Journal of the Society of Automotive Engineers Malaysia
Volume 3, Issue 4 (Special Issue), pp 2-7, October 2019
e-ISSN 2550-2239 & ISSN 2600-8092

Factors Affecting Bus Rollover

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ORIGINAL ARTICLE *Open Access*

Article History:

Received
4 Dec 2018

Received in revised form
25 Aug 2019

Accepted
1 Sep 2019

Available online
1 Oct 2019

Abstract – *The objectives of this study are to identify factors affecting bus rollover and to study the association between vehicle and environment factors on bus rollover. For analysis, an analytical mathematical model of steady-state vehicle stability for heavy vehicle was used. For the analysis, four parameters were selected namely the super elevation and gradient of road, the track width of the vehicle and the radius of curvature. The design factorial was used to analyse the effect of these four factors to the increase of rollover index. This study has demonstrated the effect of superevelation, gradient, track width of vehicle and radius of curvature to the rollover index of vehicle. It is shown that the most significant factor on rollover index of vehicle is the radius of curvature during manoeuvring.*

Keywords: Bus, crashes, rollover, road geometry, stability

Journal homepage: www.jsaem.saemalaysia.org.my

1.0 INTRODUCTION

Rollover is the most dangerous heavy vehicle accident (Matolcsy, 2007). Statistics show that the average casualty rate is 25 victims per accident. Failure of the side and roof vehicle structures to sustain the passenger safety compartment can cause severe and fatal injuries to the trapped occupant inside. Statistics related to rollover impact from all around the world excluding Europe is 11% accident rate before year of 2001, 38% from 2001 to 2003 and 49% from 2004 to 2006. Vehicle crashes involving lorries and buses in Malaysia is 22.4% and 7.9% from the total accident around 2007 till 2010 respectively (Zainal Abidin et al., 2012). 11.1% of bus accident is caused by the factor of superstructure under rollover with highest percentage of fatalities occurrence (60%) (MIROS, 2009).

In Malaysia, high deck buses have become popular by bus operators due to the higher capacity of passenger load per trip. In terms of physical dimension specification, the height of a single deck bus varies between 3 to 3.5 m while a double-deck bus and high deck bus can go up to 4.5m and 3.9m respectively. The other significant difference between these categories (single and multiple decks) is the seat capacity. Usually double deck and high deck buses are designed to accommodate up to 50 to 60 seat passengers while single deck is limited to 30 to

40 seat passengers. Due to recent accidents involving high deck buses, the issue on the suitability of use of such vehicles on Malaysian roads has been raised. The hazards imposed by high deck buses are mainly due to the greater risk of rollover. This type of bus has a lower stability static factor ratio (i.e. SSF 0.6-0.75) and a higher load distribution compared to other types of heavy vehicles (Prochowski et al., 2012). In addition, high deck buses which are commonly used for transporting tourists to mountainous attractions, have greater exposure to a higher number of horizontal and vertical road curves, thus increasing the risk. The goal of this study is to identify the effect of longitudinal and lateral angle of road and also the effect on track width of vehicle in the outcome of risk of rollover.

2.0 METHODOLOGY

For analysis, an analytical mathematical model of steady-state vehicle stability for heavy vehicle was used (Malviya & Mishra, 2014). This work is primarily on the effect of various vehicle parameters on the rollover tendency of vehicle. The parameter includes the effect of longitudinal and lateral angle of road and also the effect on track width of vehicle in the outcome of risk of rollover. The analytical model was further developed on programming language.

For the analysis, four parameters were selected namely the super elevation and gradient of road, the track width of the vehicle and the radius of curvature. The outcome of the analysis is the rollover index of vehicle. Rollover index is defined as follows:

$$Rollover\ Index = \frac{(Fr-Fl)}{(Fr+Fl)} \tag{1}$$

where F_r and F_l are the tyre force on the right and the left respectively. The value of the rollover index ranges from -1 to 1. From the formula, it is shown that the event of tyre lifting will occur when the rollover index is either -1 or 1. This is because as either tyre force approach zero the rollover index will approach the value 1.

The design factorial was used to analyse the effect of these four factors to the increase of the rollover index. Table 1 depicted the full factorial design for 4 input factors. For this analysis, the input factor was set to two-level namely high (+) and low (-). The total number of runs was 16 tests. The value selected for each input factor is depicted in Table 2. These values were obtained from the existing regulation by Malaysian Road Authorities on curve design (JKR, 1986).

In this study, the vehicle was simulated to negotiate a right curve of 30 or 50m with the given initial speed of 35km/h. The vehicle steering angle was also set to neutral steering angle of 11.4 degrees. This is based on the multiplication factor of vehicle wheelbase length and radius of cornering (Gillespie, 1992). The other vehicle parameter was set to the fixed values.

Table 1: Number of run for 2^4 full factorials

Test	S	G	C	T	RI
1	-	-	-	-	
2	+	-	-	-	
3	-	+	-	-	
4	+	+	-	-	
5	-	-	+	-	
6	+	-	+	-	
7	-	+	+	-	
8	+	+	+	-	
9	-	-	-	+	
10	+	-	-	+	
11	-	+	-	+	
12	+	+	-	+	
13	-	-	+	+	
14	+	-	+	+	
15	-	+	+	+	
16	+	+	+	+	

S=super elevation, G=gradient, C=road curve,
T=track width, RI=rollover index

Table 2: Input factor and value for each level

Input Factor	High (+)	Low (-)
S (degree)	5	1
G (degree)	-10	-5
C (m)	50	30
T (m)	2	1.6

3.0 RESULTS AND DISCUSSION

This section discusses the effect of selected input factors on the rollover index of bus. The analysis of tyre force of each tyre and the effect of each input factor will be highlighted in this section.

Table 3 depicts the different level for each input factor in correspond to the tyre force of vehicle and rollover index. The table shows that the highest rollover index value was 0.78. Further, it is also shown that the highest rollover occurs at Test '3' in which the vehicle track width is 1.6m and negotiating at 30m radius cornering with a super elevation of 1 degree and gradient slope of -10 degree. The table also shows that the rear right tyre was the first tyre to lift of during this manoeuvring. This is shown by the negative value of tyre force which indicates tyre lifting event.

Table 3: Input factors, tyre force (N) and rollover index

Test	S	G	C	T	Vfl	Vbl	Vbr	Vfr	RI
1	1	5	30	1.6	51113.1	32502.2	-3771	14839.4	0.77
2	5	5	30	1.6	47666	28629.7	952.2	19988	0.57
3	1	10	30	1.6	52001.4	30845.9	-5451.5	15703.5	0.78
4	5	10	30	1.6	48604.5	27022.7	-775.6	20805.7	0.58
5	1	5	50	1.6	49317	27777.2	6811.6	28351	0.37
6	5	5	50	1.6	45491.3	23729.4	11303.6	33065.1	0.22
7	1	10	50	1.6	50205.2	26120.9	5131.2	29215	0.38
8	5	10	50	1.6	46429.8	22122.5	9575.8	33882.7	0.22
9	1	5	30	2	47384.2	28774.1	-44.6	18565	0.61
10	5	5	30	2	44790.5	25758.3	3815.3	22847	0.45
11	1	10	30	2	48270.1	27115.4	-1722.7	19431.5	0.62
12	5	10	30	2	45716.9	24139.2	2099.6	23676.8	0.46
13	1	5	50	2	47183.6	25644.1	8944.1	30483.2	0.3
14	5	5	50	2	44209.6	22449.2	12580.8	34340.7	0.17
15	1	10	50	2	48069.4	23985.4	7266.1	31349.6	0.3
16	5	10	50	2	45136.1	20830.2	10865.1	35170.5	0.18

Figure 1 shows the mean of the rollover index against the different level for each input factor. Except for gradient, all other input factors show a decrease in rollover index when the input factor goes to high-level input. It is also shown that the highest decrease in rollover index occurs when the radius of curve is increased from 30m to 50m radius. The rollover index decreased from approximately 0.6 to 0.3.

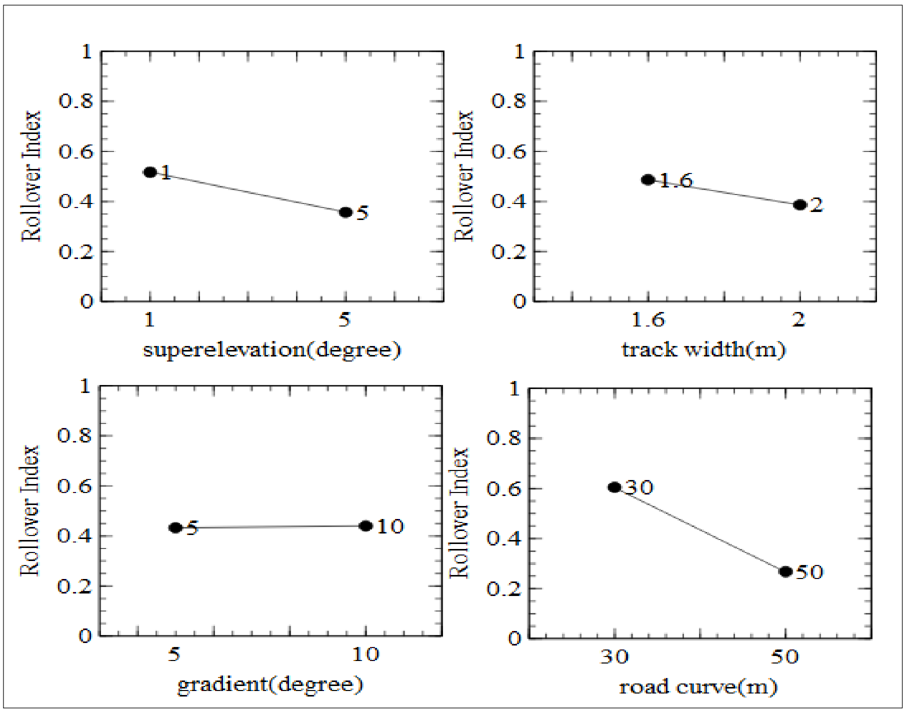

Figure 1: Mean of rollover index against the different level for each input factor

In order to determine the magnitude and the importance of the effects for all the factors in contributing to the rollover index, Pareto chart was used. Figure 2 shows the Pareto chart and it indicated that Radius of Curvature, Super elevation and Track Width are statistically significant in contributing to the rollover index with radius of curvature having the largest effects. It is also shown from the chart that the gradient did not statistically affect the rollover index.

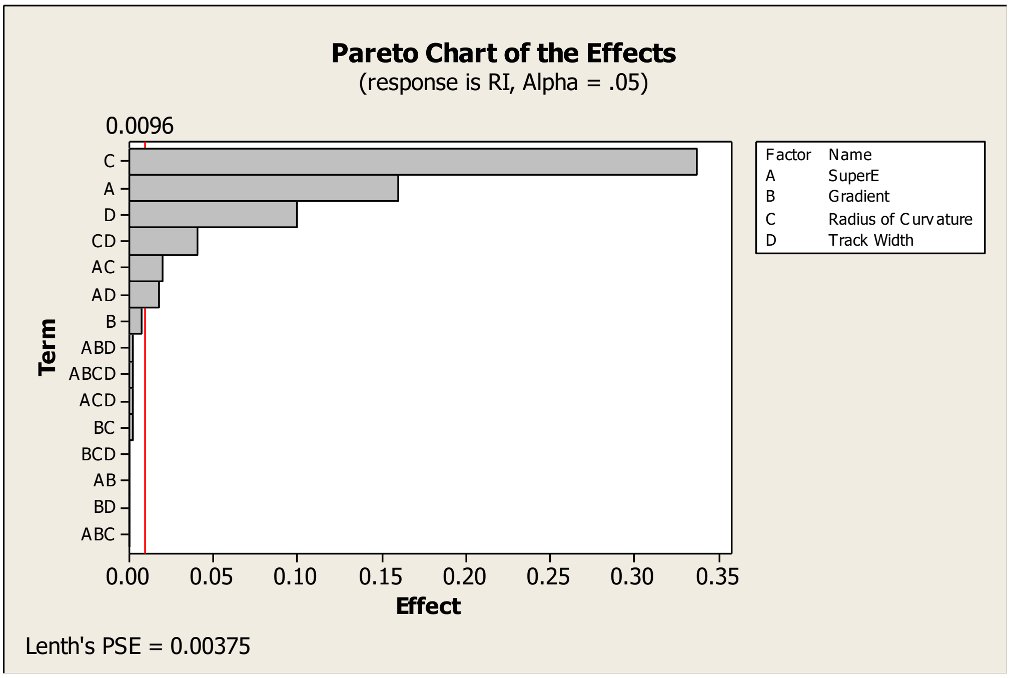

Figure 2: The magnitude and effects of each factor in contributing to the rollover index

From this analysis, it is shown that the most significant factor on the rollover index of vehicle is the radius of curvature. By definition the centripetal force during cornering is equal to velocity squared divided by the radius of curvature. By this definition, when the vehicle moves at 35km/h in a 30m radius the lateral force the vehicle subjected is approximately 0.32 as compared to 0.19 for 50m radius. Previous study has shown that the rollover for heavy vehicle occurs when the lateral acceleration is 0.3-0.4 (Ibrahim et al., 2003). This strongly suggests that the radius of curvature is a significant factor for rollover tendency of vehicle. This finding also suggests that the speed of vehicle by the use of GPS as an indicator for monitoring safe driving may not be adequate. The lateral acceleration of vehicle should be also part of the indicator in monitoring safe driving especially during cornering as lane-change manoeuvre. With an increase number of tool and equipment available in market this parameter can be easily captured and analysed.

The analysis indicates that the rollover index for all configurations range from 0.17-0.78 for all configurations. However, in common engineering design, a safety factor is used in order to incorporate unexpected actual loads and unusual road condition that may occur in real-life applications. For example, a high-deck bus operates on various road gradients and geometries on hilly roads in Malaysia. The most common safety factor used in engineering applications is 1.5 (Zhu, 1993). It is therefore recommended to use this safety factor for the application of vehicle rollover limit. The safety factor of 1.5, therefore, corresponds to the rollover index of 0.67 (i.e. 1/1.5). In addition, the dynamic rollover threshold is generally lower than the static rollover threshold. The findings from dynamic performance of heavy tanker show that the difference between dynamic rollover threshold and tilt table test can be as high as 10 to 15% difference (Gertsch & Eichelhard 2003). Therefore, from Table 3 test 1 (Ri=0.77) and Test 3 (RI=0.78) should be treated as non-allowable configuration and considered as dangerous to rollover stability of bus.

This study is limited to the manoeuvring of a curve without any change in longitudinal braking. It is recommended that the effect of braking while cornering the curve is investigated in future study.

4.0 CONCLUSION

This study has demonstrated the effect of super elevation, gradient, track width of vehicle and radius of curvature to the rollover index of vehicle. It is shown that the most significant factor on rollover index of vehicle is the radius of curvature during manoeuvring. This study is limited to the manoeuvring of curve without any change in longitudinal braking. It is recommended that the effect of braking while cornering the curve is investigated in future study.

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