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The Effect of Vehicle and Road Conditions on Rollover of Commercial Heavy Vehicles during Cornering: A Simulation Approach

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Abstract: Heavy vehicles make up a relatively small percentage of traffic volume on Malaysian roads compared to other vehicle types. However, heavy vehicles have been reported to be involved in 30,000–40,000 accidents yearly and caused significantly more fatalities. Rollover accidents may also incur cargo damages and cause environmental or human disasters for vehicles that carry hazardous cargos if these contents are spilled. Thus, in this paper, a comprehensive study was conducted to investigate the effects of vehicle and road conditions on rollover of commercial heavy vehicles during cornering at curved road sections. Vehicle conditions include the heavy vehicle class (based on the axle number and vehicle type), speed and gross vehicle weight, while road conditions include the cornering radius and coefficient of friction values. In order to reduce the risks involved in usage of actual heavy vehicles in crash experiments, a simulation approach using a multi-body vehicle dynamic software was applied in this study, where the verified virtual heavy vehicle model was simulated and the output results were extracted and analyzed. The results showed that a maximum of 40% and a minimum of 23% from the total number of simulations resulted in an unsafe condition (indicated as failed) during the simulations. From the unsafe conditions, two types of rollover accidents could be identified, which were un-tripped and tripped rollovers. The heavy vehicle speed was also found to have a strong correlation to the lateral acceleration (to cause a rollover), followed by gross vehicle weight, coefficient of friction and cornering radius, respectively.

Keywords: rollover; heavy vehicle; single unit truck; single truck-trailer; lateral acceleration

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1. Introduction

Many developing countries including Malaysia have shown rapid growth in the past decades, particularly in the industrial sectors and infrastructure developments. Parallel to this, Malaysia has seen remarkable a period of economic expansion and growth in terms of its population, industrialization and motorization. According to the Malaysian Automotive Association [1], an average of 60,000 new vehicles are registered in Malaysia every year, with the total number of new vehicles of 604,287 in 2019. These include various types of land vehicles, ranging from passenger cars to commercial vehicles, such as trucks, prime movers, pick-ups, panel vans and buses. This in turn adds up to the traffic composition on Malaysian roads, where 24.57% of traffic was contributed by heavy vehicles, such as light lorries (14.21%), medium lorries (6.29%) and heavy lorries (4.07%) [2].

Heavy vehicles have been reported to be involved in 30,000–40,000 accidents yearly and caused significantly more fatalities than cars [2]. The study by Karim et al. revealed that more than 10% of the fatalities occurred in accidents involving heavy vehicles were caused by a rollover [3]. Based on the National Automotive Sampling System Crashworthiness Data System (NASS-CDS), rollover accidents can be further classified into several types. Based on the data, a trip-rollover is the one that occurs more often (60%) compared to other types of rollover accidents [4]. Meanwhile, a study from NHTSA reported that 95% of single-vehicle rollovers are tripped [5].

Accidents involving heavy vehicle rollovers affect other road users in various aspects and endanger the safety of nearby vehicles or road users. According to Hamidun et al. [6], the involvement of heavy vehicles in road accidents often resulted in more than 80% of second vehicle fatalities. In addition, the probability of a fatal accident to occur has also been reported to significantly increase at locations with higher percentage of trucks in traffic [7]. Load displacements that often occur in such accidents may also cause cargo damages, which may significantly impact the companies' expenses [8]. Heavy vehicles that carry hazardous cargos such as chemicals or flammable fuels have the potential to cause environmental or human disasters if these contents are spilled. In addition to that, a rollover accident is also much more likely to result in driver fatalities compared to other type of crashes that do not involve a rollover [6,9,10]. As a result, heavy vehicle accidentsundoubtedly cause severe traffic disruption, as the wreckage and casualties are more difficult to clear compared to accidents involving other types of vehicles.

Several studies on heavy vehicle rollover have been conducted via conventional means [11–13], such as crash experiments [14]. However, these approaches are time consuming and costly. To reduce or eliminate these consequences or risks, a simulation approach can be employed during such analyses to complete the project. Numerous researchers nowadays are migrating to make use of simulation approaches to study vehicle dynamics and safety. For example, Sun et al. [15], in their study, have developed a full heavy vehicle model with MWorks and analyzed the performance of kinematic and compliance of the heavy vehicle. The usage of validated virtual vehicle models has been shown to similarly to that of actual vehicles, with an acceptable percentage of error [16,17]. Other than that, simulation approaches have also been used to study other aspects that are involved in a rollover, such as the effect of tire criteria [18,19]. The robustness of simulation techniques has allowed for analyses and development of models to be carried out. For example, Inhwan et al. [20] have utilized the rollover test criteria developed by the National Highway Traffic Safety Administration (NHTSA) to simulate both un-tripped and tripped rollovers. Meanwhile, Ertlmeier et al. [21] and Shi et al. [22] have developed a physical model for tripped rollovers, which was then used to establish a rollover criteria improvement. Recently, Elamrani et al. reported on the development of real-time crash prediction models based on traffic and weather data by using machine learning techniques such as the support vector machine (SVM) and deep neural network multilayer perceptron (MLP) [23]. Zou et al. have also used real climate data sets to simulate the relationship between climatic conditions and social development factors in fatal traffic accidents [24].

However, very few reports can be found on the simulation analyses of rollovers involving various types of commercial heavy vehicles, particularly the single unit trucks (SUT) and single truck-trailers (STT) that can be commonly found on Malaysian roads. Thus, in this study, a simulation analysis was conducted with the aim to understand the key factors involved in the occurrence of rollovers in these commercial heavy vehicles, such as (in general) the heavy vehicle conditions and road conditions. To achieve that, IPG TruckMaker(R), a multi-body dynamic simulation software, was used to generate output data of lateral acceleration with various simulation input data, such as heavy vehicle classes, gross vehicle weights, heavy vehicle speeds, road friction coefficient, cornering radius of the road and driver capabilities.

2. Materials and Methods

2.1. Simulation Settings

Validation of the virtual heavy vehicle model with the actual heavy vehicle is important when a simulation approach is employed. This is to ensure that the virtual heavy vehicle model is replicating the actual heavy vehicle as accurately as it can, in terms of its performance and dynamic behavior (Figure 1), as we have reported previously [25]. The virtual model was found to closely represent the actual heavy vehicle and this was further validated by multiple performance indices. As shown in Table 1, the root mean square error (RMSE) of lateral acceleration was very close to 0, indicating a good correlation was obtained between both experimental and simulation data. The lateral acceleration mean absolute error (MAE) was also very close to 0, implying that the simulation model accurately represents the experimental data. The regression coefficient (R) for lateral acceleration was also observed to be close to 1, indicating that the simulation model has explained the majority of the variances observed.

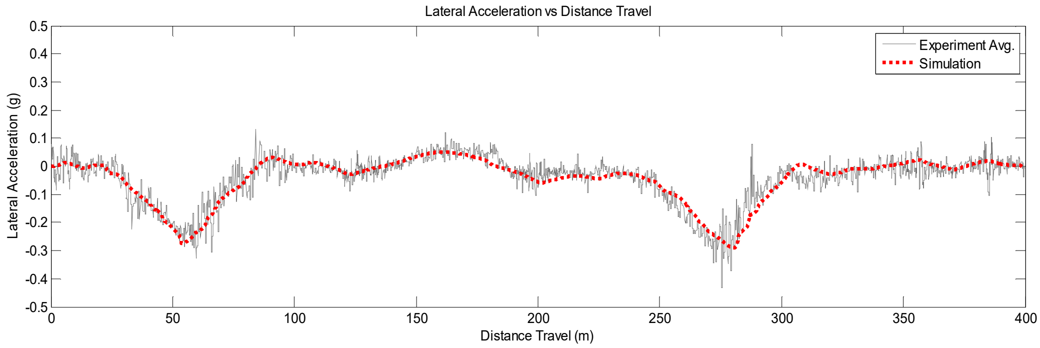

Figure 1. Validation graph of lateral acceleration against distance travel of two-axle SUT [25].

Table 1. Values of RMSE, MAE and R for experimental and simulation data for lateral acceleration.

Output	RMSE	MAE	R
Lateral acceleration	0.0445	0.0325	0.7797

Thus, in this paper, several classes of verified heavy vehicles with various independent parameters were simulated. These independent parameters were divided into several categories as outlined in Table 2, while Figure 2 shows the flowchart describing the simulation process that had been conducted using the IPG TruckMaker(R) software. The analysis took into consideration the common single unit trucks (SUT) and single truck-trailers (STT) that are commonly used in Malaysia, which are SUTs with two, three and four axles and SSTs with four and five axles. Figure 3 shows the SUTs and STTs used in the simulations conducted in this study.

Table 2. Summary of independent parameters used in the simulation settings.

Category	Heavy Vehicle Characteristics	Environment and Road Factor	Other Parameters
Details	Heavy vehicle class Heavy vehicle speed Gross vehicle weight (GVW)	Cornering radius Road friction Super-elevation	Corner cutting value Driver behavior Selected drive lane

It has been reported that GVW, speed and road condition were among the contributing factors in a rollover accident [5,9,10,26–31]. Thus, in this study, the simulation of the heavy vehicles was conducted using various speed values, gross vehicle weights (GVW), coefficient of friction and cornering radius. Additionally, Karim et al. [32] have analyzed and reported the prevalence and degree of GVW and speed violations in selected areas in Malaysia; these data were used as the reference value and input data for the simulation settings in this study. Karim et al. [32] have also reported that 2-axle vehicles recorded the highest percentage of GVW violation, with 120% from its permissible GVW, followed by 3-axle (101%), 4-axle (83.9%) and 5 axle ones (51.9%). It was also reported that 46% of the total heavy vehicles weighing more than 20t violated the permissible speed (driving at more than 90 km/h) [32]. However, heavy vehicles driven at very low speeds (below 40 km/h) were also recorded. Table 3 shows the summary of heavy vehicle settings for speed and GVW used in the simulation.

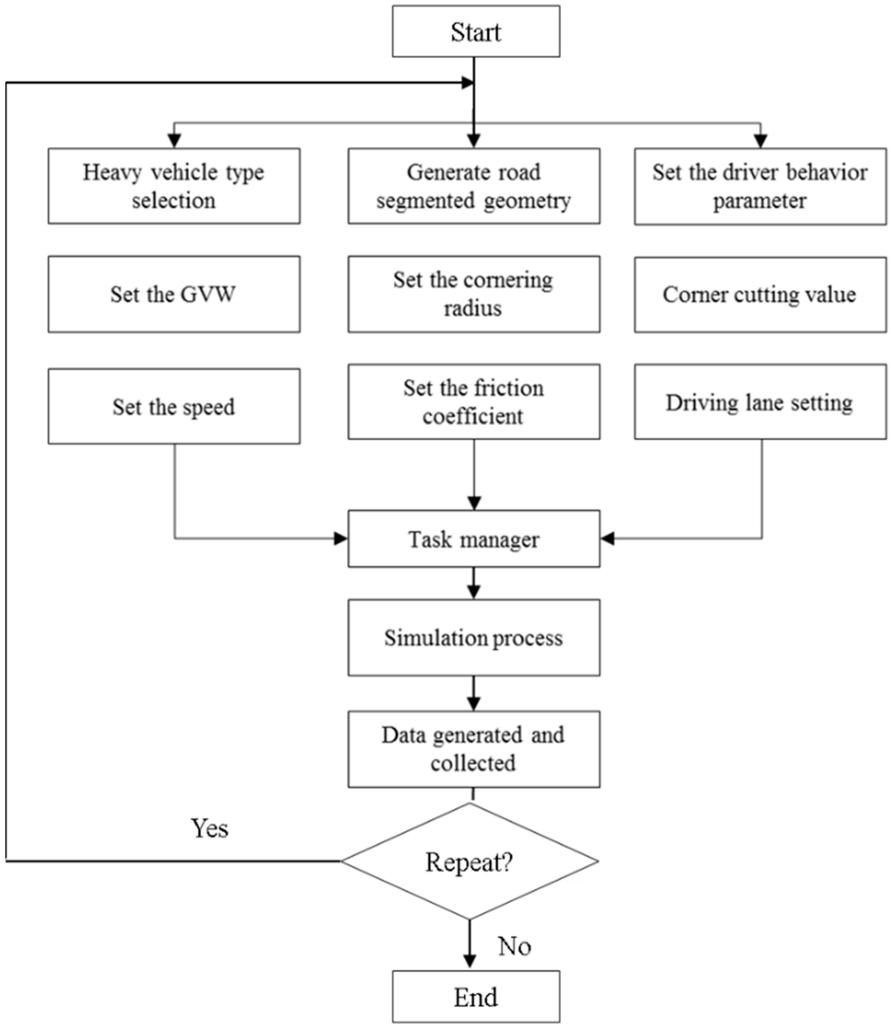

Figure 2. Flowchart of the heavy vehicle simulation process using IPG TruckMaker(R).

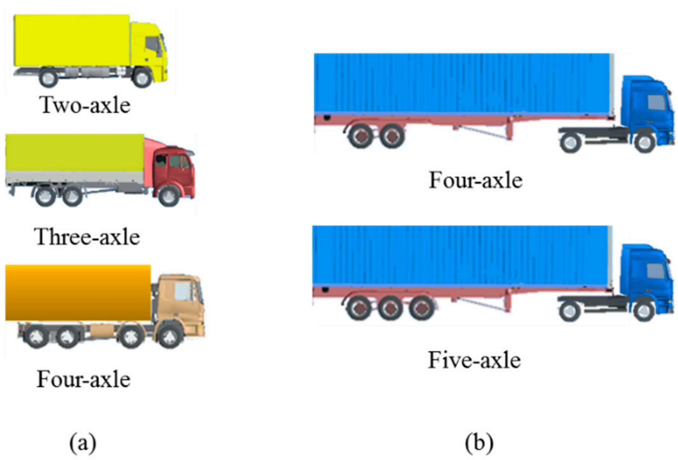

Figure 3. Pictures showing the different types of heavy vehicles used in the simulations: (**a**) single unit truck (SUT), (**b**) single truck-trailer (STT).

Table 3. Summary of heavy vehicle settings (speed and gross vehicle weight, GVW) used in the simulation.

Type	No of Axles	Max GVW in kg *	Speed (km/h)
SUT	2	35,000	Varied starting from 40 km/h to 120 km/h (with intervals of 10 km/h)
	3	57,000	
	4	71,000	
STT	4	71,000	
	5	86,000	

* GVW is added starting from curb weight until max GVW with interval of 5 t.

In order to precisely determine the vehicle stability, the location of the vehicle center of gravity should be considered [10]. However, in this study, the location of the center of gravity (CoG) for each of the different heavy vehicle types was established by the IPG Truck Maker(R) software, where the volume and the height of the load was assumed to be uniform, regardless of the load weight (GVW) applied. According to Elischer and Prem, even though homogeneous loading does not fully represent the actual situation, it can be used to represent the "worst case" loading configuration, when used to determine the stability and safety of the heavy vehicle [33].

Jones and Childers defined the coefficient of friction of wet condition as 0.4 and 0.9 for dry condition [34]. Meanwhile, Kordani et al. mentioned the coefficient of friction of the roads used in his study is between 0.18 (icy) to 0.9 (dry) [29]. In addition, several studies have also reported on coefficients of friction that ranged from as low as 0.17 to 0.7 [35,36]. Thus, five values of road coefficient were also used to represent the real condition of Malaysian roads, which were 0.3 (wet condition), 0.4 and 0.5 (normal conditions) and 0.6 and 0.7 (dry conditions). In the simulation, the road segmented geometry was designed to have a cornering section that started and continued with a straight lane. This road was purposely designed in order to observe the effect of the vehicle stability and safety when maneuvering on the curved section of the road with different coefficients of friction and cornering radius values. Three values of cornering radius, which were 150 m, 200 m and 250 m, calculated 90 degrees of turning from its center, were selected. Figure 4 shows the road geometry generated using the IPG TruckMaker(R). Each cornering radius was designed to follow the superelevation value and the left side was set as the drive lane, in accordance with the Malaysian law. IPG TruckMaker(R) also offered the driving and maneuvering mode features to accurately replicate the driving experience, which were the corner cutting value and driving mode. The corner cutting value was set to "1", which indicated that the heavy vehicle was only allowed to drive on the driving lane area for the entire simulation, while the driving mode was set as "normal"; this was to indicate that the driver was in a calm condition while driving through the simulation. This normal driving mode was rated by a maximum value of the longitudinal and lateral acceleration (known as G-G diagram) of 3.0 ms^{-2} or approximately 0.31 g while cornering. Other driving modes available in the software were "defensive" and "agressive" conditions with different maximum G-G diagram value [37].

There are several parameters that can be used to measure the roll stability of a vehicle, such as through lateral load transfer (LTR), vehicle roll angle and lateral acceleration [10,38,39]. In this study, lateral acceleration was chosen as dependent parameter as it is commonly used to determine the roll stability and rollover propensity [15,17].

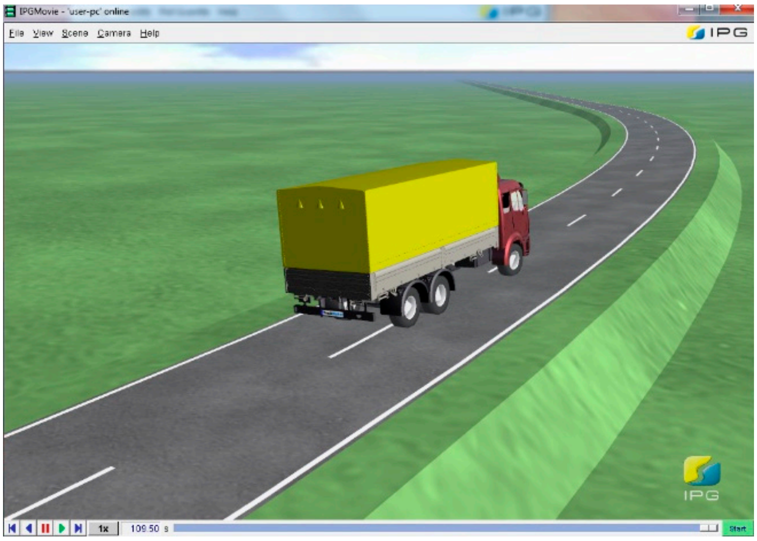

Figure 4. Road geometry generated in IPG TruckMaker(R).

2.2. Post-Processing and Correlation Analysis

A number of simulations were run with various parameters, thus generating numerous sets of simulation files in spreadsheet format. Each file consisted of thousands of output data (lateral acceleration). The exhaustive list of data values was then screened to reveal the data of interest, i.e., the values for maximum lateral acceleration that occurred during vehicle cornering. For this purpose, a computer program language software, MATLAB was used. Through the use of custom-generated coding, the maximum values of lateral acceleration were sorted and transferred into a dedicated file. The flow of the screening process using MATLAB is as shown in Figure 5.

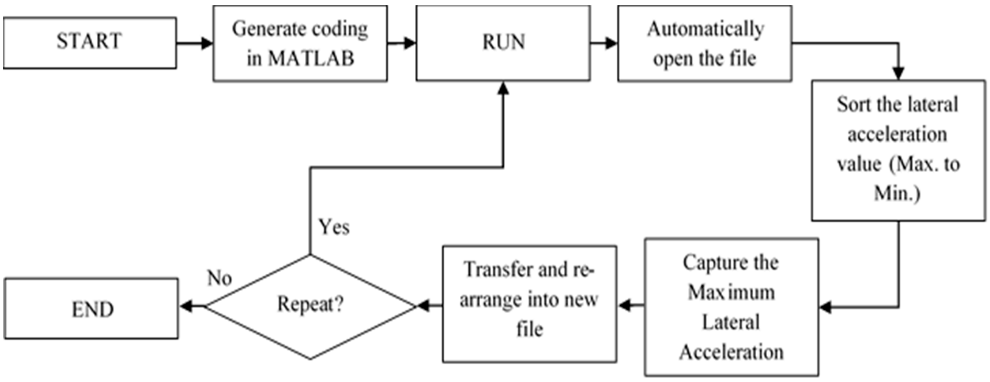

Figure 5. The flow of screening of data procedure in MATLAB.

The data collected were then tabulated and entered into a statistical analysis software, SPSS. A multivariate Pearson coefficient correlation analysis was employed to investigate the significance and degree of relationships between the independent and dependent variables. The correlation analysis was essential to determine which and whether the independent variables played a significant role in the occurrence of rollovers.

3. Results and Discussion

3.1. Simulation of Virtual Heavy Vehicle Models

The simulation files for the results obtained from IPG TruckMaker(R) were exported into spreadsheet format (Microsoft Excel) using an IPG TruckMaker(R) feature called IPG Control. This enabled the data to be screened and thoroughly analyzed. In total, there were 8235 simulation files that had been generated, with 1080 files from two-axle SUTs, 1485 files from three-axle SUTs, 1755 files from four-axle SUTs, 1755 files from four-axle

STTs and 2160 files from five-axle STTs. Different types of heavy vehicles generated a different amount of simulation data due to the different maximum number of GVW sets (see Figure 2), as, the higher the maximum GVW, the more simulation data would be generated for the same speed, coefficient of friction and cornering radius. After all data had been successfully screened and sorted, they were then imported into a statistical analysis software (SPSS) to be further analyzed.

3.2. Data Screening and Processing

Each simulation file for each vehicle class produced a data set which consisted of the distance travelled, vehicle speed, GVW, CoF, curve radius and lateral acceleration. The maximum value of lateral acceleration was screened from each data set by using a customized programming language on MATLAB. The selected screened data for two-axle SUTs maneuvered at cornering radius of 150 m, CoF of 0.3 and GVW of 10,000 kg and 15,000 kg are shown in Table 4.

Table 4. Selected simulation results for two-axle SUTs maneuvered at cornering radius of 150 m, CoF of 0.3, GVW of 10,000 kg and 15,000 kg at various speeds.

Input/Variables			**Output/Dependent Value**	
Heavy Vehicle Type	**GVW (kg)**	**Speed (km/h)**	**Maximum Lateral Acceleration (ms^{-2})**	**Test Result**
2-axle SUT	10,000	40	0.87	Pass
		50	1.36	Pass
		60	1.56	Pass
		70	2.07	Pass
		80	2.65	Failed
		90	2.90	Failed
		100	2.96	Failed
		110	3.08	Failed
		120	3.27	Failed
	15,000	40	0.87	Pass
		50	1.36	Pass
		60	1.86	Pass
		70	2.27	Pass
		80	2.85	Failed
		90	3.08	Failed
		100	3.22	Failed
		110	3.30	Failed
		120	3.50	Failed

Table 5 shows a summary of vehicle safety conditions generated through the simulations. The vehicle was categorized to be in either safe or unsafe (rollover) conditions based on a large number of simulations. Two-axle SUTs recorded the highest percentage of unsafe conditions (40%), followed by three-axle SUTs (32%), four-axle SUTs (27%), five-axle STTs (25%) and four-axle STTs (23%), out of the total number of simulations. These different percentage values of unsafe conditions could be due to the number of axles on the heavy vehicle. For example, for simulations computed using the same GVW, vehicle speed and road conditions, the three-axle SUT was likely to be more stable than the two-axle SUT, since three-axle SUTs would have more tire contact patches on the road to hold the lateral force and slide slip, compared to the two-axle SUT. However, four-axle STTs recorded 4% less unsafe conditions compared to four-axle SUTs, even though similar GVW, speed and road condition settings were used in the simulation. This was due to the fact that four-axle SUTs have a shorter wheelbase than four-axle STTs, thus generating more lateral force during cornering. In addition, Figure 6 shows the number of unsafe conditions when arranged according to the heavy vehicle speed, coefficient of friction and cornering radius. Based on Figure 6, it can be observed that speed has a positive correlation with the occurrence of unsafe conditions, whereby as the vehicle speed increased, the number of unsafe conditions also increased. This observation obeys the principle of circular motion where the increase of lateral acceleration value is directly proportional to the speed of the vehicle, when the cornering radius is constant. In contrast, as the CoF and cornering radius increased, the number of unsafe conditions were observed to decrease, due to the better road grip during vehicle maneuvering.

Table 5. The number and percentage of unsafe and safe conditions for all types of heavy vehicles.

Vehicle Class	Frequency	Safe Condition	Unsafe Condition	Total no. of Simulations
Two-axle SUT	No. of sim.	644	436	1080
	%	60%	40%	100%
Three-axle SUT	No. of sim.	1014	471	1485
	%	68%	32%	100%
Four-axle SUT	No. of sim.	1282	473	1755
	%	73%	27%	100%
Four-axle STT	No. of sim.	1348	407	1755
	%	77%	23%	100%
Five-axle STT	No. of sim.	1620	540	2160
	%	75%	25%	100%

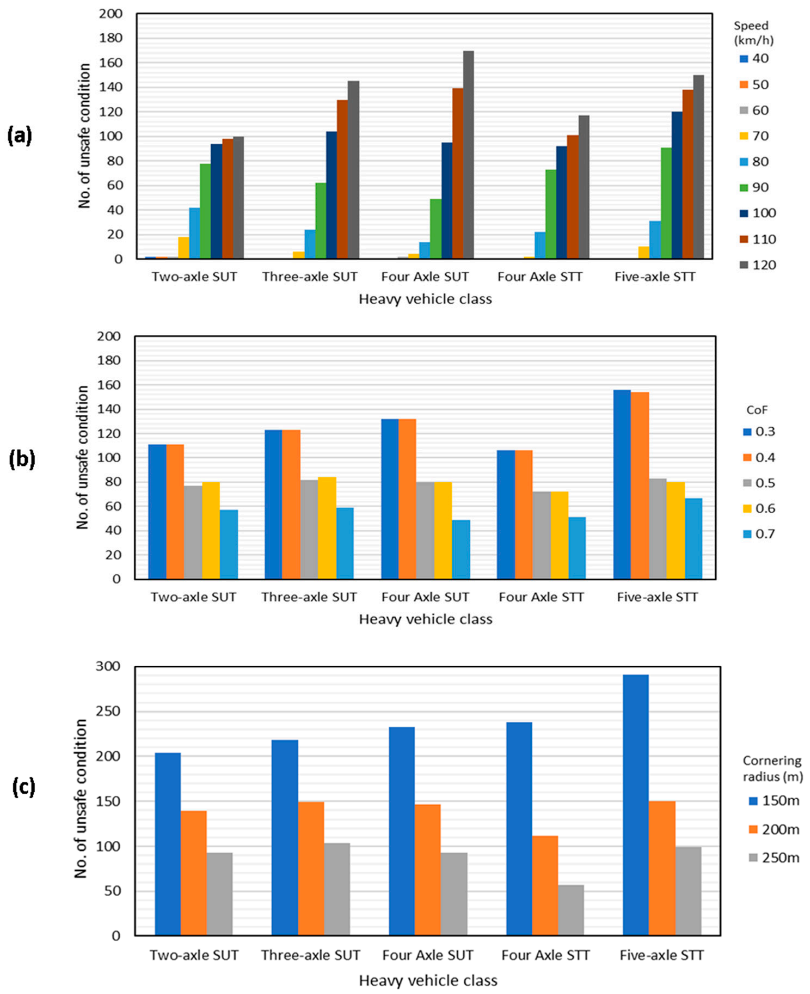

Figure 6. The number of unsafe conditions for all vehicle class, arranged by (**a**) heavy vehicle speed, (**b**) coefficient of friction and (**c**) cornering radius.

The unsafe conditions in these simulation cases can be divided into two types, which are tripped rollover and un-tripped rollover [19]. The tripped rollover occurred when the heavy vehicle left the driving lane, tripped to the curb and rolled over (Figure 7). Meanwhile, an un-tripped rollover occurred when the heavy vehicle started to roll over on the driving lane due to overspeeding and excessive GVW. The road coefficient of friction (CoF) was found to be the main contributing factor that resulted in the occurrence of either tripped or un-tripped rollovers. For instance, when the same vehicle type, GVW, speed and cornering radius were used during the simulation, a lower CoF would result in a tripped rollover, while a higher CoF would result in an un-tripped rollover. Table 6 shows the percentage of tripped and un-tripped rollovers from the unsafe conditions of the different heavy vehicle classes.

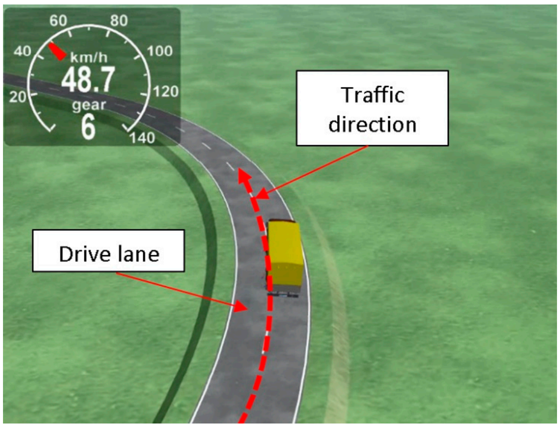

Figure 7. The two-axle SUT leaves the drive lane during cornering (tripped rollover).

Table 6. The number and percentage of tripped and un-tripped rollovers for all types of heavy vehicles.

Vehicle Class	Frequency	Tripped Rollover	Un-Tripped Rollover	Total no. and Percentage of Unsafe Conditions
Two-axle SUT	No. of sim. %	285 65%	151 35%	436 100%
Three-axle SUT	No. of sim. %	294 62%	177 38%	471 100%
Four-axle SUT	No. of sim. %	325 69%	148 31%	473 100%
Four-axle STT	No. of sim. %	315 77%	92 23%	407 100%
Five-axle STT	No. of sim. %	387 72%	153 28%	540 100%

3.3. Analysis of Simulation Results

Data analysis revealed that there is a relationship between the maximum lateral acceleration and the heavy vehicle speed (Table 4), where the maximum lateral acceleration increases with increasing heavy vehicle speed, at any coefficient of friction values. In other words, the faster the heavy vehicle is, the higher is the maximum lateral acceleration that would be generated during cornering, thus increasing the risks of unsafe conditions and rollover propensity. To understand these in detail, the graphs generated by a two-axle SUT when maneuvering a 150 m, 200 m and 250 m cornering radius are shown in Figures 8–10. The heavy vehicle rollover incidences were indicated by the red-colored line in the graphs. The maximum lateral acceleration values that were beyond the right section of the red-colored lines were the lateral acceleration values at which an impending rollover would occur.

The graphs show that, at the same speed and CoF, the maximum lateral acceleration increased when GVW increased. However, these can be seen clearly at the speed of 60 km/h and above, since speeds of 40 km/h and 50 km/h showed a very minimal change of maximum lateral acceleration value when GVW increased. Hence, it can be concluded that the heavier the load carried by the heavy vehicle is, the higher are the risks of rollover during cornering [27,28]. Furthermore, as the CoF increased, the maximum lateral acceleration also increased. This was due to the road surface becoming rougher as the CoF values increased, resulting in a better tire contact patch on the road (more grip), hence more lateral acceleration was required for a rollover and unsafe condition to occur [29]. Data analysis conducted on three-axle SUTs, four-axle SUTs, four-axle STTs and five-axle STTs also showed similar trends (graphs not shown).

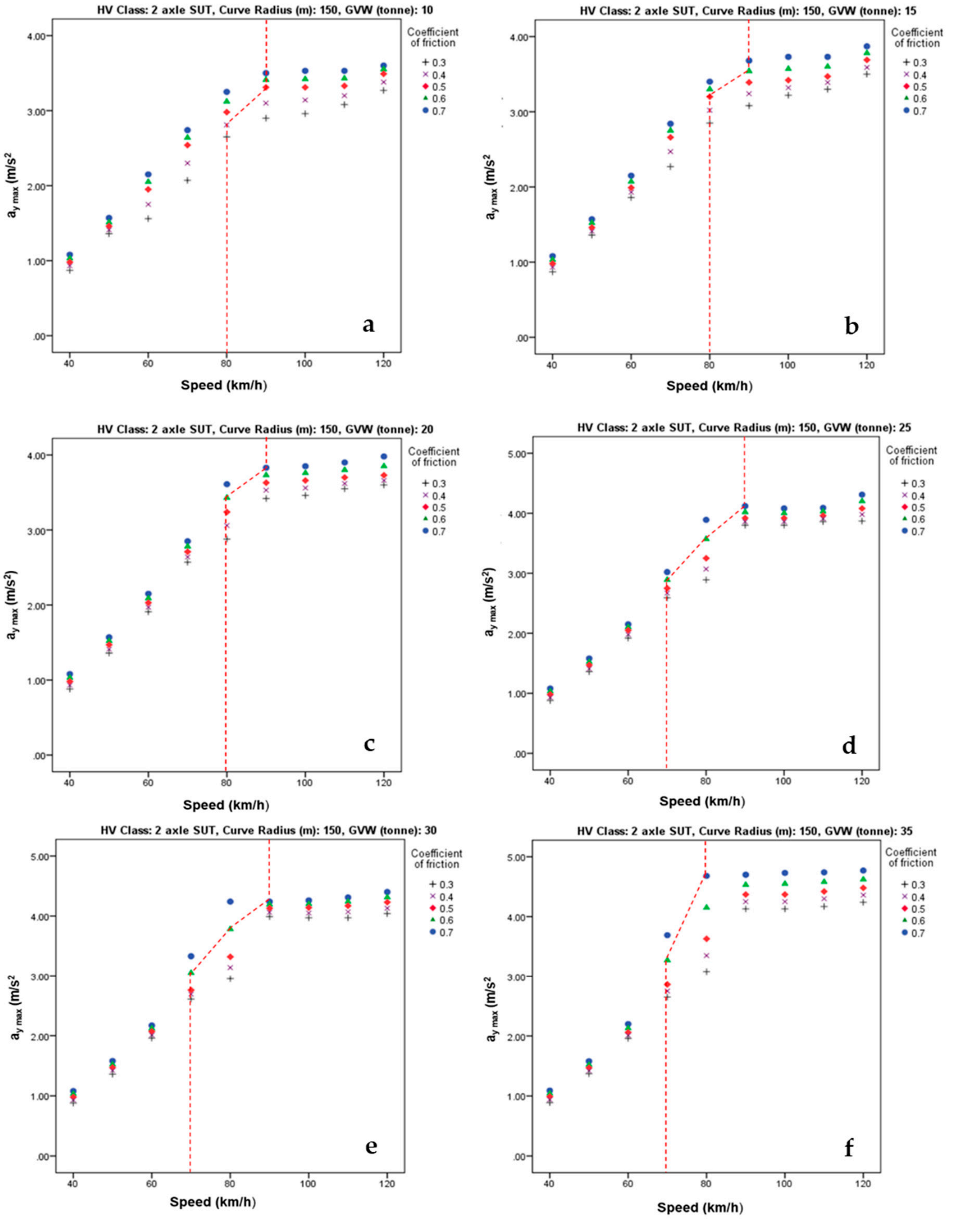

Figure 8. Maximum lateral acceleration vs. speed for two-axle SUTs, when maneuvering at r = 150 m, GVW = (**a**) 10,000 kg, (**b**) 15,000 kg, (**c**) 20,000 kg, (**d**) 25,000 kg, (**e**) 30,000 kg, (**f**) 35,000 kg.

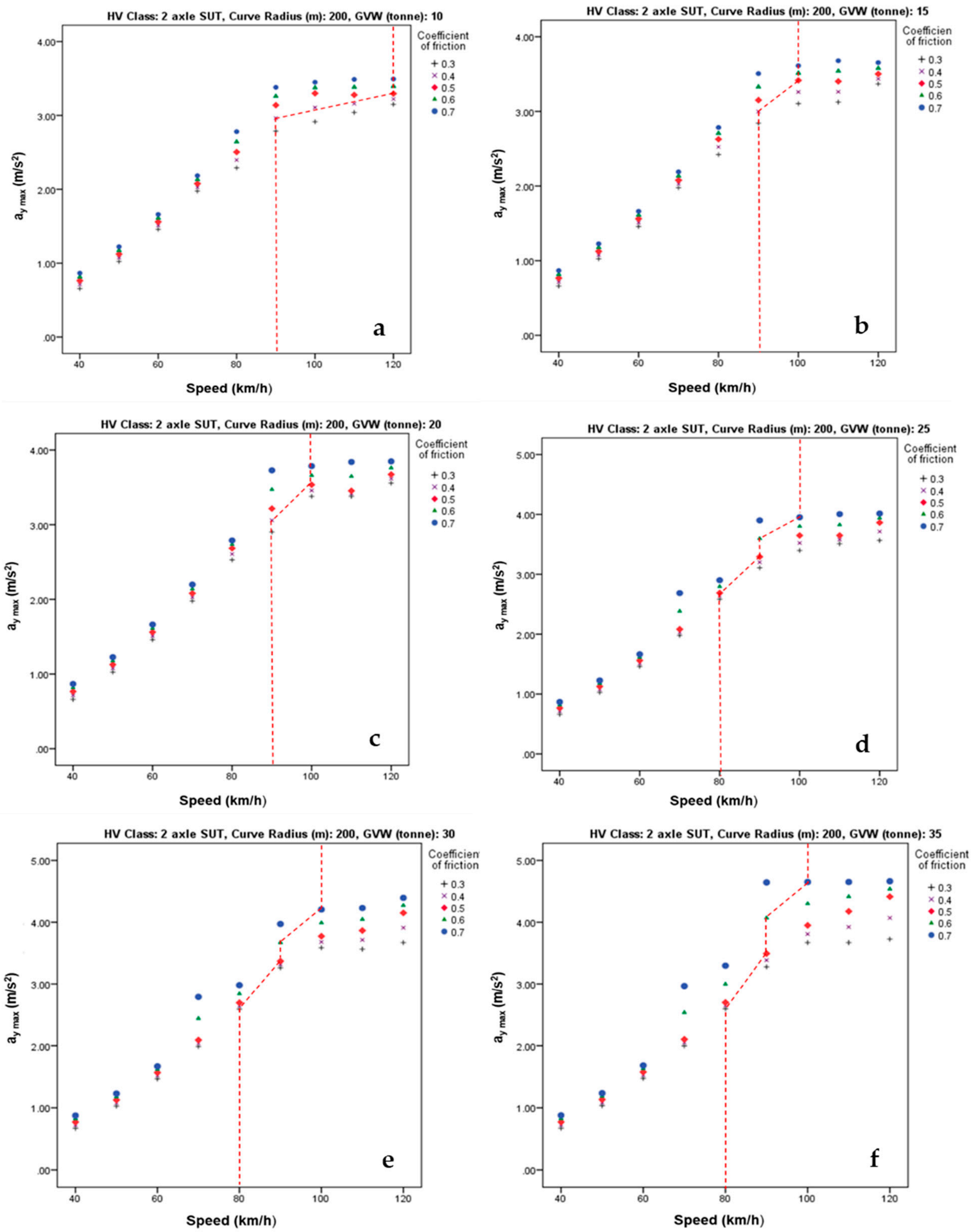

Figure 9. Maximum lateral acceleration vs. speed for two-axle SUTs, when maneuvering at r = 200 m, GVW = (**a**) 10,000 kg, (**b**) 15,000 kg, (**c**) 20,000 kg, (**d**) 25,000 kg, (**e**) 30,000 kg, (**f**) 35,000 kg.

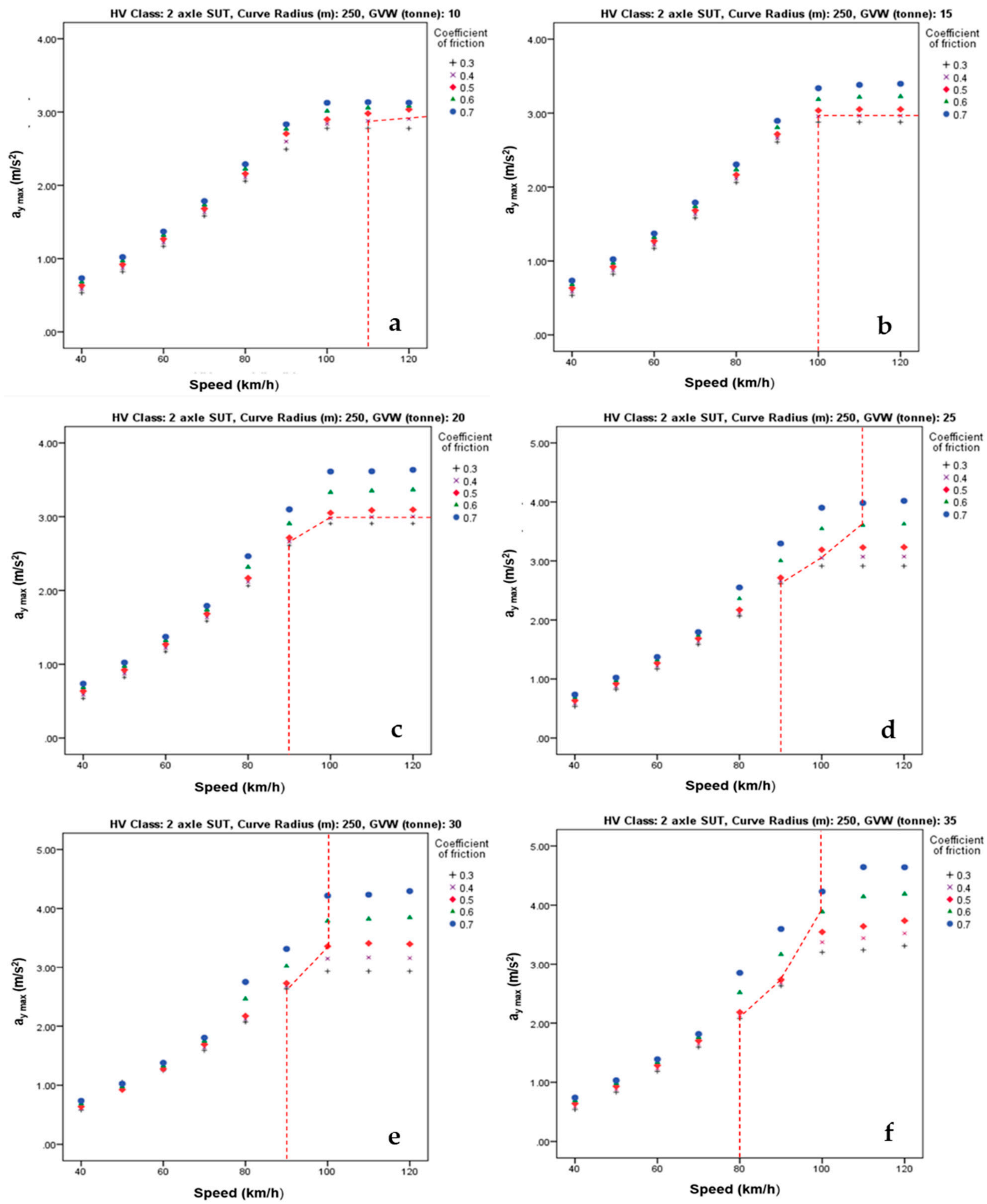

Figure 10. Maximum lateral acceleration vs. speed for two-axle SUTs, when maneuvering at r = 250 m, GVW = (**a**) 10,000 kg, (**b**) 15,000 kg, (**c**) 20,000 kg, (**d**) 25,000 kg, (**e**) 30,000 kg, (**f**) 35,000 kg.

For every heavy vehicle type, the maximum lateral acceleration values resulting from the different GVW (at the same speed, CoF and cornering radius) were tabulated and used to determine the mean maximum lateral acceleration. Table 7 shows an example of the calculated mean maximum lateral acceleration of a two-axle SUT driven at 40 km/h, with CoF of 0.3 and cornering radius of 150 m. The relationship between the mean maximum lateral acceleration and vehicle speeds (at various cornering radius) of other heavy vehicle classes were also analyzed and these are shown in Figure 11, for other SUTs, and Figure 12 for STTs. For two-axle SUTs, the trends observed for cornering radii of 200 m and 250 m were similar to those for 150 m, as explained in previous paragraphs. Data analysis also revealed that the mean maximum lateral acceleration increased when vehicle speed was increased (for all heavy vehicle classes). On the other hand, the mean maximum lateral acceleration increased when the CoF increased.

Table 7. Determination of mean maximum lateral acceleration for two-axle vehicles driven at 40 km/h, with CoF of 0.3 and cornering radius of 150 m.

No	GVW (kg)	Speed (km/h)	Coe. of Friction	Cornering Radius (m)	Maximum Lateral Acceleration (m/s^2)
1	10,000	40	0.3	150	0.872
2	15,000				0.874
3	20,000				0.880
4	25,000				0.881
5	30,000				0.883
6	35,000				0.892
					Mean maximum lateral acceleration = 0.880 (plotted in graph)

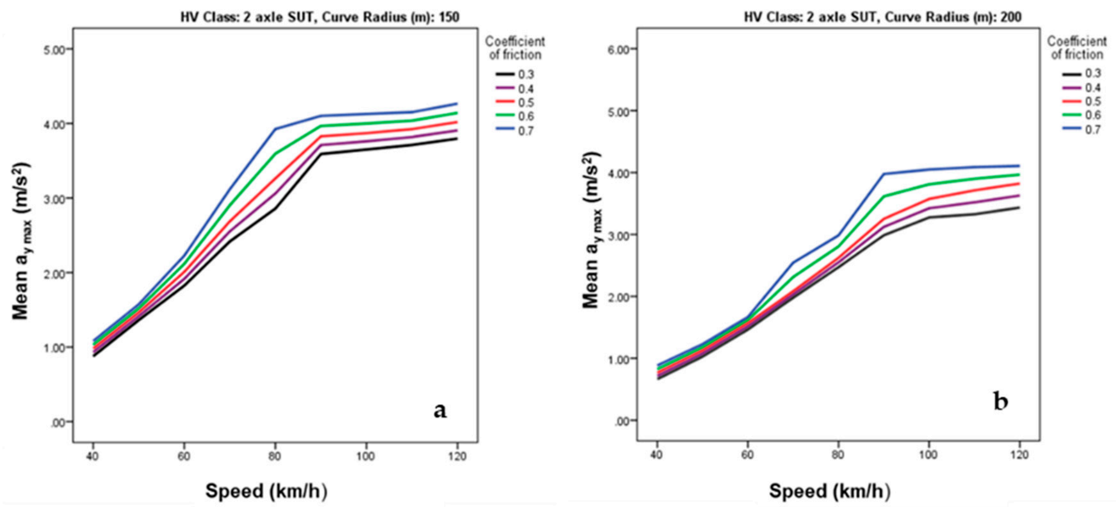

Figure 11. *Cont.*

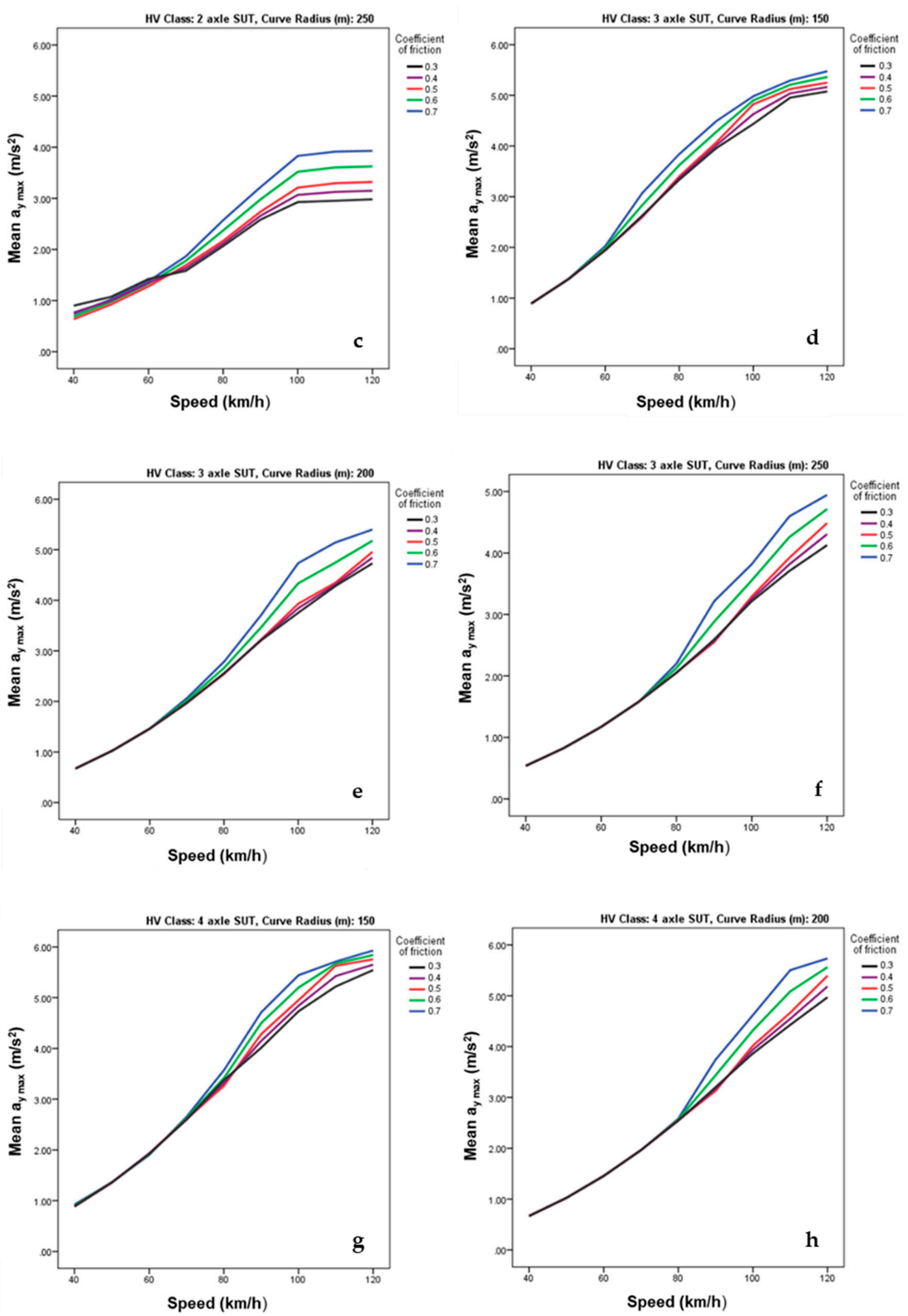

Figure 11. *Cont.*

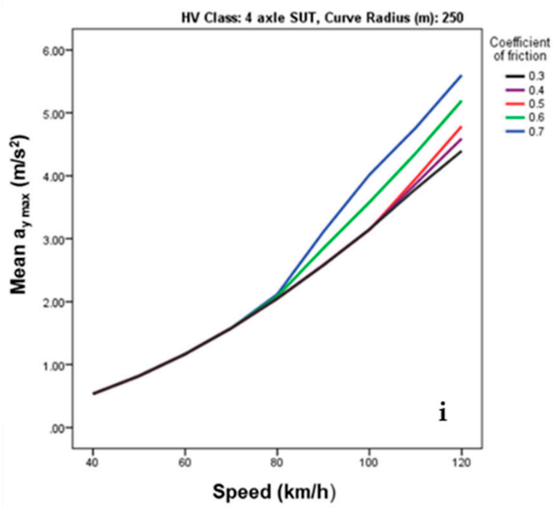

Figure 11. Average maximum lateral acceleration against heavy vehicle speed for SUTs. (**a**) 2-axle, r = 150 m. (**b**) 2-axle, r = 200 m. (**c**) 2-axle, r = 250 m. (**d**) 3-axle, r = 150 m. (**e**) 3-axle, r = 200 m. (**f**) 3-axle, r = 250 m. (**g**) 4-axle, r = 150 m. (**h**) 4-axle, r = 200 m. (**i**) 4-axle, r = 250 m.

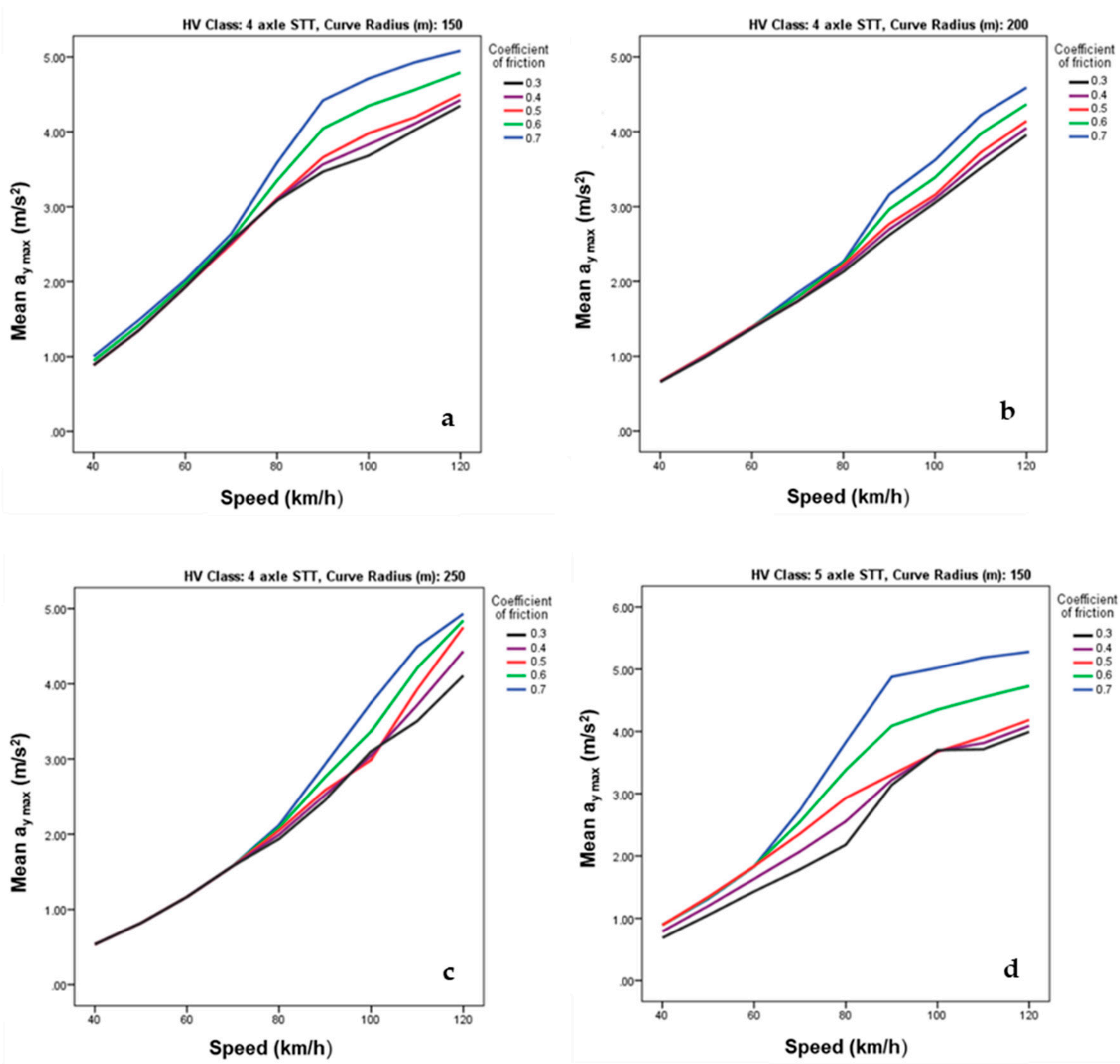

Figure 12. *Cont.*

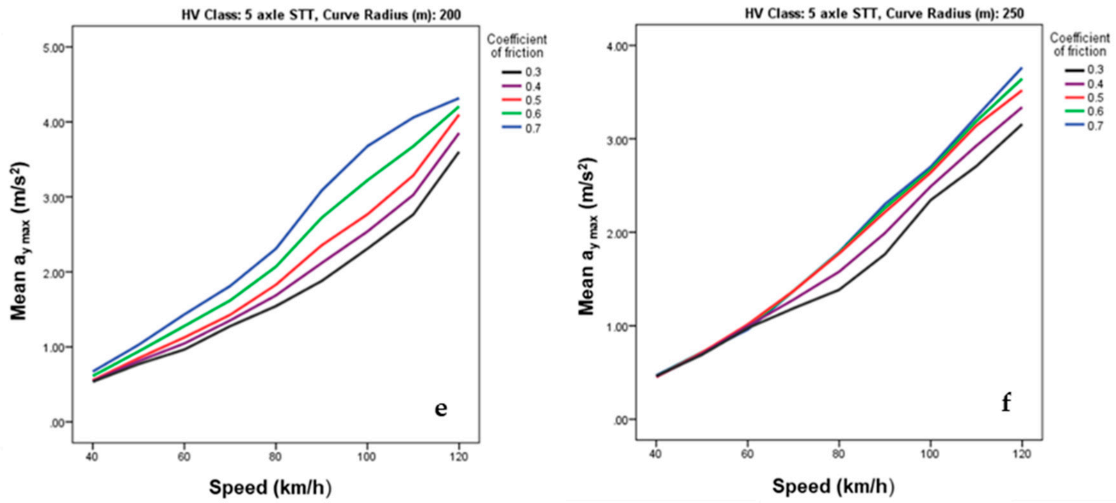

Figure 12. Average maximum lateral acceleration against heavy vehicle speed for STTs. (**a**) 4-axle, r = 150 m. (**b**) 4-axle, r = 200 m. (**c**) 4-axle, r = 250 m. (**d**) 5-axle, r = 150 m. (**e**) 5-axle, r = 200 m. (**f**) 5-axle, r = 250 m.

3.4. Correlation Analysis

A Pearson correlation analysis was performed to determine the degree and strength of the relationships between the dependent and independent variables. This exercise was also done to ensure that any change (in value) of the independent variables would correlate and result in a significant change to the dependent variables. Otherwise, the independent variables could be deemed as not important and thus neglected.

In the case of two-axle SUTs (Table 8), a significantly strong correlation was observed between the speed of the two-axle SUT and maximum lateral acceleration (r = 0.873, $p < 0.01$). A significant correlation was also observed between the two-axle SUT GVW and the maximum lateral acceleration, but this correlation was observed to be low (r = 0.352, $p < 0.01$). Meanwhile, a significant correlation was found between the two-axle SUT CoF and the maximum lateral acceleration (r = 0.346, $p < 0.01$), indicating that the maximum lateral acceleration increased when CoF values increased. In contrast, a very weak and negligible correlation (albeit significant) was observed between the two-axle SUT cornering radius and the maximum lateral acceleration (r = −0.214, $p < 0.01$).

Similar observations were also recorded when a Pearson correlation analysis was conducted for all classes of heavy vehicles (Table 9). These findings further confirmed that vehicle speed, GVW and CoF are significant factors that influenced the maximum lateral acceleration that can cause a heavy vehicle to roll over, in parallel with findings in previous reports [27–29]. These results are consistent with those reported in previous studies, where vehicle speed and road conditions (CoF) have been shown to significantly influence lateral acceleration [40–42]. In parallel with our results, Ryu et al. [43] also stated that vehicles with a heavy load often have a higher center of gravity, thus increasing the risk to roll over in an accident. However, in this study, the location of the center of gravity (CoG) for each of the different heavy vehicle types was established by the IPG Truck Maker(R) software, where the volume and the height of the load were assumed to be uniform, regardless of the load weight (GVW) applied. Even though homogeneous loading does not fully represent the actual situation, we postulate that this configuration would represent the "worst case" scenario that could happen, when a particular heavy vehicle with high GVW (with high loading) maneuvers a curved section of the road.

Table 8. Output of Pearson correlation analysis conducted on SPSS for two-axle SUTs.

Correlations						
		Max. Lateral Acceleration (m/s^2)	**HV Speed (km/h)**	**GVW (Tonne)**	**Coefficient of Friction**	**Curve Radius (m)**
Max. Lateral Acceleration (m/s^2)	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	1080				
HV speed (km/h)	Pearson Correlation	0.873	1			
	Sig. (2-tailed)	0.000				
	N	1080	1080			
GVW (tonne)	Pearson Correlation	0.352	0.000	1		
	Sig. (2-tailed)	0.000	1.000			
	N	1080	1080	1080		
Coefficient of friction	Pearson Correlation	−0.346	0.000	0.000	1	
	Sig. (2-tailed)	0.000	1.000	1.000		
	N	1080	1080	1080	1080	
Curve Radius (m)	Pearson Correlation	−0.214	0.000	0.000	0.000	1
	Sig. (2-tailed)	0.000	1.000	1.000	1.000	
	N	1080	1080	1080	1080	1080

Table 9. Output of Pearson correlation analysis conducted on SPSS for all heavy vehicle classes.

Correlations						
		Max. Lateral Acceleration (m/s^2)	**HV Speed (km/h)**	**GVW (Tonne)**	**Coefficient of Friction**	**Curve Radius (m)**
Max. Lateral Acceleration (m/s^2)	Pearson Correlation	1				
	Sig. (2-tailed)					
	N	8235				
HV speed (km/h)	Pearson Correlation	0.853	1			
	Sig. (2-tailed)	0.000				
	N	8235	8235			
GVW (tonne)	Pearson Correlation	0.373	0.000	1		
	Sig. (2-tailed)	0.000	1.000			
	N	8235	8235	8235		
Coefficient of friction	Pearson Correlation	−0.341	0.000	0.000	1	
	Sig. (2-tailed)	0.000	1.000	1.000		
	N	8235	8235	8235	8235	
Curve Radius (m)	Pearson Correlation	−0.214	0.000	0.000	0.000	1
	Sig. (2-tailed)	0.000	1.000	1.000	1.000	
	N	8235	8235	8235	8235	8235

4. Conclusions

This study has demonstrated the application of multibody dynamics software in investigating the effects of vehicle conditions and road conditions that can influence rollover of heavy vehicles during maneuvering on a curved road section. This approach can reduce the time taken and cost compared to the experimental testing. Previous research has shown that there are many cases of heavy vehicle speed violations and exceeding permissible GVW that can lead to serious accidents (especially rollovers) during cornering. In this study, the verified heavy vehicle models with different classes were simulated with various independent factors such as gross vehicle weight, speed, coefficient of friction of the road and radius of curvature. Lateral acceleration was used as the dependent value to indicate the rollover propensity. Based on the results, two-axle SUTs recorded the highest percentage of unsafe conditions (40%) followed by three-axle SUTs (32%), four-axle SUTs (27%), five-axle STTs (25%) and four-axle STTs (23%), out of the total number of simulations. A strong correlation was then observed between the heavy vehicle speed and maximum lateral acceleration, followed by GVW and CoF, accordingly. In contrast, a very weak and negligible correlation was observed between the cornering radius and the maximum lateral acceleration. The results of this study provide essential information and further elaborate on the key factors and their degree of influence on rollover propensity of heavy vehicles, compared to a description of rather general factors, as claimed in previous studies. Data analysis also revealed that speed and GVW violations are among the main contributors in a heavy vehicle rollover during cornering, despite the published speed limit and permissible GVW stipulated under the Malaysian law. Thus, we strongly recommend that a stricter and more vigilant law enforcement by the authorities is required. In terms of the practical application of the current findings, the data collected through the simulation analysis can be used in future studies to predict the rollover propensity of a heavy vehicle based on several factors such as GVW, speed, cornering radius and road coefficient of friction. Such findings will be of great importance and have the potential to be commercially utilized as part of the existing rollover warning system (RWS).

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