.

Abdul Manan, M. M., Ho, J. S., Syed Tajul Arif, S. T. M., Abdul Ghani, M. R., & Várhelyi, A. (2017). Factors associated with motorcyclists' speed behaviour on Malaysian roads. *Transportation Research Part F: Traffic Psychology and Behaviour, 50,* 109 – 127.

Abdul Manan, M. M., Várhelyi, A., Çelik, A. K., & Hashim, H. H. (2018). Road characteristics and environment factors associated with motorcycle fatal crashes in Malaysia. *IATSS Research, 42*(4), 207-220.

Åberg, L. (2003). *The role of attitudes in transportation studies*. Dalarna University, Borlänge & Uppsala University, Uppsala, Sweden. Retrieved from http://www.tft.lth.se/fileadmin/tft/dok/KFBkonf/6Aaberg.PDF

Ayati, E., & Abbasi, E. (2011). Investigation on the role of traffic volume in accidents on urban highways. *Journal of Safety Research*, *42*(3), 209-214.

Blows, S., Ameratunga, S., Ivers, R. Q., Lo, S. K., & Norton, R. (2005). Risky driving habits and motor vehicle driver injury. *Accident Analysis & Prevention, 37*(4), 619-624.

Braimaister, L. (1999). *Specific safety measures for emergency lanes and shoulders of motorways: A proposal for motorways' authorities in the framework of the European research project Safety Standards for Road Design and Redesign SAFESTAR, Workpackage 1.1*. Leidschendam, the Netherlands: SWOV Institute for Road Safety Research. Retrieved from https://www.swov.nl/publicatie/specific-safety-measures-emergency-lanes-and-shoulders-motorways

Crundall, D., Bibby, P., Clarke, D., Ward, P., & Bartle, C. (2008). Car drivers' attitudes towards motorcyclists: A survey. *Accident Analysis & Prevention*, *40*(3), 983-993.

DOT (2006). *Large truck crash causation study: Analytical user's manual*. In: NHTSA ed. Washington D.C.: US Department of Transportation.

Dupont, E., Papadimitriou, E., Martensen, H., & Yannis, G. (2013). Multilevel analysis in road safety research. *Accident Analysis & Prevention*, *60*, 402-411.

Guo, G., & Zhao, H. (2000). Multilevel modeling for binary data. *Annual Review of Sociology*, *26*(1), 441-462.

Hurt, H. H., & DuPont, C. J. (1977). *Human factors in motorcycle accidents* (No. 770103). SAE Technical Paper.

Jones, A. P., & Jørgensen, S. H. (2003). The use of multilevel models for the prediction of road accident outcomes. *Accident Analysis & Prevention*, *35*(1), 59-69.

Kasantikul, V. (2001). *Motorcycle accident causation and identification of countermeasures in Thailand Volume I: Bangkok study*. Bangkok, Thailand: Chulalongkorn University.

Nordqvist, M., & Gregersen, N. P. (2010). *Motorcyclist's behavior and attitude towards road safety sveriges motor cyklister (SMC)*. Nationalföreningen för Trafiksäk-erhetens Främjande (NTF).

Penumaka, A. P., Savino, G., Baldanzini, N., & Pierini, M. (2014). In-depth investigations of PTW-car accidents caused by human errors. *Safety Science, 68*, 212-221.

Rasbash, J., Steele, F., Browne, W. J., & Goldstein, H. (2009). *A user's guide to MLwiN version 2.10* (p. 314). Bristol: Centre for Multilevel Modelling, University of Bristol.

Revelt, D., & Train, K. (1998). Mixed logit with repeated choices: households' choices of appliance efficiency level. *Review of Economics and Statistics*, *80*(4), 647-657.

Savolainen, P., & Mannering, F. (2007). Probabilistic models of motorcyclists' injury severities in single-and multi-vehicle crashes. *Accident Analysis & Prevention*, *39*(5), 955-963.

Starnes, M. (2006). *Large-truck crash causation study: An initial overview* (Vol. 810). National Center for Statistics and Analysis, National Highway Traffic Safety Administration, US Department of Transportation.

Theofilatos, A., & Yannis, G. (2014). A review of the effect of traffic and weather characteristics on road safety. *Accident Analysis & Prevention*, *72*, 244-256.

Washington, S., Karlaftis, M. G., & Mannering, F. L. (2003). *Statistical and econometric methods for transportation data analysis*. Boca Raton, FL: CRC Press, Taylor & Francis Group.