INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 20, ISSUE 3, 2023, 10626 – 10634
DOI: https://doi.org/10.15282/ijame.20.3.2023.06.0820

RESEARCH ARTICLE

Rollover Investigation of Two-Axle Heavy Vehicle Based on Load Transfer Ratio with Vehicle and Road Condition: A Simulation Approach

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ABSTRACT - Commercial heavy vehicle is commonly used to transport goods and people efficiently and safely. A previous study has shown a number of gross vehicle weight (GVW) and speed violations recorded in selected areas in Malaysia, and two-axle single unit truck (SUT) is the most commercial heavy vehicle type that violated the weight and speed regulation. Moreover, accidents involving heavy vehicles result in severe traffic disruption and fatalities to other road users due to heavy vehicle size and capability to carry huge amounts of goods. Thus, the objective of this paper is to investigate the correlation and effect of the vehicle and road condition on the two-axle SUT rollover during cornering on the curved road using the simulation approach. The verified two-axle SUT model is simulated using IPG-TruckMaker® with different GVW, speed, and coefficient of friction values while the cornering radius, driver behaviour and load's center of gravity remain constant. A correlation based on performance indices is established, and it is found that the heavy vehicle speed has a strong correlation to the lateral load transfer to cause a rollover followed by GVW and coefficient of friction, respectively.

ARTICLE HISTORY

Received	:	22nd Feb 2023
Revised	:	23rd July 2023
Accepted	:	22nd Aug 2023
Published	:	20th Sept 2023

KEYWORDS
Rollover;
Heavy vehicle;
Load transfer ratio;
Pearson correlation;
IPG-TruckMaker®

1.0 INTRODUCTION

Heavy goods vehicle (HGV) plays an important role in transporting goods and industrial materials as it helps the development of the multiple sectors of industries and infrastructure in Malaysia. This rapid development led to the increasing number of registrations of heavy vehicle class and contributed to the traffic numbers on Malaysian roads, where 24.57% of traffic was contributed by lorries, specifically by light lorries (14.21%), medium lorries (6.29%) and heavy lorries (4.07%) [1]. The trend has unfortunately led to a consequent increase in the incidence of road traffic accidents. Although the frequency and percentage of heavy vehicles to be involved in road accidents was generally lower compared to light vehicles (4.23% of total accident in 2017), they usually resulted higher fatality rates [2]. Furthermore, road accidents involving heavy vehicles often result at least 80% of second-vehicle fatalities [3]. Rollover accident is one of the serious incidents mainly involving heavy vehicles and usually occur at the cornering section of the road. Rollover accidents would cause severe traffic disruption due to the heavy vehicle size, cargo damage and environmental disaster if the heavy vehicle is carrying hazardous cargo and spilled when the accident occurs as shown in Figure 1.

Figure 1. An example of a rollover accident involving a heavy goods vehicle

Casually, factors that may cause a heavy vehicle accident to happen are the vehicle and road condition, apart from the driver's condition. Whereby, the load carried by the heavy vehicle is an essential parameter in vehicle design study that can affect the vehicle's dynamic and handling characteristics. Thus, an overloaded heavy vehicle has more potential to be involved in an accident [4, 5]. In addition, an experiment from a previous study to collect heavy vehicle data through weigh-in-motion (WIM) system has been done. Through the experiment, it shows there is a number of gross vehicle weight and speed violations among the heavy vehicles recorded at specific locations in Malaysia [6, 7]. Furthermore, a

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slippery road condition, especially after heavy rain, reduce the friction between vehicle tires and the road surface, thus causing instability to the heavy vehicles [8]. Tsourapas, in his study, proposed a rollover prediction model based on load transfer ratio (LTR), however, the model was established from a single value vehicle's condition variables and simulated on specific maneuver tests based on NHTSA standard [9]. LTR is defined as the ratio of the weight on one side of the vehicle to the other, as depicted in Eq. (1). When the vehicle is travelling in a straight line, the LTR is equal to 0 as the weights on both sides are equal. However, during a rollover, the LTR is equal to 1 as all the weight is on one side of the vehicle [10] as shown in Figure 2. Moreover, the target value of the load transfer ratio has been recommended as 0.6 [9, 12].

$$LTR = \frac{|\sum_{i=1}^{n}(FL_i - FR_i)|}{\sum_{i=1}^{n}(FL_i + FR_i)} \tag{1}$$

where, FL_i, and FR_i are normal loads acting on the left and right- wheels, respectively, of the equivalent axle i, and n is the total number of axles used for a complete roll unit.

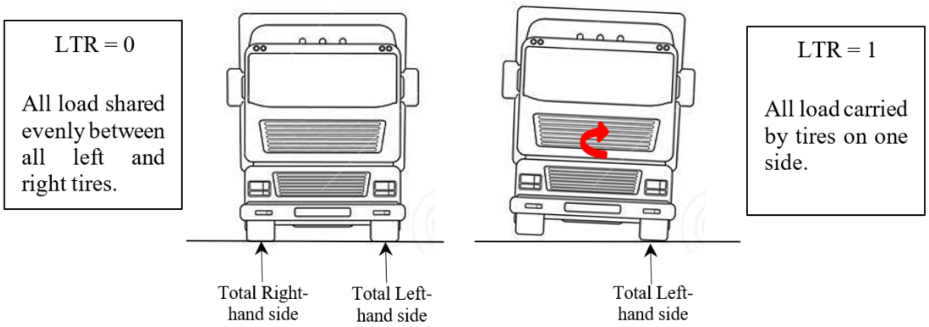


Figure 2. Load transfer ratio on heavy vehicle

A rollover prediction model was also established by other studies, considering heavy vehicle speed and gross vehicle weight with different loading locations [10-11, 13]. This led to limited application of the model to be used in various heavy vehicles and road conditions. Thus, in order to generate an accurate predictive rollover model, it is important to study the correlation of factors involved, with different values of vehicle load, speed and road coefficient to the vehicle safety and stability. The main purpose of this paper is to conduct a simulation of a validated virtual heavy vehicle model to investigate the effect of the independent parameters (gross vehicle weight (GVW), speed and road coefficient) towards vehicle stability (load transfer ratio) during cornering on the curved road section. It is expected the correlation of the independent parameters successfully established in order to suggest the best solution for heavy vehicle safety and improve the existing rollover prediction model based on load transfer ratio.

2.0 METHODOLOGY

2.1 Virtual Heavy Vehicle Model

Achieving research objectives involved several important steps. It starts with simulating the validated virtual heavy vehicle model on a vehicle dynamic simulation software package called IPG-TruckMaker®, with multiple independent parameters. Generates and extracts data from the simulation to be analyzed for further discussion. In order to produce an accurate and reliable simulation result, a virtual heavy vehicle model has to be accurately generated as close as the existing actual heavy vehicle in terms of vehicle performance, sub-system specification, parts properties and physical dimension, as shown in Figure 5(b). The virtual heavy vehicle model used based on a two-axle single unit truck (SUT) in this paper has been validated with the experimental, where ISUZU FSR two-axle SUT were used as experimental vehicles as shown in Figure 3 and its vehicle geometry is shown in Table 1, as reported previously [14].

Based on the research, the simulation and experimental data were plotted and it found that the data trend tabulated were consistently similar, indicating that the virtual heavy vehicle model closely represented the actual, as shown in Figure 4. Furthermore, the data were further validated by multiple performance indices to analyze the data variance. Based on the result, the root means square error (RMSE) and mean absolute error (MAE) of heavy vehicle lateral acceleration were 0.045 and 0.033, respectively. A good correlation between experimental testing and simulation data is observed as the value is close to zero (0); thus, the virtual heavy vehicle model and simulation setting accurately represent the experimental testing. Besides, the performance indices based on a regression coefficient (R) value of 0.780, which is close to 1, indicating that the simulation has explained the majority of the variances analyzed.

(a) (b)

Figure 3. (a) ISUZU FSR two-axle SUT use for experiment, (b) virtual two-axle SUT model generated for simulation

Table 1. ISUZU FSR two-axle SUT vehicle geometry

General Vehicle Specification and Dimension	
Make	ISUZU
Model	FSR
Measured Tare Mass (kg)	5485
Max. GVW (kg)	11000
Overall dimension, LxWxH (mm)	6900 x 2200 x 2700
Measured wheelbase, *L* (mm)	4200
Measured Track Width, *w* (mm)	1800

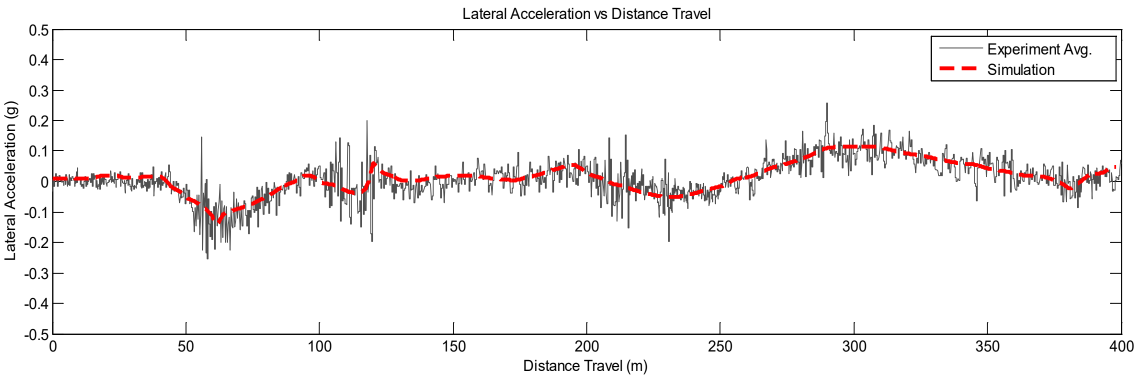
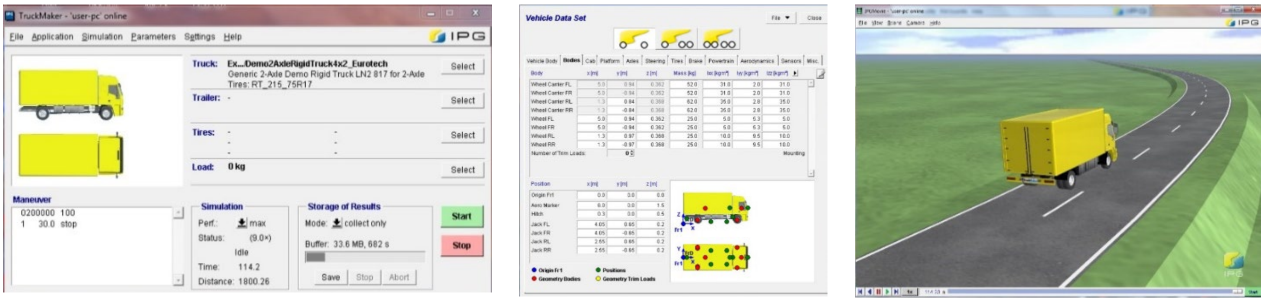


Figure 4. Validation plots of lateral acceleration against distance travel of two-axle SUT to observe the variance between simulation and experimental data [14]

2.1.1 Vehicle modeling and simulation setting

The aim of this study is to identify the effect of the multiple independent parameters, which are gross vehicle weight (GVW), speed and road coefficient on the heavy vehicle rollover during travel on the cured road section. Karim et al. in their study, found and reported that there were GVW and speed violations in selected areas in Malaysia. Among all of heavy vehicles class, two-axle SUT recorded the highest percentage of GVW violations [6]. Some previous researcher also mentioned that heavy vehicle condition (Vehicle class, GVW and speed) and road condition (coefficient of friction and cornering radius) were among the factors that contribute to a rollover accident, thus making these as important factors to be analyzed and the selected input data to be used in this study [7, 15]. Apart from that, there are also other parameters such as road geometry design, selected driving lane, corner cutting value and driver behaviour setting that need to be considered, and these parameters were set as a constant for the entire simulation.

The road geometry developed on the IPG-TruckMaker® is designed based on standards requirements provided by Public Work Department of Malaysia [16]. The curved road section was designed to follow the superelevation value standards [16, 17]. For this study, a cornering radius of 150 meters is selected. A 500 m straight road before and after the curvature is added into the road design to allow the heavy vehicle to obtain a constant speed before cornering. For this study, the driver behaviour was set up as a 'normal' mode, which is in calm and common conditions. The simulation allows the driver to drive in a range of longitudinal and lateral acceleration for a maximum of 3 g and minimum longitudinal and lateral deceleration of -3g and drive on the left lane of the road. The corner cutting value was set as one (1), whereby the virtual heavy vehicle model is allowed to drive and maneuverability only on the driving lane. The detail for the simulation setting is summarized in Table 2. Figure 5 and 6 show the overview of IPG-TruckMaker® software features and the flowchart describing the detailed simulation process using the IPG-TruckMaker ® software, respectively.



(a) (b) (c)

Figure 5. The overview of IPG-TruckMaker ® software (a) Heavy vehicle parameters setting, (b) Sub-System specification and pats properties setup (b) Graphical simulation through IPGMovie

Table 2. Summary of simulation setting

Heavy vehicle class	Two-axle single unit truck
Goss vehicle weight (GVW)	From 5,000 kg to 40,000 kg with 5,000 kg interval
Vehicle speed	From 40 km/h to 120 km/h with 10 km/h interval
CoG locations (m)	2.39, 0.86,2.2
Road coefficient	0.3 to 0.7 with 0.1 interval
Cornering radius	150 m, curve to the left side
Rate of superelevation	5.9%
Driver behaviour setting	Normal, drive on the left lane
Corner cutting value	1 (with a range from 0-1)

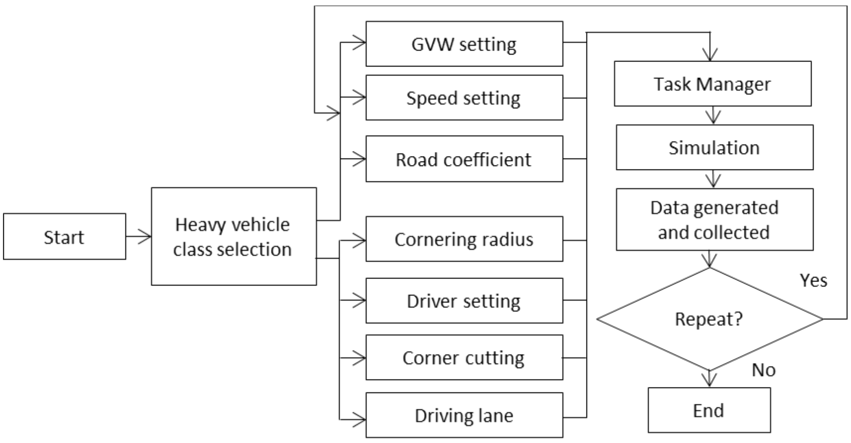


Figure 6. Flowchart of the simulation using IPG-TruckMaker®

In addition, as the study employed a simulation approach, some assumptions have to be made, which are all constraints were assumed to be ideal, minor influence factors such as wind loads on the vehicle were neglected, the vehicle model sub-system was working ideally during simulations, the road was to be assumed to have smooth (no debris), flat surface (no potholes and patch) and constant coefficient of friction for all areas.

2.1.2 Data generation and interpretation

The simulation result was obtained from IPG/control, a data post-processing tool available in IPG-TruckMaker®. As the simulation involved various independent parameters, numerous simulation data files are generated and exported to Microsoft Excel. Each data file consists of thousands of output values (load transfer ratio), as shown in Table 3. The maximum value of the load transfer ratio is identified from the full list of output values by screening the data using coding generated from MATLAB software. The screened data were plotted to analyze the rollover threshold. To investigate the significance and relationship between the independent and dependent parameters, a multivariate Pearson coefficient correlation analysis was employed through a statistical analysis software, SPSS.

Table 3. Overview of the tabulated output value from data file

Time (s)	GVW (kg)	Road Coefficient	Cornering radius (m)	Distance (m)	Speed (km/h)	Load transfer ratio
0.0	10000	0.3	150	0.00	0.0	0.00
0.1	10000	0.3	150	0.01	0.2	0.02
.	.	.	.	.	.	.
.	.	.	.	.	.	.
0.3	10000	0.3	150	550.21	60	0.32
.	.	.	.	.	.	.
.	.	.	.	.	.	.
70.1	10000	0.3	150	108.00	59.5	0.05
71.2	10000	0.3	150	110.01	60.4	0.06

3.0 RESULTS AND DISCUSSION

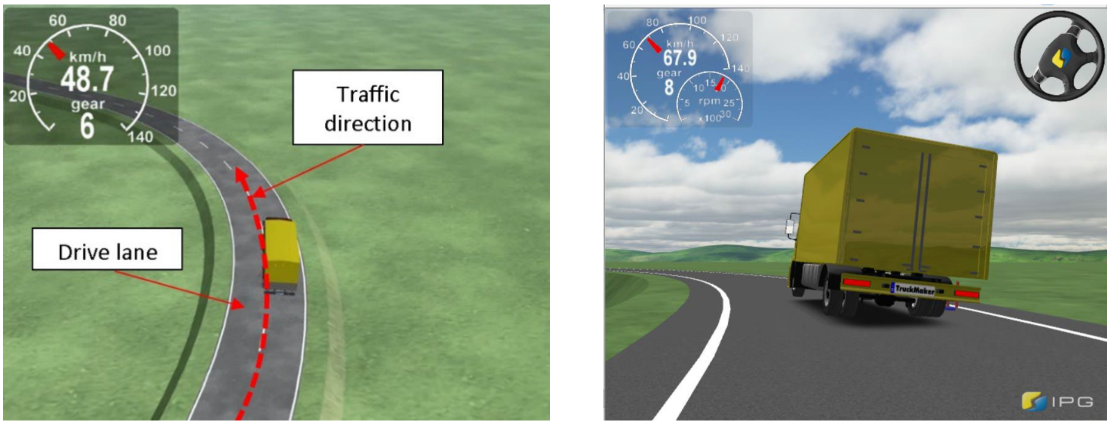
3.1 Data Screening and Simulation Analysis

As mentioned previously, the simulation process with multiple independent parameters generates numbers of data files. In total, there are 360 simulation data files exported to individual spreadsheets with different GVW, speed and road coefficient values. After successfully screening and sorting the data through MATLAB, statistical analysis software (SPSS) is employed to analyze the data. Table 4 shows an example of output data obtained from the simulation.

Table 4. Selected simulation result for two-axle SUT at μ = 0.3

Input/independent parameters			Output/dependent parameter:	Test result
Heavy vehicle class	GVW (kg)	Speed (km/h)	maximum load transfer ratio	
two-axle SUT	10,000	40	0.08	Pass
		50	0.19	Pass
		60	0.32	Pass
		70	0.48	Pass
		80	0.56	Failed
		90	0.69	Failed
		100	0.72	Failed
		110	0.76	Failed
		120	0.79	Failed

Table 4 also reveals the simulation result on the vehicle condition. The simulation is said to have failed (did not finish/complete) when the two-axle SUT is in unsafe condition. Figure 7 shows an example of the unsafe condition of the two-axle SUT during the simulation, whereby the heavy vehicle is leaving the driving lane, and the wheel is lifted off at only one side. The heavy vehicle tends to leave the driving lane when the centrifugal force and lateral acceleration act on it with different independent parameter values (GVW, speed, road coefficient). Furthermore, this study simulates heavy vehicles at a constant value of the cornering radius, to investigate the safety threshold data on the cornering section. In the simulation, the unsafe condition can be determined by two categories, which are tripped rollover and untripped rollover [18, 19]. The tripped rollover happens when the heavy vehicle model leaves the driving lane, slides sideways and trips to the roadside object such as a curb or guardrail and rollover, regardless of the load transfer ratio value [20]. At the same time, untripped rollover happened when the heavy vehicle rollover on the driving lane, perhaps due to road conditions, over-speed and excessive GVW. Untripped rollover usually happens when the load transfer ratio is more than 0.9 or 90% of the vertical load is on one side of the vehicle [13, 21]. Table 5 and Table 6 show the number and percentage of unsafe and safe conditions and the number and percentage of tripped and untripped rollover generated through the simulations, respectively. Out of the total of 360 simulation cases, more than 50% were recorded as an unsafe condition, and based on this percentage, 55.9% was a tripped rollover.



(a) (b)

Figure 7. (a) Two-axle SUT leaving the drive lane during cornering when carrying heavy loads at slippery roads, and (b) two-axle SUT start to wheel lift-off on the driving lane (unsafe condition = rollover)

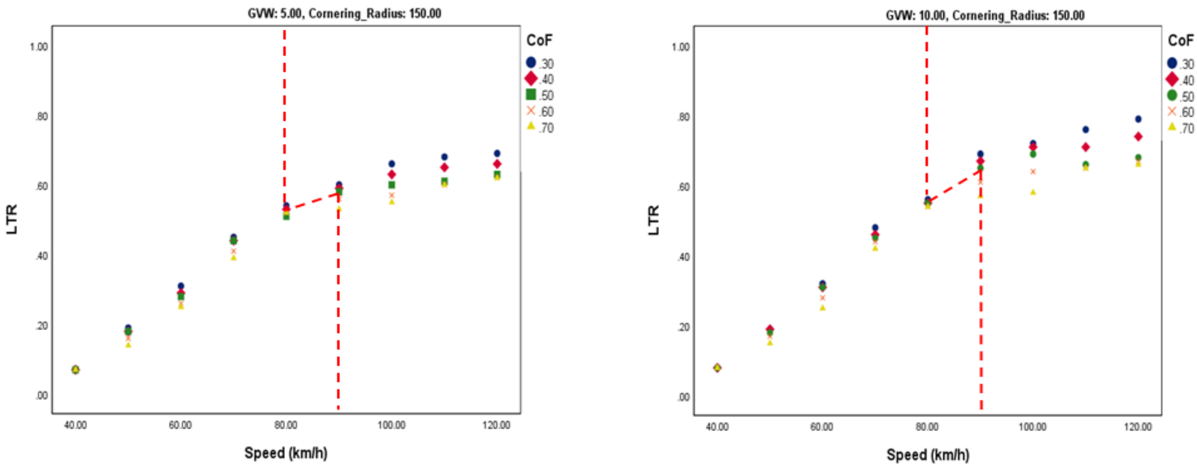
Table 5. The number and percentage of unsafe and safe conditions for two-axle SUT

	Number of simulation	Percentage (%)
Safe condition	156	43.3
Unsafe condition	204	56.7
Total number of simulations	360	100.0

Table 6. The number and percentage of tripped and untripped rollovers for two-axle SUT

	Number of simulation	Percentage (%)
Tripped rollover	114	55.9
Un-tripped rollover	90	44.1
Total number and percentage of unsafe conditions	204	100.0

Data analysis also showed that there is a relationship between the maximum load transfer ratio and all independent parameters used. Figure 8 shows a scatter plot of the maximum load transfer ratio against heavy vehicle speed for two-axle SUT when maneuvering at a cornering radius of 150 m with varies in GVW and coefficient of friction value. From the plot, it can clearly be observed that the maximum load transfer ratio increases when the vehicle speed is increasing regardless of coefficient of friction values. Furthermore, the maximum load transfer ratio was also increased when GVW increased especially when the heavy vehicle maneuvering speed of 80 km/h and above. This observation justified the rule of equation of motion. Thus, it can be concluded that the faster and heavier heavy vehicle, the risks of impending rollover during cornering were also high. On the other hand, the maximum load transfer ratio value increased as the coefficient of friction decreased at a particular speed and GVW value. The road surface became slippery as the coefficient of friction values decreased, resulting in worse tire contact with the road. The scatter plots also indicate the safe and unsafe conditions by the red-colored line. An impending rollover would occur at the maximum load transfer value beyond the right section of the red-colored lines.



(a) (b)

Figure 8. Maximum load transfer ratio against heavy vehicle speed for two-axle SUT when maneuvering at a cornering radius of 150m with varies coefficient of friction value, GVW = (a) 5,000 kg, (b) 10,000 kg

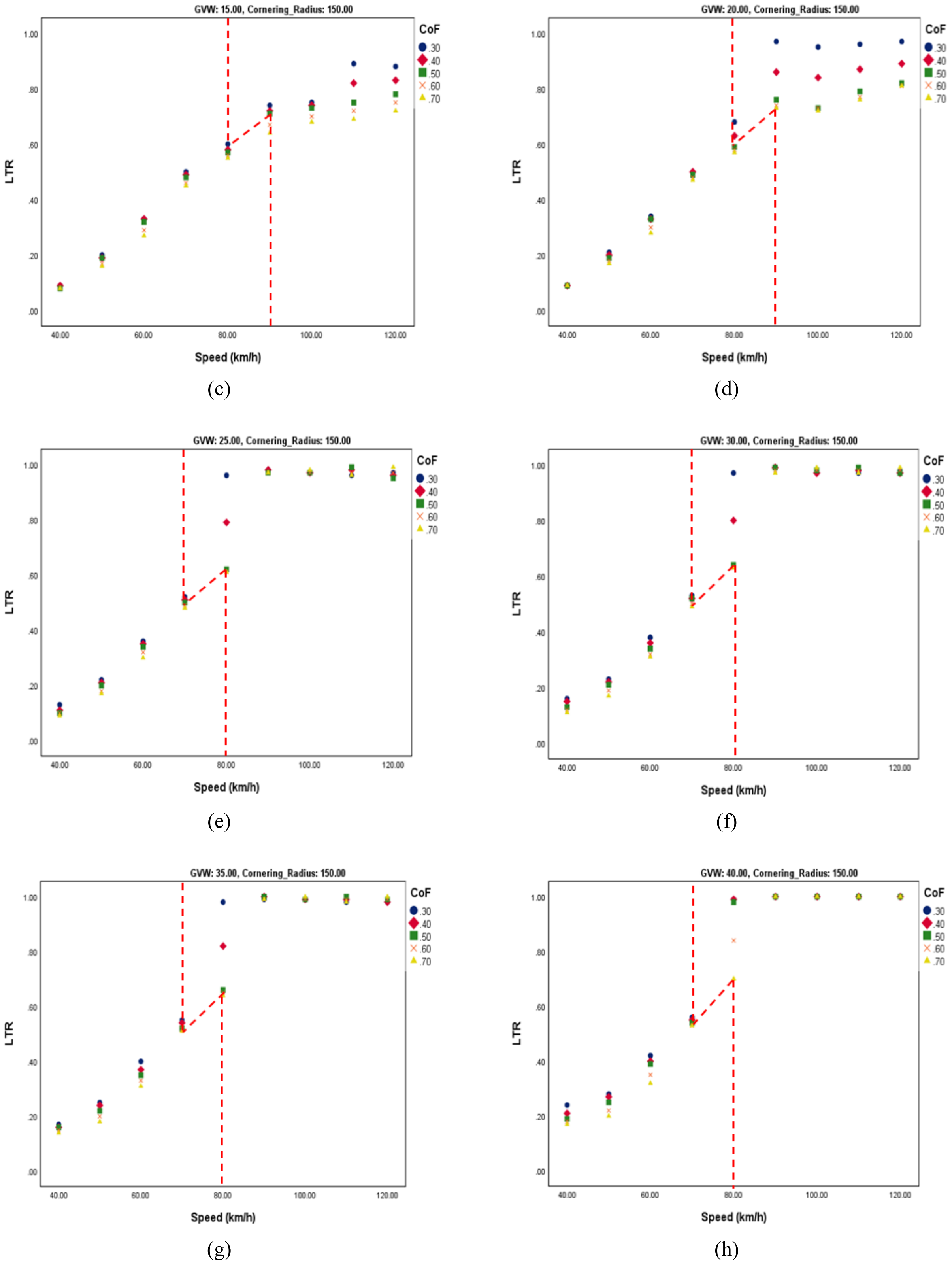


Figure 8. (cont.) Maximum load transfer ratio against heavy vehicle speed for two-axle SUT when maneuvering at a cornering radius of 150 m with varies coefficient of friction value, GVW = (c) 15,000 kg, (d) 20,000 kg, (e) 25,000 kg, (f) 30,000 kg, (g) 35,000 kg and (h) 40,000kg

3.2 Correlation Analysis

Simulation analysis explained from the scatter plot generated was based on the observation of data behavior and tabulated. Thus, another method was employed to determine the strength of the relationship level between the dependent and independent parameters. In this study, Pearson correlation analysis was performed. This method shows that any change in the value of the GVW, vehicle speed and coefficient of friction would result in a significant change to the load transfer ratio.

Table 7. Pearson correlation analysis conducted on SPSS for two-axle SUT

Correlations					
		LTR	Speed	GVW	CoF
LTR	Pearson Correlation	1			
	Sig. (2-tailed)				
	N	360			
Speed	Pearson Correlation	.887**	1		
	Sig. (2-tailed)	0.000			
	N	360	360		
GVW	Pearson Correlation	.389**	0.000	1	
	Sig. (2-tailed)	0.000	1.000		
	N	360	360	360	
CoF	Pearson Correlation	.283**	0.000	0.000	1
	Sig. (2-tailed)	0.005	1.000	1.000	
	N	360	360	360	360

** Correlation is significant at the 0.01 level (2-tailed).

Based on Table 7, a significantly strong correlation was observed between the speed and maximum load transfer ratio ($r = 0.887$, $p < 0.01$). The GVW and coefficient of friction are observed to have a significant correlation to the load transfer ratio; however, it was observed to be low ($r = 0.389$, $p < 0.01$ and $r = 0.283$, $p < 0.01$). In this study, the location of the vehicle center of gravity was established by the IPG-TruckMaker®, where the homogeneous loading is assumed, regardless of the load weight applied, thus resulting in the low correlation between GVW and coefficient of friction to the maximum load transfer ratio. However, all independent parameters still correlate to the maximum load transfer ratio and cannot be negligible.

4.0 CONCLUSIONS

In this paper, a virtual two-axle single-unit-truck model has been successfully simulated with various independent parameters considering heavy vehicle conditions (gross vehicle weight and speed) and road conditions (coefficient of coefficient of friction). The model used in this study has been validated with an actual heavy vehicle through experimental previously. Based on simulation data, a correlation towards vehicle safety and stability was measured through the effect of heavy vehicle load transfer ratio. From the simulation data obtained, the safe and unsafe conditions of heavy vehicles when maneuver on the cornering section of the road were obtained and the propensity of heavy vehicle rollover was analyzed. Based on Pearson correlation analysis, it is found that heavy vehicle speed has a significant and strong correlation to the load transfer ratio followed by GVW and coefficient of friction value. Which means, any change in heavy vehicle speed would contribute more to the load transfer ratio effect (towards unsafe conditions), compared to GVW and coefficient of friction. Finally, for further work, a similar methodology can be applied to other heavy vehicle classes and the finding in this paper could be used to establish a prediction model for heavy vehicle safety during cornering on the curved road section based on the load transfer ratio effect.

5.0 ACKNOWLEDGEMENT

The authors appreciate and acknowledge the support from the School of Mechanical Engineering, College of Engineering, Universiti Teknologi MARA and Computational and Applied Mechanics (ACAM) Research Group, Faculty of Engineering, Universiti Malaya, Malaysia.

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