The Effect of Gross Vehicle Weight on the Stability of Heavy Vehicle during Cornering

Nurzaki Ikhsan, Ahmad Saifizul Abdullah, Rahizar Ramli

Abstract**—**One of the functions of the commercial heavy vehicle is to safely and efficiently transport goods and people. Due to its size and carrying capacity, it is important to study the vehicle dynamic stability during cornering. Study has shown that there are a number of overloaded heavy vehicles or permissible Gross Vehicle Weight (GVW) violations recorded at selected areas in Malaysia assigned by its type and category. Thus, the objective of this study is to investigate the correlation and effect of the GVW on heavy vehicle stability during cornering event using simulation. Various selected heavy vehicle types and category are simulated using IPG/Truck Maker® with different GVW and road condition (coefficient of friction of road surface), while the speed, driver characteristic, center of gravity of load and road geometry are constant. Based on the analysis, the relationship between GVW and lateral acceleration were established. As expected, on the same value of coefficient of friction, the maximum lateral acceleration would be increased as the GVW increases.

Keywords**—**Heavy Vehicle, Road Safety, Vehicle Stability, Lateral Acceleration, Gross Vehicle Weight.

I. Introduction

MANY developing countries such as Malaysia have shown rapid growth in the past decades particularly in the industrial sectors and infrastructure. Consequently, this has led to an increase in the use of heavy vehicle on the road. Table I shows the number of new registered motor vehicles (goods vehicle category) in Malaysia from 2009 until 2012. It shows that there were an increasing number of 95,782 goods vehicles for this 4 years period. This trend may lead to the contribution of the number of road traffic injuries and accidents. Several common contributors that may cause accidents to occur are the vehicle characteristic, driver's characteristic and environmental condition. Vehicle characteristic involves the mechanical failures such as braking system, powertrain and drivetrain, gross vehicle weight (GVW) and vehicle stability while driver's condition and characteristic are more towards inexperience, speeding, fatigue and lack of concentration while driving.

Environmental condition of slippery road surface, bumps and potholes and road geometry (curvature radius, width, gradient and super-elevation)

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One of the major contributing factors under vehicle characteristic in developing countries is excessive loading or overloading [1]. As mentioned by [2], the overloaded truck has more potential to be involved in an accident.

TABLE I
NEW REGISTERED MOTOR VEHICLES (GOOD VEHICLES) IN MALAYSIA (2009 – 2012) [3]

Year	No. of new registration	Total no. of active vehicles
2009	34731	936222
2010	40887	966177
2011	39718	997649
2012	40742	1032004

Bixel et al. [4] also mentioned that overall vehicle weight is an essential parameter in vehicle design study that can affect the vehicle dynamic and handling characteristic. There was study conducted by ARRB Transport Research [5] showing the effect of higher mass on the performance of general access truck/trailer combination and it was suggested that mass ratios up to 1:1.6 would compromise safety. Karim [6] and Saifizul [7] conducted an experiment with a total of more than 100,000 commercial vehicles during four months in Malaysia showing the violation on GVW of various heavy vehicle classes. The statistic showed that the 3-axle trucks recorded the highest number of violations followed by 4-axle and 2-axle trucks. Tables II and III show the statistic of road accidents occurred in Malaysia for year 2009 until 2012 and maximum permissible laden weight (GVW) by vehicle class. The accident statistic covers the failure condition modes such as rear end-collision, head on collision, jack-knifing and rollover cases. The accident involving heavy vehicle would cause severe traffic disruption compared to the other type of vehicle accidents due to its size and capability to carry a huge amount of goods. It might also cause an environmental and human disaster if the heavy vehicle is carrying some hazardous cargos which are spilled when accident occurs [8], [9].

TABLE II
TOTAL OF HEAVY VEHICLES INVOLVED IN ROAD ACCIDENTS, MALAYSIA, 2009 - 2012 [10]

Year	Total
2009	46724
2010	50438
2011	53078
2012	42158

TABLE III
MAXIMUM PERMISSIBLE LADEN WEIGHT (GVW) BY VEHICLE CLASS [7]

	Class			
	2 axle	3 axle	4 axle	5 axle
GVW (tons)	16.8	27.3	33.6	39.9

The aim of the paper is to investigate the effect of GVW on vehicle stability during cornering. This is achieved through simulation by considering some other parameters. It is expected that, the correlation of GVW and lateral acceleration as a vehicle dynamic stability component will have significance and importance in order to improve or suggest the best solution for heavy vehicle safety.

II. Methodology

The process for this study involves several important steps. It starts with validation of heavy vehicle model with the experimental data. Next is the configuring of heavy vehicle model for simulation purposes. This is followed by, employing simulation with several of the design parameters and generating data from simulation for discussion.

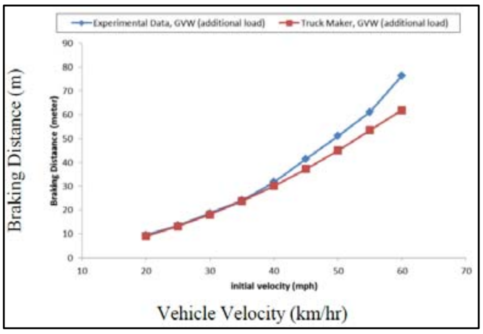

Fig. 1 Simulation and Experimental data comparison on laden weight applied

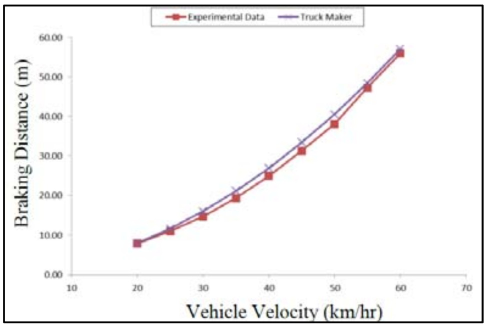

Fig. 2 Simulation and Experimental data comparison on unladen weight applied

A. Model Validation

Validation step is a way to prove the correctness of heavy vehicle model configuration and modelling to ensure the model to be the same as actual heavy vehicle used on the road. The validation process was done by Manap using the same heavy vehicle models for this research [11]. It was found that the model was validated with experimental data conducted by National Highway Traffic Safety Administration (NHTSA). The experiment conducted was classified into two categories which are braking distance on the straight road with a loading applied to the vehicles (laden weight) and braking distance on the straight road without any additional loads (unladen weight). Figs. 1 and. 2 show the comparison data between simulation and experiment for both categories.

B. Vehicle Configuration

This is an important step to configure realistic heavy vehicle model in accordance to the available actual heavy vehicle on the road. This study only focuses on the selected Single Unit Truck (SUT) and Truck-Trailer types with limitation in the number of axles used (Table IV). Fig. 3 shows an example of the final view of 2 and 3-axle SUT that has been constructed and configured.

TABLE IV
Vehicle Type and Basic Design Specification

Vehicle type	Model	Kerb Weight (tons)	Maximum load added (tons)
2-Axle SUT	Iveco-Eurotech	2.3	35
3-Axle SUT	MB-Atego	6.9	50
4-Axle SUT	MB-Atros	10.0	60
4-Axle Truck-trailer	MB-Atros	11.0	60
5-Axle Truck-trailer	MB-Atros	13.0	75

Fig. 3 Heavy vehicle model for 2 and 3-axle SUT

C. Simulation Setting

To begin a simulation, some parameters need to be set up, these are road/path design, driver mode setting, maneuver setting and location of load applied on the heavy vehicles.

The road design specification is determined based on local road design standards provided by Road Branch, Public Work Department of Malaysia [12]. For this study, cornering radius of 280 meter is selected. Based on standard, the design speed and super-elevation percentage allowable for this particular cornering radius are 80 km/h and 6% applicable for road width of 3.5 m per lane. A straight section of 500 m before and after the curvature is added into road design to allow the heavy vehicle to obtain a constant speed before cornering. To relate the stability of heavy vehicle with effect of GVW, the value of coefficient of friction of 0.3, 0.5 and 0.7 are selected and all these settings and road design is generated using Truck Maker®/IPG-Road.

There are three types of driver mode provided in the Truck Maker® software; these are defensive, normal and aggressive. For this study, the driver was set up as normal modes, which is the driver can sustain a longitudinal and lateral acceleration for a maximum of 3g and minimum longitudinal deceleration of -3g with exponent value of 1 for both acceleration and deceleration. This means, the driver will drive so that the accelerations (g) applied to the vehicle remain in the area defined by the exponents and the maximum limits. The driver

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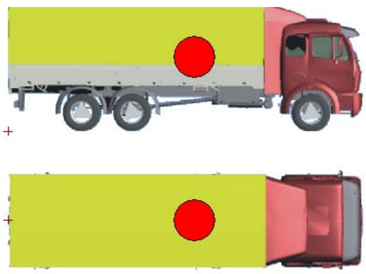
also was assigned to drive on the left lane along the simulation process with a constant speed, 80 km/h, the same as standard design speed for selected road design specification.

Once all the requirement setting and heavy vehicle are constructed, the workflow proceeds to the simulation. For all of the heavy vehicles, simulation starts with the kerb weight and 5 tons is then added for each next simulation until reaching the maximum load added (Table IV). This maximum load is determined from the statistic of overloaded truck conducted by [7]. The center of gravity of the load is assumed to be at the center of wheelbase for x axis, center of the heavy vehicles width for y axis and center of heavy vehicle height for z axis (Fig. 4 (b)). The heavy vehicle will start from zero velocity until it reaches constant velocity before entering the corner and will remain constant until simulation ends (reaching the end of the path/road).

TABLE V
SIMULATION SETTING FOR ROAD DESIGN AND DRIVER MODE

Cornering radius	280 m, curve to the left side
Super-elevation	6%
Coefficient of friction	0.3, 0.5 and 0.7
Speed	Constant 80 km/h
Driver mode	Normal, drive on left lane

(a)



(b)

Fig. 4 Heavy vehicle model; (a) during simulation on cornering; (b) location of the center of gravity of load applied

D. Data Generation and Interpretation

This is the last stage in this methodology. All the resulst will be obtained from visualization and analysis tool provided by the software. It enables user to view selected output quantities in real-time, and to plot and analyze the results. Finally, all acquired data and information such as heavy vehicle type, GVW, coefficient of friction, simulation time, radius of curvature, vehicle speed and lateral acceleration are analyzed using statistical method.

III. Result and Discussion

A. Data Preparation

The simulation generates 183 data sets for all heavy vehicle types consisting of the number of axles, GVW, coefficient of friction and lateral acceleration as independent and dependent variables. Meanwhile, cornering radius, speed, driver characteristic and maneuver setting are constant throughout the simulation test. All of the simulation test data are tabulated at the beginning process to identify the maximum value of lateral acceleration of heavy vehicles for each simulation test. This maximum value is identified as the unstable driving condition of the driver and vehicle, and it happens most in the middle of the cornering. Table VI shows the summary og one of the simulation test obtained for 2-axle SUT, simulated with GVW of 2300 kg (kerb weight) and 0.3 as coefficient of friction value. It is shown that a maximum lateral acceleration of 1.85294 m/s2 occurred at 48.751s after simulation begins. The maximum lateral acceleration values of 2-axle SUT simulation test with several of GVW and coefficients of friction are tabulated in Table VII.

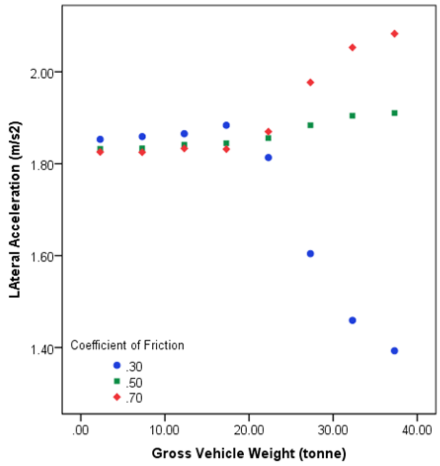
TABLE VI
SUMMARY OF 2-AXLE SIMULATION WITH KERB WEIGHT AND 0.3 COEFFICIENT OF FRICTION SIMULATION RESULT

Time (s)	Max. Lateral Acceleration (m/s^2)
0.271	0.00288
0.281	0.00259
.	.
.	.
48.751	1.85294
.	.
.	.
87.281	0.000000797
87.291	0.000000797

TABLE VII
THE LATERAL ACCELERATION OBTAINED FOR 2-AXLE SUT SIMULATION TEST

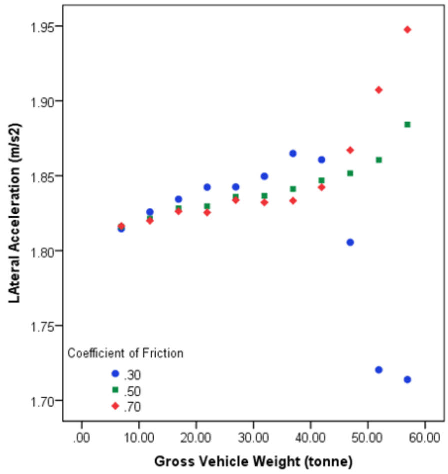
GVW (tonne)	Coefficient of friction 0.3	0.5	0.7
	Max. Lateral Acceleration (m/s^2)		
2.3	1.85294	1.83922	1.82550
7.3	1.85899	1.84190	1.82482
12.3	1.86517	1.84917	1.83318
17.3	1.88355	1.85760	1.83166
22.3	1.81332	1.84152	1.86973
27.3	1.60426	1.79060	1.97694
32.3	1.45912	1.75601	2.05290
37.3	1.39290	1.73788	2.08285

Lateral Acceleration (m/s^2) vs GVW (kg) for 2 Axle SUT



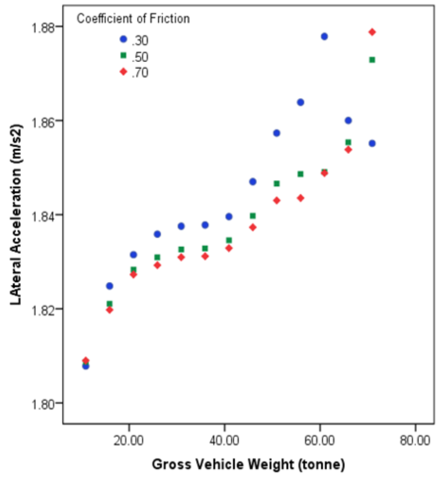
(a)

Lateral Acceleration (m/s^2) vs GVW (kg) for 3-Axle SUT



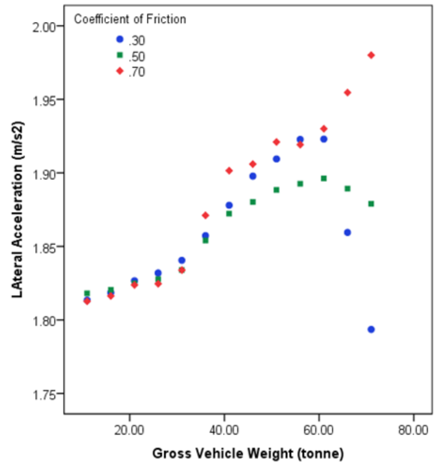
(b)

Lateral Acceleration (m/s^2) vs GVW (kg) for 4-Axle SUT



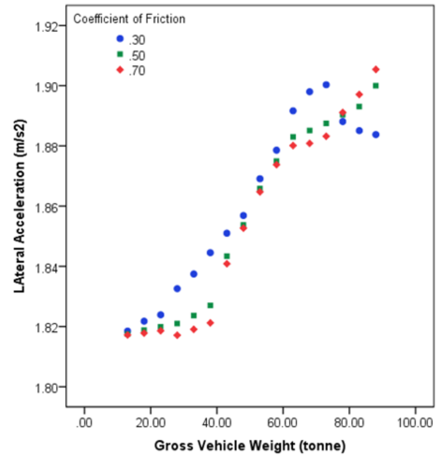
(c)

Lateral Acceleration (m/s^2) vs GVW (kg) for 4-Axle Truck Trailer



(d)

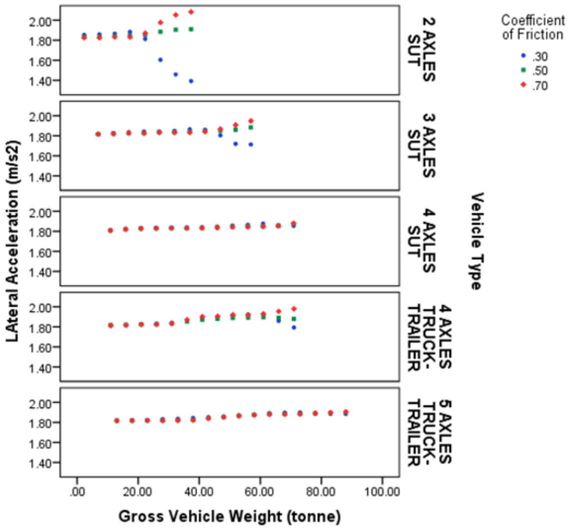
Lateral Acceleration (m/s^2) vs GVW (kg) for 5-Axle Truck Trailer



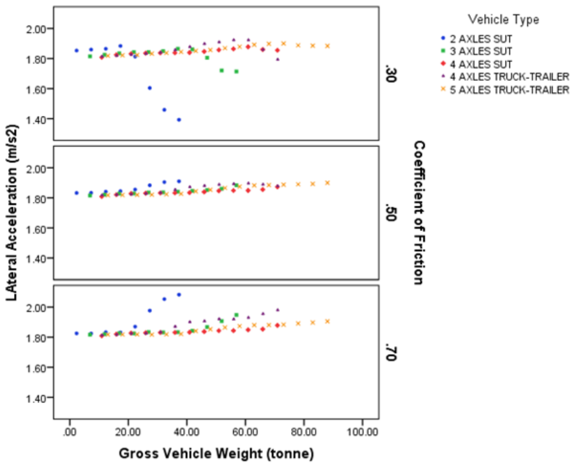
(e)

Fig. 5 The effect of GVW to the lateral acceleration of heavy vehicles with various of coefficients of friction; (a), 2-axle SUT; (b) 3-axle SUT; (c), 4-axle SUT; (d), 4-axle Semi Trailer (e), and 5-axle Semi Trailer

All the data generated are organized on scatter plot as shown in Figs. 5 (a)-(e) to indicate the effect of the GVW on the vehicle dynamic stability of lateral acceleration for 2-axle, 3-axle, 4-axle SUT, 4-axles and 5-axles of Truck-trailer. Based on simulation and data tabulated, all heavy vehicle types showed an increasing pattern on lateral acceleration when the load is added until maximum permissible GVW for all values of coefficient of friction. However, when the heavy vehicles are overloaded, by certain amount of GVW (e.g. >20 tons for 2-axle and >40 tons for 3-axle for SUT), and travelled on the road having coefficient of friction of 0.3, an unstable condition (most likely skidding) appeared when cornering. The value of lateral acceleration is suddenly and drastically decreased when the heavy vehicle is failed to accommodate the carried weight. The same case also happened on 4-axle Truck-trailer when travelled on the road having coefficient of friction of 0.5 when GVW is more than 60 tons (Fig. 5 (d)). It is also observed that maximum lateral acceleration occurred when the heavy vehicles are travelled on road t having 0.7 coefficient of friction. Furthermore, lateral acceleration reading on 2-axle SUT was recorded as the highest among the others which is 2.08285 m/s^2 followed by 4-axle Truck-trailer, 3-axle SUT, 5-axle Truck-trailer and 4-axle SUT. It means that 2-axle SUT has more tendency for not having stability during cornering compared to the others. Apart from all simulations for all heavy vehicle types, no sign of accident or vehicle stability failure such as rollover or jack-knifing was observed through simulation even though maximum.



(a)



(b)

Fig. 6 Summary of the effect of GVW to the lateral acceleration of heavy vehicles; (a), assigned to the vehicle type to compare with the coefficient of friction; (b) assigned to the coefficient of friction to compare with vehicle type

IV. Conclusion

The outcome of this research has found the correlation between the GVW and lateral acceleration of heavy vehicle during cornering. As the GVW increases, the lateral acceleration is also increased. However, it depends on the value of coefficient of friction at certain limit of GVW. Lower value of coefficient can reflect the stability of heavy vehicle.

Finally, for further work, this statistical result can be used to generate a mathematical model to develop a safety system for the heavy vehicle's driver during cornering.

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