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Rollover Risk Probability Analysis for SUVs and MPVs in the ASEAN Market

S. P. Santosa[*1,2], A. Jusuf[1,2], L. Gunawan[1,2], K. A. Abu Kassim[3], M. L. Hakim[1] and B. P. E. Wiranto[1]

[1]Light-weight Structures Research Group, Faculty of Mechanical and Aerospace Engineering
[2]National Center for Sustainable Transportation Technology,
Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
[3]ASEAN New Car Assessment Program,
Lot 125-135, Jalan TKS 1, Taman Kajang Sentral, 43000 Kajang, Selangor, Malaysia

[*]*Corresponding author: sigit.santosa@itb.ac.id*

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Abstract – *The number of single vehicle and rollover accidents in Indonesia has reached approximately 10,000 (7%) per year. Such an accident is typically followed by a large number of fatality, especially in the case for SUVs and MPVs. In the US, motor vehicle rollovers involving passenger cars, pickup trucks, and sport utility vehicles result in around 10,000 deaths and 27,000 serious injuries each year. Although single vehicle and rollover accident in Indonesia accounts for less than 10% tow-away crashes involving light vehicles, it has recorded almost one-third of light-vehicle occupant fatalities. The aim of this research is to develop a method to predict rollover probability. One of the key geometrical parameters to describe the rollover risk of vehicles is Static Stability Factor (SSF) which can be correlated with rollover probability using NHTSA statistical data. SSF is defined as the vehicle half-track width divided by its center of gravity height. Since information pertaining to the location of centre of gravity is not publicly available, a method was developed to predict it by using published technical data which were validated using NHTSA database. It was then used to predict rollover probability data for MPVs and SUVs in Indonesia. The method can be a tool for manufacturers, consumers, and regulators to reduce the number of rollover accidents which in turn may reduce occupant fatalities. The result can also be a means to assess the trend of rollover accident risk in the ASEAN region and will be beneficial for ASEAN NCAP in determining SUVs and MPVs safety rating.*

Keywords: Rollover risk, Static Stability Factor, SUV, MPV, ASEAN NCAP

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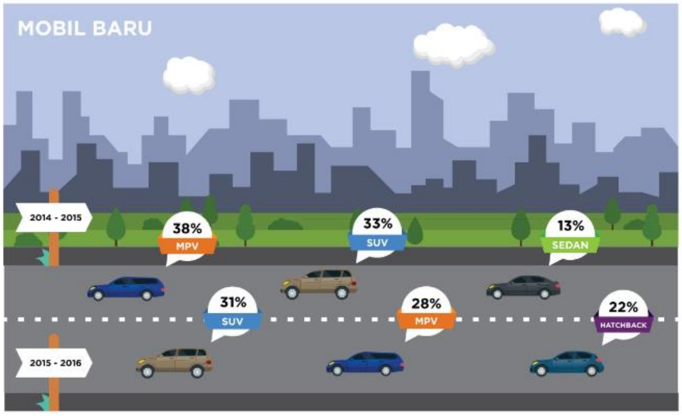
1.0 INTRODUCTION

The use of a vehicle has become a necessity for human mobility. According to the Government Regulation of the Republic of Indonesia Number 55 Year 2012, a vehicle is a means of transportation comprising both motor- and non-motor vehicles. In addition, a motor vehicle is defined as any vehicle driven by mechanical equipment in the form of engine other than railway vehicles (Republic of Indonesia Government, 2012). Today, motorized vehicles with high occupancy for personal transportation include the Sport Utility Vehicles (SUVs) and the Multi-Purpose Vehicles (MPVs). SUVs and MPVs are defined as motor vehicles with 5-8 passenger capacity with high center of gravity (C.G.).



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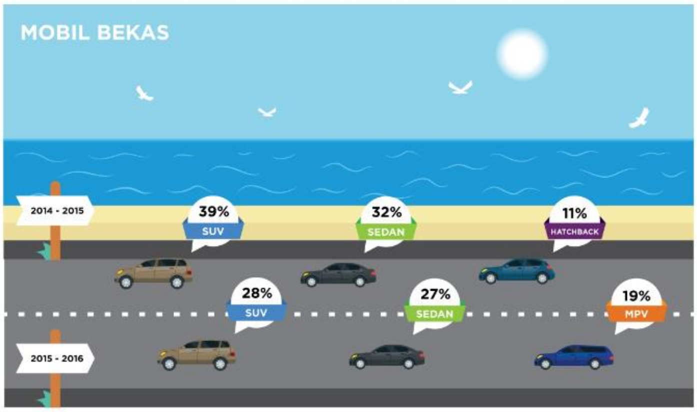


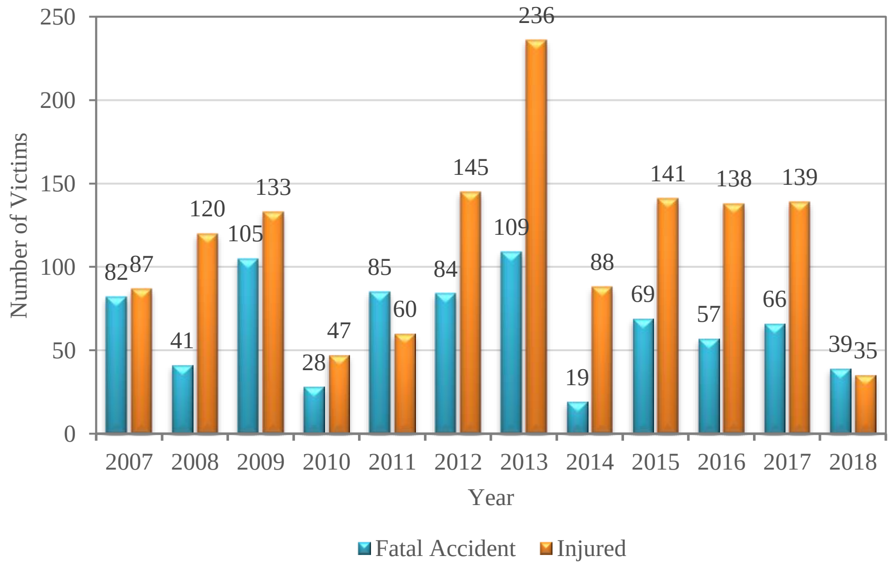
(b)

Figure 1: Indonesia market share based on types of vehicle (a) new car, (b) second-hand car, 2014-2016 (Carmudi, 2016)

Figure 1 reveals that in the period between 2015 to 2016, Indonesia's new cars market share based on the types of vehicle comprised 31% SUVs, 28% MPVs and 22% hatch backs. The second-hand cars market shares in the same period indicated a slightly different trend, i.e. 28% SUVs (still in the first position), 28% sedans (the 2nd most popular car type), and 19% MPVs. Passenger cars categorized as SUV or MPV are popular in Indonesia because the consumers want a car to accommodate more passengers. Sedans are less preferred because they are considered less efficient to support consumers' everyday activities despite their arguably more luxurious features. In general, Indonesians are opting for cars to fulfil individual needs such as to commute to work on weekdays and to take the whole family on weekend vacations.

However, there have been many single-vehicle related accidents (rollover) and multiple-vehicle accidents in Indonesia as reported by Jusuf et al. (2017) and Santosa et al. (2017).

In the United States of America (USA), motor vehicle rollovers involving passenger cars, pickup trucks, and SUVs result in approximately 10,000 deaths and 27,000 serious injuries each year. Although rollover accidents in Indonesia occur in fewer than 10% tow-away crashes involving light vehicles, such crashes accounted for almost one-third of light-vehicle occupant fatalities. Research in Indonesia and in other countries have shown that SUV and MPV rollover risks rise dramatically as the number of occupants increases from less than five to more than ten. The number of single vehicle or rollover accidents in Indonesia has risen to approximately 10,000 (7%) per year. Based on data reported by National Transportation Safety Committee (NTSC) of Indonesia, Figure 2 reveals that from 2007 to March 2018, 31.25% of traffic accidents which required special investigations comprised rollover accidents (NTSC, 2018). Such an accident is typically followed by a large number of fatality, especially in the case for SUVs and MPVs. In Indonesia, there have been two studies of bus rollover accidents by Hakim (2018) and a bus side impact accident by Wiranto (2018); that explain the safety assessment of buses.



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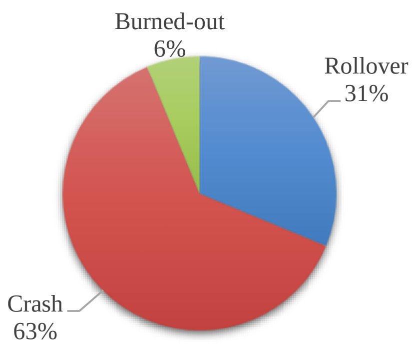

(b)

Figure 2: NTSC of Indonesia traffic accident data (NTSC, 2018)

Due to the surging number of SUV and MPV sales in Indonesia and their high rollover risks, a study of accident characteristics of this vehicle type is urgently required to reduce death rates in road crashes. The objective of this research is to provide rollover probability analysis of SUVs and MPVs in an ASEAN country. Data for this research are based on 26 SUVs and MPVs in Indonesia that occupy the top 50 best-selling cars in Southeast Asia in 2017. The increasing popularity of these SUVs and MPVs in Indonesia is expected to represent high risk of rollover accidents in the ASEAN region.

One of the key geometrical parameters to predict the rollover risk of vehicles is the Static Stability Factor (SSF), which is defined as the half-track width of a vehicle divided by the height of its C.G. The C.G. computational model, the SSF calculation, and the rollover stability prediction method to be developed in this study can become a tool for manufacturers, consumers, and regulators to study in order to reduce the rolling probability of vehicles. The results presented in this paper can also be used by relevant parties to assess the trend of rollover accident risk in the region and will be beneficial for ASEAN NCAP in determining SUV and MPV safety rating in the ASEAN market.

2.0 VEHICLE DATA

The SUVs and MPVs selected in this study have been listed as among the top 50 best-selling cars in ASEAN by Focus2Move; a market leader in automotive intelligence and industry data that provides insights, research findings and forecast for 140 countries, 320 brands and 3,800 models (Focus2move, 2018). In addition, several SUVs and MPVs were added to the data although they were not in the list of 50 best-selling cars. The details of SUVs and MPVs and other information such as selling rank in 2017, vehicle brand, model year, vehicle category, and availability in ASEAN and USA markets are presented in Table 1. Vehicles in the US were included in this study since their rollover probability values data were made available by the National Highway Traffic Safety Administration (NHTSA) and therefore used to validate the methodology developed in this study.

Table 1: The details of SUV and MPV vehicles

No	Selling Rank	Vehicle Brand	Model Year	Type	ASEAN	USA
1	1	Toyota Hilux DC	2018	SUV	√	-
2	3	Toyota Avanza / Daihatsu Xenia	2016	MPV	√	-
3	5	Toyota Fortuner	2017	SUV	√	-
4	6	Toyota Innova	2016	MPV	√	-
5	7	Honda HR-V	2018	SUV	√	√
6	11	Toyota Calya / Daihatsu Sigra	2016	MPV	√	-
7	18	Suzuki Ertiga	2017	MPV	√	-
8	20	Honda BR-V	2017	SUV	√	-
9	24	Mitsubishi Triton	2015	SUV	√	-
10	27	Honda CR-V	2016	SUV	√	√
11	29	Mitsubishi Pajero Sport	2017	SUV	√	-
12	34	Honda Mobilio	2017	MPV	√	-
13	37	Isuzu MU-X	2014	SUV	√	-

No	Selling Rank	Vehicle Brand	Model Year	Type	ASEAN	USA
14	39	Ford Everest	2016	SUV	√	-
15	40	Chevrolet Colorado	2017	SUV	√	√
16	41	Toyota New Sienta	2016	MPV	√	-
17	42	Mazda CX-5	2017	SUV	√	√
18	43	Toyota Rush / Daihatsu Terios	2018	SUV	√	-
19	-	Suzuki New Grand Vitara	2014	SUV	√	√
20	-	Nissan Juke	2016	SUV	√	√
21	-	Toyota New Voxy / Toyota Nav1	2017	MPV	√	-
22	-	Toyota Alphard / Toyota Vellfire	2016	MPV	√	-
23	-	Mitsubishi Expander	2017	MPV	√	-
24	-	Chevrolet Captiva	2015	SUV	√	√
25	-	Hyundai All New Tucson	2017	SUV	√	√
26	-	Mitsubishi Outlander Sport	2013	SUV	√	√

3.0 STATIC STABILITY FACTOR (SSF) AND ROLLOVER PROBABILITY

SSF is basically to measure how top-heavy a vehicle is. A vehicle's SSF is calculated using the following formula (NHTSA, 2005):

$$SSF = \frac{T}{2H} \tag{1}$$

where T is the track width of a vehicle or the distance between the center of the right and left tires along the axle. Meanwhile, H is the center of gravity height of a vehicle above the ground.

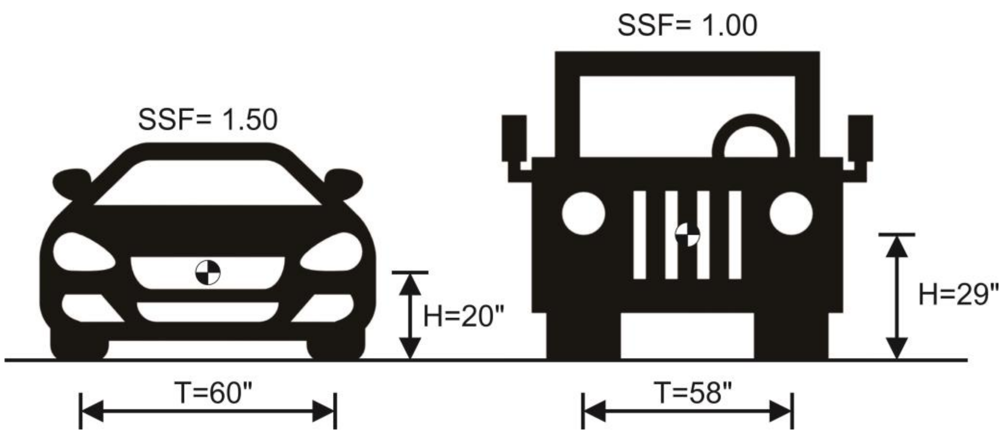

Figure 3: Static Stability Factor for (a) sedan, b (SUV)

Figure 3 illustrates the SSF, where the sedan shown in Figure 3(a) has higher SSF value indicating it is more stable and less top-heavy, while the SUV in Figure 3(b) has lower SSF value indicating it is more unstable and tends to rollover in a single vehicle accident. All vehicle types have SSF values ranging from around 1.00 to 1.50. Typically, higher-riding SUVs, pickup trucks, and vans usually have SSF values ranging from 1.00 to 1.30 while most passenger cars have SSF values ranging from 1.30 to 1.50 (NHTSA, 2005).

A vehicle's SSF is related to its rollover risk potential. NHTSA has performed statistical analyses based on data of 226,000 accident investigations and concluded that in the event of a single-vehicle crash, the SSF significantly affects the probability of rollover. Based on the statistical data, a model correlating a vehicle rollover probability and its SSF has been established as shown in Figure 4. The predicted correlation is given as a dotted line, while the correlations with upper and lower 95% confidence limits are given as solid lines.

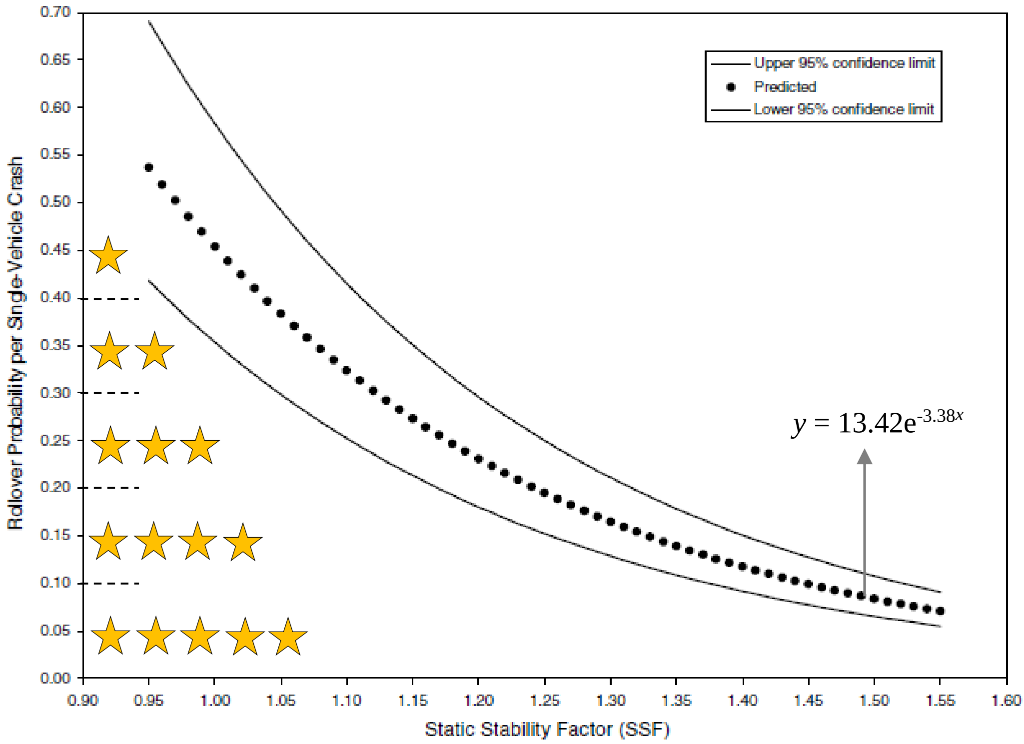

Figure 4: Statistical correlation between SSF and rollover probability and NHTSA's rollover resistance rating system (NHTSA, 2002)

The statistical relation between SSF and the rollover probability forms the basis for NHTSA to determine the rollover resistance rating system for various vehicles (NHTSA, 2002). NHTSA divides the rollover probabilities into five intervals by using boundaries at 0.1, 0.2, 0.3, and 0.4 (shown as four horizontal dashed lines in Figure 4). Vehicles with rollover probabilities within the first interval (0-0.1) are rated as five stars (highest safety rating), while those with rollover probabilities within the second interval (0.1-0.2) are rated as four stars, and so on up to those with rollover probabilities larger than 0.4, which are rated as one star (lowest rating).

4.0 METHODOLOGY

The rollover probabilities of SUVs and MPVs in Indonesia were predicted based on their SSF by using the statistical correlation developed by NHTSA. Since the SSF of MPVs and SUVs in Indonesia was unavailable, a method to calculate SSF was developed based on publicly available technical data. Calculation of SSF and its probability risk is presented in this paper using the 2016 Honda CR-V with its illustrations and specifications presented in Figure 5 and

Table 2, respectively. The method was validated by comparing the results for all vehicles available in both ASEAN and US markets with data from NHTSA.

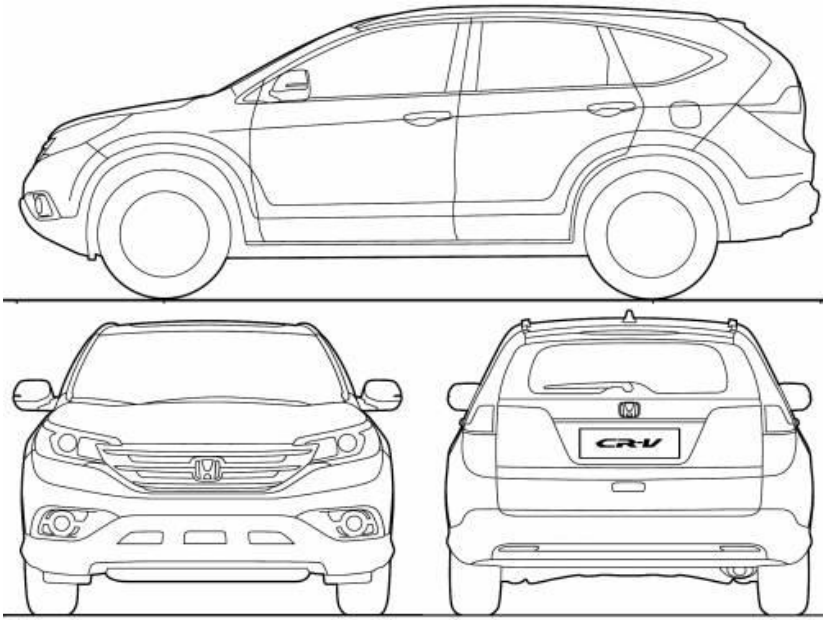

Figure 5: Three view drawing of Honda CR-V (The-Blueprints, 2013)

Table 2: Honda CR-V Specifications (OtoManiac, 2018)

Vehicle's Brand	Honda CR-V
Model Year	2016
Overall Length [mm]	4557
Overall Width [mm]	1855
Overall Height [mm]	1652
Front Tread [mm]	1580
Rear Tread [mm]	1580
Ground Clearance [mm]	170
Engine Type	2.4L I4 DOHC 16-valve
Engine Volume [cc]	2400
Wheel	P225/65R17
Curb Weight [kg]	1619
Gross Vehicle Weight [kg]	2070
Maximum Payload [kg]	451
Fuel Tank Capacity [litre]	58
Amount of Passenger	5

4.1 Developing Methods to Predict the Vehicle's Center of Gravity Location

The C.G location is one of the parameters to determine a vehicle's SSF. Information pertaining to the C.G location is difficult to obtain due to limited data released by car manufacturers. Therefore, in this research, a method to predict the vehicle's C.G. location in vertical distance (height) above the horizontal ground level was developed.

4.1.1 Determining the Car Components Mass

The car components mass was determined based on the pie chart shown in Figure 6. Due to limited information in the pie chart's source such as the type of car used and its specifications, external data were utilized to represent a more realistic condition. External data were required in the form of more detail component's mass which was dominant in weight percentage and other components that were not stated in the pie chart. The external data were therefore obtained from the actual mass of each component available from Indonesia's e-commerce webpages. If there was no adequate information from such external data, information from the pie chart was directly used, such as exterior, structure, closure etc., as stated in Table 3. For example, for Honda CR-V components, the percentage of component weight to its curb weight was provided in great detail in Table 3 and those independent of the curb weight were separated and shown in Table 4. Independent of the curb weight were the components not based on the curb weight and only depended to the car's specification.

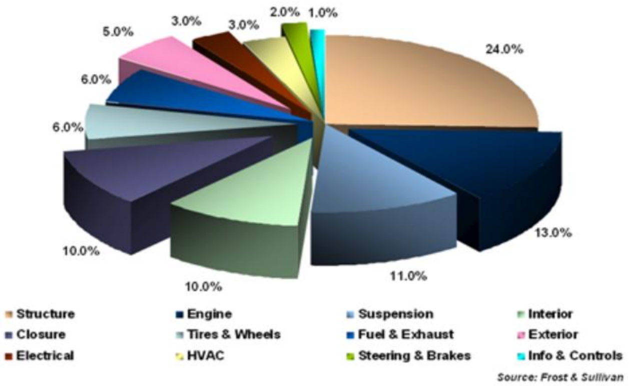

Figure 6: The mass of car component percentage to vehicle's curb weight (Mohamed Mubarak, 2009)

Table 3: The weight percentage of Honda CR-V components to its curb weight

Components	Weight Percentage
Tyres	1.24
Drum Brake	0.29
Disk Brake	1.00
Power Steering System	1.00
Front Suspension	0.86
Rear Suspension	0.67
Electrical	3.00
HVAC	3.00
Engine	13.00
Differential	4.70
Transmission	4.20
Drive Shaft	1.57
Body, Closure, and Exterior	39.00
Control	1.50
Exhaust System	1.47
Front Interior	1.33
Upper Interior	0.57

Table 4: The mass of Honda CR-V components independent to the vehicle's curb weight

Components	Weight (kg)
Captain Seat	15
2nd Row Seat	25
Driver Knee Side Airbag	2
Passenger Airbag	3
Curtain Airbag	5

The mass of fuel (m_{fuel}) and fuel tank (m_{tank}) in Table 4 was calculated using the following equations:

$$m_{fuel} = \rho_{fuel} \; x \; Vol \tag{2}$$

$$m_{tank} = \rho_{tank} x \; 6 \; x \; Vol^{2/3} \; x \; t \tag{3}$$

where, *Vol* is the fuel capacity (m^3), ρ_{fuel} is the fuel density (kg/m^3), ρ_{tank} is the fuel tank's material density (kg/m^3) and *t* is the thickness of the tank (m). The density of fuel and tank material are set to be constant of 900 kg/m^3 and 7750 kg/m^3 respectively.

4.1.2 Determining the C.G. Position

Calculation of the height of the C.G was carried out using graphical method employing a template mass and location for each component. All of the component masses were plotted on 2D picture of a full scale car with CAD software, which are shown as yellow dots in Figure 7. The height of components C.G with respect to the ground level was measured using the CAD measurement facility. The results are presented in Table 5 where each row correlates to each component shown in Figure 7. The height of the vehicle's C.G. was then calculated using the following equation:

$$H = \frac{\sum_{i=1}^{n} M_i H_i}{\sum_{i=1}^{n} M_i} \tag{4}$$

where, M_i is the component mass (kg), H_i is the height of C.G. of the component (mm), and *H* is the height of C.G. of the car (mm).

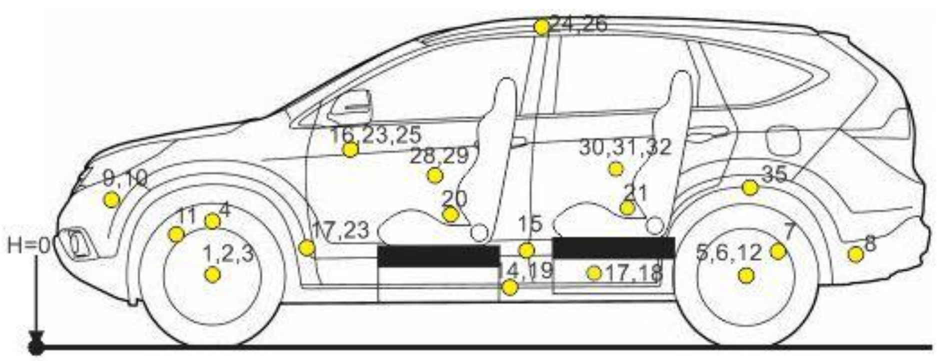

Figure 7: Example of component mass plotting on Honda CR-V

Table 5: The detail results of component's and vehicle's center of gravity

No.	Components	M_i (kg)	H_i (mm)	$M_i \times H_i$ (kg mm)
1	Front Tyre*	40.2	362	14552
2	Steering	16.2	362	5864
3	Front Brake*	32.4	362	11729
4	Front Suspension*	27.7	609	16869
5	Rear Tyre*	40.2	362	14552
6	Rear Brake*	32.4	362	11729
7	Rear Suspension*	49.3	482	23763
8	Spare Wheel	20.1	476	9568
9	Electrical System	48.6	745	36207
10	HVAC	48.6	745	36207
11	Engine	210.5	562	118301
12	Axle	76.1	362	27548
13	Transmission	80.0	462	36960
14	Drive Shaft	25.4	385	9779
15	Body Structure + Closure + Exterior	631.4	529	334011
16	Control System	24.3	963	23401
17	Fuel	52.2	460	24012
18	Fuel Tank	21.0	460	9660
19	Exhaust System	23.8	385	9163
20	Driver and 1st Row Seat	30.0	706	21180
21	2nd Row Seat	25.0	751	18775
22	3rd Row Seat	-	-	-
23	Airbag	9.0	963	8667
24	Knee Airbag	10.0	1602	16020
25	Front Interior	21.5	963	20705
26	Upper Interior	9.2	1602	14738
27	Extra Curbs Weight	14.0	462	6468
28	Driver	75	896	67200
29	Passenger 1	68	896	60928
30	Passenger 2	68	940	63920
31	Passenger 3	68	940	63920
32	Passenger 4	68	940	63920
33	Passenger 5	-	-	-
34	Passenger 6	-	-	-
35	Baggage	111	846	87984
	Total M_i	**2070**	**Total $M_i \times H_i$**	**1288300**
	C.G. Height, H (mm)		**622.36**	

*__Note:__ Left-Side and Right-Side Components

5.0 RESULTS AND DISCUSSION

5.1 SSF Calculation and Validation

SSF is calculated using Equation 1. The track width (*T*) was well known but the height of the vehicle's C.G. was obtained from the approximation method described in the previous section, and hence the calculated SSF was validated using available data. NHTSA rollover probability data (NHTSA, 2016) were available for MPVs and SUVs available in the US market and listed in Table 1, and their SSF could be determined using the correlation presented in Figure 4. The method for obtaining SSF, specifically the determination of C.G. height, was validated by comparing the obtained SSF value to NHTS data for a similar vehicle. The method was accepted if the difference between the available and calculated SSF was less than 5%.

Table 6 shows results of the determination of SSF of Honda CRV upon applying the developed method to the weight distribution and its C.G. location of the components. It can be seen that the SSF calculated using the methodology developed in this study corresponded with NHTSA data and this confirms that the method developed in this research could precisely predict SSF of the SUVs and MPVs and subsequently their rollover probability.

Table 6: The SSF, rollover probability for Honda CR-V

Track Width, *T* (mm)	1580
C.G. Height, *H* (mm)	622.36
Calculated SSF	1.27
Calculated Rollover Probability	0.182
NHTSA Rollover Probability	0.174
SSF calculated from NHTSA	1.28
SSF error	0.8%

5.2 Discussion

The SSF calculation method developed in this study was used to assess the rollover probability and to determine the rollover resistance ratings of the 26 SUVs and MPVs as listed in Table 1. This methodology is capable to calculate the C.G. for various types of vehicle configuration and drivetrains, namely all-wheel drive (AWD) and front wheel drive (FWD). Figure 8 shows the values of the calculated SSF and their rollover probabilities according to the NHTSA statistical model. The blue dots are the position of vehicles available in both ASEAN region and the US and the green ones are of the vehicles in ASEAN.

Detailed calculation results are presented in Appendix I. For vehicles in the US market, it can be seen that the SSF and rollover probability obtained from the developed methodology corresponded with NHTSA test database. Therefore, it is confirmed that the method developed in this research could precisely predict SSF and rollover risk probability of the SUVs and MPVs. The results also indicate that the safety ratings of SUVs and MPVs in ASEAN are between two and four stars. Hence, the cars available only in ASEAN countries had lower ratings compared to the cars available in the US. This was due to the fact that the SUV and MPV for the US market had different components than those in ASEAN market. Although the brand name and vehicle type were the same, several components such as the all-wheel drive and fuel tank volume were different. These contents resulted in a lower C.G. for the US market vehicles. It also led to the rollover probability difference between SUVs and MPVs in the ASEAN region and the US.

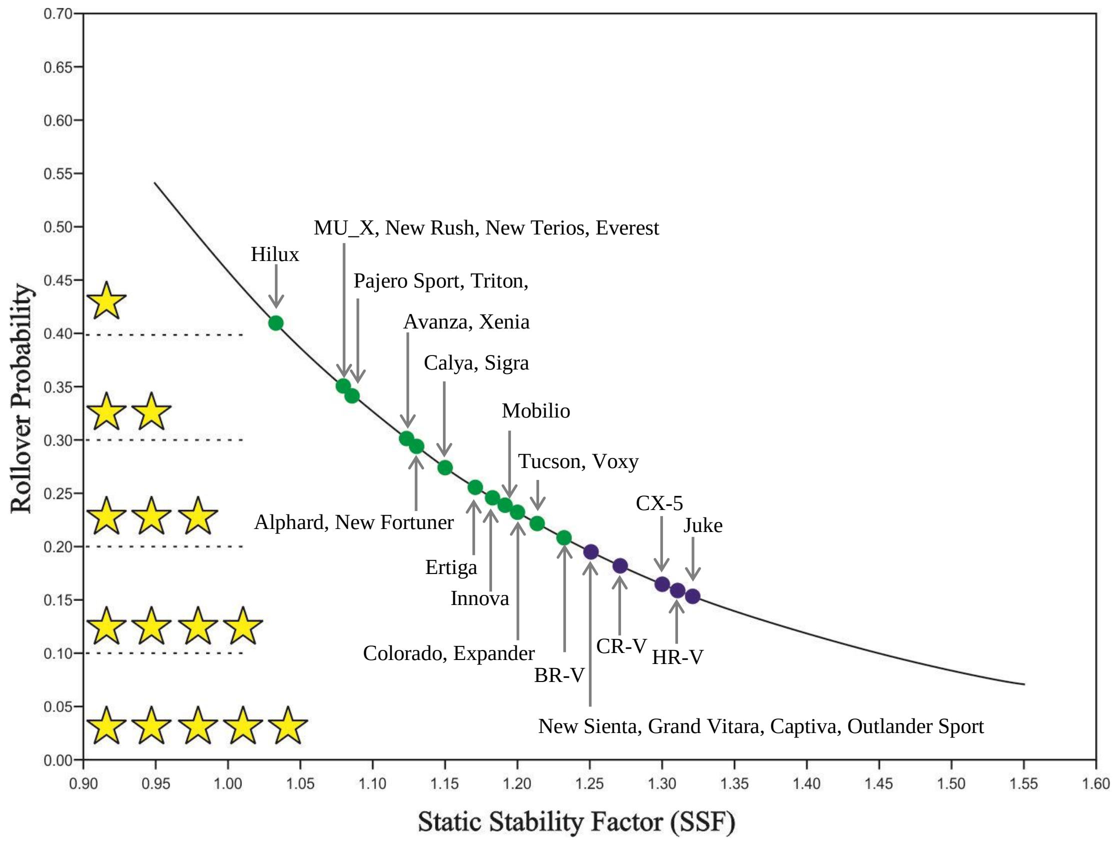

Figure 8: The result of rollover risk probability versus SSF of ASEAN SUV and MPV

6.0 CONCLUSION

All in all, a method to assess the rollover risk probability of vehicles was developed in this study. Results of the methodology developed corresponded well with NHTSA test database, whereby the static stability factor error was less than 5%. Such a method was used to analyse the rollover probabilities of the top 50 SUVs and MPVs in the ASEAN market. The study indicated a strong correlation between the measured values of static stability factor (SSF) for a range of vehicles and corresponding rollover rates determined from single-vehicle crash data. SSF was shown to have a significant influence on the result of actual crashes, i.e. rollover versus no rollover. Strategies to increase the stability on SUV or MPV can certainly be implemented by reducing the C.G. height, such as by placing heavy components into the lower location of the vehicle, and by widening the vehicle track. There was a strong correlation between the rollover accident risk analysis and SSF developed by NHTSA with the real world rollover accident data in the US. As such, the data can be adopted for vehicles in the ASEAN market. Results of this SSF study and its correlation to the rollover accident risks in Indonesia/ASEAN region can become a tool for manufacturers, consumers, and regulators to reduce the number of accidents and fatalities in a single-vehicle and rollover accidents. In addition, these results can also be used to assess the trend of rollover accident risk and will be beneficial for ASEAN NCAP in determining the safety rating of SUVs and MPVs sold in the ASEAN region.

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Appendix I. Comparison between rollover risk probability of developed method with NHTSA test data

Selling Rank	Vehicle Brand	Year	Type	ASEAN	US	SSF			Rollover Probability			Star Rating
						Empirical	NHTSA [A]	Error	Empirical	NHTSA	Error	(Empirical)
1	Toyota Hilux DC	2018	SUV	√	-	1.03	-	-	41.3	-	-	1
2	Toyota Avanza / Xenia	2016	MPV	√	-	1.12	-	-	30.5	-	-	2
3	Toyota New Fortuner	2017	SUV	√	-	1.13	-	-	29.4	-	-	3
4	Toyota Kijang Innova	2016	MPV	√	-	1.18	-	-	24.9	-	-	3
5	Honda HR-V [B]	2018	SUV	√	√	1.31	1.32	0.8%	16.0	15.3	4.7%	4
6	Toyota Calya / Daihatsu Sigra	2016	MPV	√	-	1.15	-	-	27.5	-	-	3
7	Suzuki Ertiga	2017	MPV	√	-	1.17	-	-	25.7	-	-	3
8	Honda BR-V	2017	SUV	√	-	1.23	-	-	21.0	-	-	3
9	Mitsubishi Triton	2015	SUV	√	-	1.08	-	-	34.9	-	-	2
10	Honda CR-V [B]	2016	SUV	√	√	1.27	1.28	0.8%	18.3	17.4	5.4%	4
11	Mitsubishi Pajero Sport	2017	SUV	√	-	1.08	-	-	34.9	-	-	2
12	Honda Mobillio	2017	MPV	√	-	1.19	-	-	24.0	-	-	3
13	Isuzu MU-X	2014	SUV	√	-	1.07	-	-	36.1	-	-	2
14	Ford Everest	2016	SUV	√	-	1.07	-	-	36.1	-	-	2
15	Chevrolet Colorado [B]	2017	SUV	√	√	1.20	1.22	1.6%	23.2	21.2	9.6%	3
16	Toyota New Sienta	2016	MPV	√	-	1.25	-	-	19.6	-	-	4
17	Mazda CX-5 [B]	2017	SUV	√	√	1.30	1.28	1.6%	16.6	17.4	4.7%	4
18	Toyota Rush / Daihatsu Terios	2018	SUV	√	-	1.07	-	-	36.1	-	-	2
19	Suzuki New Grand Vitara [B]	2014	SUV	√	√	1.25	1.26	0.8%	19.6	19.1	2.8%	4
20	Nissan Juke [B]	2016	SUV	√	√	1.32	1.33	0.8%	15.5	15.1	2.6%	4
21	Toyota New Voxy / Toyota Nav1	2017	MPV	√	-	1.21	-	-	22.5	-	-	3
22	Toyota Alphard / Toyota Vellfire	2016	MPV	√	-	1.13	-	-	29.4	-	-	3
23	Mitsubishi Expander	2017	MPV	√	-	1.2	-	-	23.2	-	-	3
24	Chevrolet Captiva [B]	2015	SUV	√	√	1.25	1.27	1.6%	19.6	18.5	6.1%	4
25	Hyundai All New Tucson [B]	2017	SUV	√	√	1.21	1.32	8.3%	22.5	16.5	36.2%	3
26	Mitsubishi Outlander Sport [B]	2013	SUV	√	√	1.25	1.26	0.8%	19.6	19.1	2.8%	4

[A] Calculated from NHTSA rollover probability data
[B] NHTSA (2002)