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Analysis of Vehicle Ride and Handling Performance on Variable Vehicle Load and Speed Using Simulation Method

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Abstract: Perodua Myvi is one of its class's leading local vehicles. However, when it comes to ride and handling, it has its own share of problems as there were many complaints circulating around saying that the Myvi is not so comfortable for both passengers and drivers. Therefore, the goals of this paper are to set up the study of vehicle ride and handling using the simulation method and to analyse the performance of vehicle ride and handling on variable vehicle load and speed. CarSim® software was utilized to analyze vehicle body bounce, pitch, roll and four-wheel vertical motion on 7-DOF of vehicle ride and handling model. The mathematical vehicle modeling software which is CarSim® software was used to represent an actual vehicle which is Perodua Myvi. The actual Perodua Myvi parameters become an input for CarSim® simulation model. In addition, two types of simulation will be conducted which are ride comfort simulation and handling simulation. For vehicle ride comfort simulation, these models were simulated on different speed which are 8, 12 and 16 km/h with chassis twist road test. The simulation was designed to compare the results on different speed. For vehicle handling simulation, double lane change procedure was conducted with variable vehicle load. Graphs were recorded and analysed for tire acceleration, body acceleration, yaw, pitch and roll acceleration. Simulation results show similar trends at different vehicle speeds and loads, but different in magnitude. The success of this project will enable researchers and consumers to significantly improve vehicle ride and handling performance.

Keywords: CarSim®, Handling Performance, Ride Performance, 7-DOF

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1. Introduction

Vehicle dynamic refers the directional performance and dynamics of road vehicles and usually based on classical mechanics. The vehicle dynamic consists as critical parts of the structure of the vehicle body (sprung mass), the suspension portion (spring and damper) and tire (unsprung mass). The dynamic performance of the vehicle can be divided into three aspects that are lateral dynamic, handling and longitudinal dynamic, acceleration and vertical dynamic performance and ride and pitch performance according to the direction of force [1]. A car's ride comfort performance is the yaw, pitching and rolling motion caused by road roughness in forced vibration [1]. The objective of the suspension in this context is to minimize passenger discomfort by selecting springs and dampers, which obviously involves minimizing some measure of vehicle body motion. Handling performance is the quality of a vehicle that allows it to be safely controlled by the driver so that the desired course is easily maintained at high longitudinal and lateral accelerations [2]. Vehicle ride comfort issues for drivers are not only related to individual driving experience satisfaction, but more importantly, due to deteriorated driving environments and performance, driving safety and long-term health of drivers. This is especially true for those occupational drivers with extended driving time and also higher duties such as public transport and large cargo trucks. It is known that ride comfort is directly related to the drivers or passengers' vehicle body vibrations. Exposure to excessive vehicle whole-body vibration can cause short-term body discomfort and long-term physical damage to the back and neck, such as musculoskeletal pain and back pain [3].

In addition, Perodua Myvi is one of the leading local vehicles in Malaysia's class. However, when many complaints circulated around alleging that the Myvi is not so convenient for both drivers and passengers, when it comes to riding and handling, it has its own share of problems. The complainants stated that even small road defects could cause ample discomfort for drivers and passengers. The result shows that Axia has the best sound quality and comfort level compared to Perodua Myvi on highways, pavements and urban roads, as indicated by the k-means clustering algorithm and GA model, from A Computational Method for Optimizing Vehicles' Interior Noise and Vibration paper [4].

To simulate the performance of passenger vehicles, CarSim® offers the most accurate, detailed and efficient method. CarSim® is universally the tool of choice for the analysis of vehicle dynamics, the development of active controllers, the calculation of car performance features and the engineering of next-generation active safety systems with twenty years of real-world validation by automotive engineers [5]. Therefore, CarSim® software was chosen to analyze vehicle body bounce, pitch, roll and four-wheel vertical motion on 7-DOF of vehicle ride and handling model. The mathematical vehicle modeling software which is CarSim® software was used to represent an actual vehicle which is Perodua Myvi. The actual Perodua Myvi parameters become an input for CarSim® simulation model. In addition, two types of simulation had been conducted which are ride comfort simulation and handling simulation. For vehicle ride comfort simulation, these models were simulated on different speed which are 8, 12 and 16 km/h with chassis twist road test. The simulation was designed to compare the results on different speed. For vehicle handling simulation, double lane change procedure was conducted with variable vehicle load. Graph of tire acceleration (unsprung mass), body acceleration (sprung mass), yaw, pitch and roll acceleration were recorded from the simulations and analyzed.

2. Materials and Methods

The method used in this study was discussed in detail. This consists of the simulated vehicle, vehicle parameter and model description and simulation in the CarSim® software.

2.1 Simulated Vehicle

Perodua Myvi 1.3 L in Figure 1 is used as a simulated vehicle in this study. Table 1 shows the value of the parameter for Perodua Myvi. The simulation of the model applied all parameters.

Figure 1: Perodua Myvi 1.3 L

Table 1: Vehicle Parameters [6]

Definition	Values
Sprung mass	573 kg
Unsprung mass front left	114.9 kg
Unsprung mass front right	114.9 kg
Unsprung mass rear left	76.4 kg
Unsprung mass rear right	76.4 kg
Spring stiffness	18000 N/m
Tire stiffness	13000 N/m
Damping coefficient	1500 Ns/m
Length from the center of gravity to the front end	0.75 m
Length from the center of gravity to the rear end	1.85 m
Length of the center of gravity to the right end	0.715 m
Length of the center of gravity to the left end	0.715 m
Moment of inertia about y – axis	289 kgm2
Moment of inertia about x - axis	3300 kgm2
Moment of inertia about z - axis	1343.1 kgm2
Wheelbase	2.5 m
Fraction Steered for front suspension	0.8
Fraction Steered for rear suspension	0.1
Wheel Center	1.43 m

2.2 Assumption and Limitation

Assumptions and limitations are very important when the simulation is created. It is important that the assumptions used to determine what is going to work and what is not going to work. Uninformed decisions are usually needed to plan workable solutions. The assumptions and limits for this simulation are as follows:

i. The suspended mass is symbolized by the spring mass.
ii. The mass of the unprung is the mass of the wheels, brakes, calipers and items not supported by the suspension.
iii. The suspension system consists of an elastic element (spring) and a dissipating element (damper)
iv. Throughout the simulation, the vehicle chassis is considered parallel to the road.
v. Tires are considered to be in contact with the road during the simulation because the vehicle can no longer be controlled if the tire loses contact with the road.
vi. Aerodynamic lift, drag and tire rotational resistance can be ignored.

2.3 Modeling and Simulation

Two different simulation were carried out to study vehicle ride and handling performance of the simulated vehicle of Perodua Myvi, and simulation was performed using the CarSim® Software. The simulations are:

i. Ride comfort test.
ii. Handling test.

2.3.1 Ride Comfort Simulation

Ride comfort simulation is based on continuous bumpy pattern of the road profile. This simulation is known as chassis twisted road test. This type of road profile is simulated bumpy road excitation resulting road profile unevenness with 0.05 meter height elevations [7]. The reason why chassis twisted road profile was chosen to test ride comfort performance is because ride quality refers to the vertical vibration effect caused by road irregularities such as road bumps and potholes. Figure 2 illustrated the chassis twisted road which used on the ride comfort simulation by using CarSim® Software.

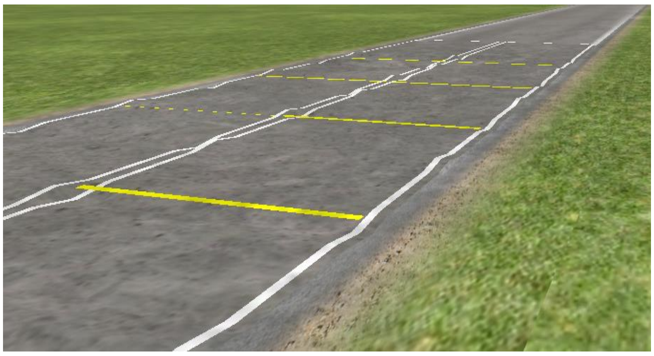

Figure 2: Chassis Twisted Road Profile

For this type of simulation, three different vehicle speeds were selected from 8, 12 and 16 km/h. It is very important to emphasize that the vehicle speed when going through this type of road profile. The reason why these three different speeds were chosen is because speed bumps generally to slow down the vehicle between 8 to 16 km/h (5-10 mph) [8]. Three different speed had been set up in the procedures section: chassis twist road in the CarSim® software as shown in Figure 3. The vehicles in the simulations are traveling at a constant speed of 8, 12 and 16 km/h with driver controls set to no brake pressure and automatic gear selection using all available gears as assumptions. Figure 4 shows the animation on vehicle ride test when navigating the chassis twist road profile. Yellow car represents vehicle with speed 16 km/h, silver car represents vehicle with speed 12 km/h and blue car represents vehicle with speed 8 km/h.

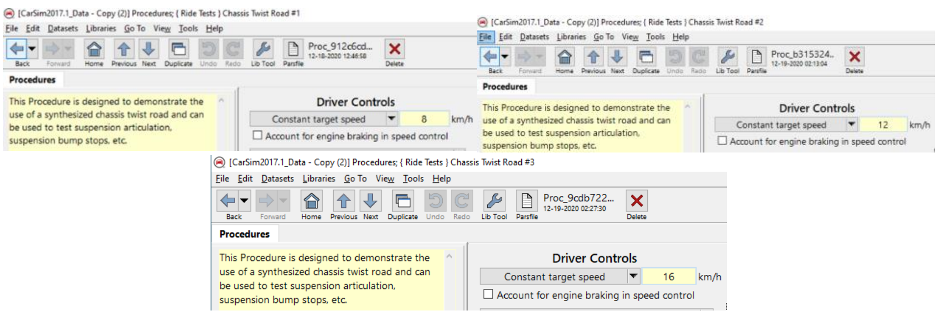

Figure 3: Vehicle Speed Setup in Procedure Section: Chassis Twist Road in CarSim®

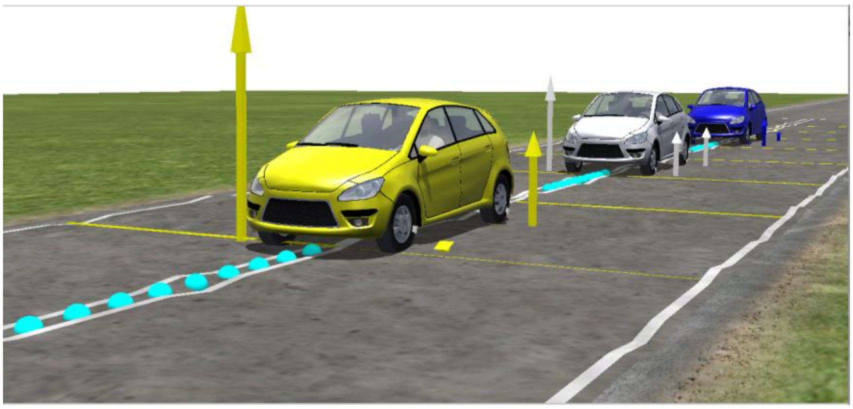

Figure 4: Animation on Vehicle Ride Test

2.3.2 Handling Simulation

For the vehicle handling test, double lane change maneuver has been selected. To test the vehicle's obstacle avoidance performance, ISO 3888-2 defines the double lane change maneuver. In this test, when the vehicle reaches a target speed, the driver should accelerate, release the accelerator pedal, turn the steering wheel to follow the path to the left lane, and turn the steering wheel to follow the path back to the right lane [9]. Cones typically mark the boundaries of the lane. The vehicle passes the test if the vehicle and driver are able to negotiate the maneuver without hitting a cone. Figure 5 shows the track of the double lane-change maneuver in accordance with Standard No. ISO 3888:1975.

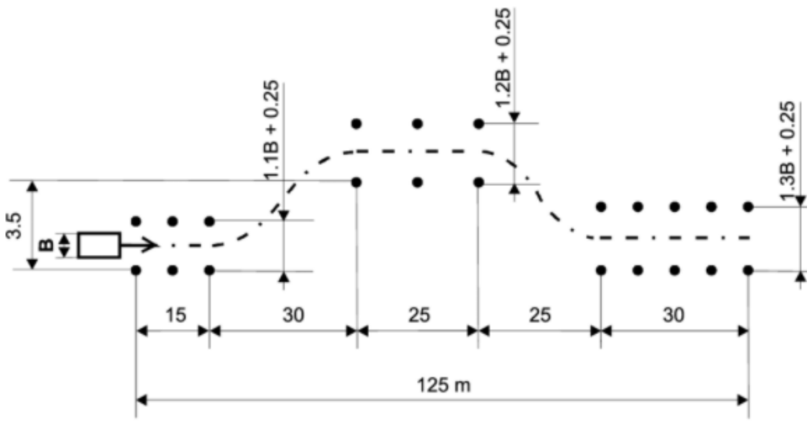

Figure 5: The Track of the Double Lane-Change Maneuver in Accordance with Standard No. ISO 3888:1975 [9]

Vehicle speed of 110 km/h was selected as a vehicle target speed for a double lane change simulation. This is because, by default, the maximum vehicle speed when driving on the highway is 110 km/h (68 mph) in Malaysia [10]. Figure 6 shows the vehicle speed setup for double lane change procedure in CarSim® Software. In addition, three different vehicle loads were varying to mimic the passenger and luggage inside of the vehicle. The first vehicle load consists of the sprung mass of the vehicle plus the mass of a driver. The second vehicle load consists of sprung mass of the vehicle plus the mass of a driver with 3 passengers. While the third vehicle load consists of sprung mass of the vehicle added with the mass of one driver and three passengers along with the mass of maximum luggage that can be accommodated by the vehicle. There are some assumptions that have been made such that the mass of a driver or a passenger is 62.65 kg because the overall mean body weight and Body Mass Index (BMI) is 62.65 kg and 24.37 kg/m^2 respectively for adult Malaysians aged 18 to 59 years [11]. Another assumption is the mass of maximum luggage that can be accommodated by the vehicle is calculated based on the load area size of Perodua Myvi 1.3 L which is 208 L [12]. Based on the assumption, 208 L is equivalent to 208 kg mass of maximum luggage that can be accommodated by the vehicle. Table 2 shows the total vehicle load for three vehicles. Figure 7 shows animation on double lane change test at 110 km/h. Purple car represents car with vehicle load of 635.65 kg, green car represents car with vehicle load of 823.6 kg and red car represents car with vehicle load of 1031.6 kg

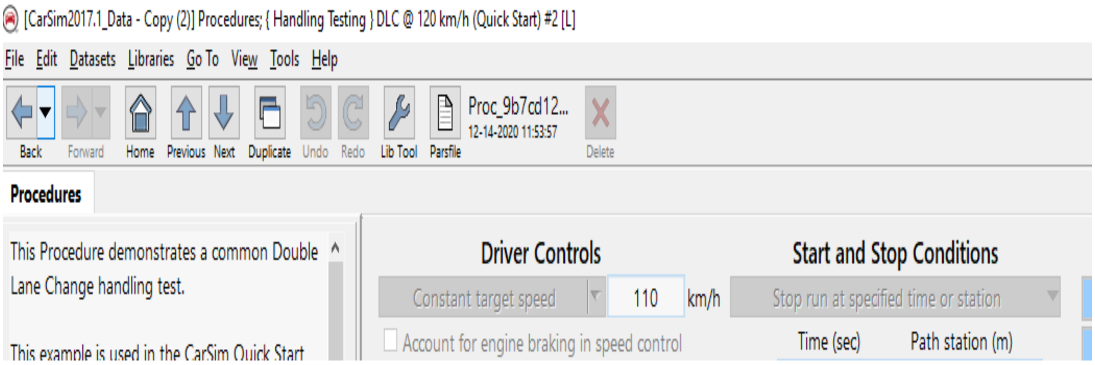

Figure 6: The Vehicle Speed Setup for Double Lane Change Procedure in CarSim® Software

Table 2: Total Vehicle Load for Three Different Vehicles

Sprung mass + One Driver	Sprung mass + 4 person (one driver + 3 passenger)	Sprung mass + 4 person (one driver + 3 passenger) + mass of maximum luggage that can be accommodated by the vehicle
573 kg + 62.65 kg = 635.65 kg	573 kg + 4(62.65) kg = 823.6 kg	573 kg + 4(62.65) kg + 208 kg = 1031.6 kg

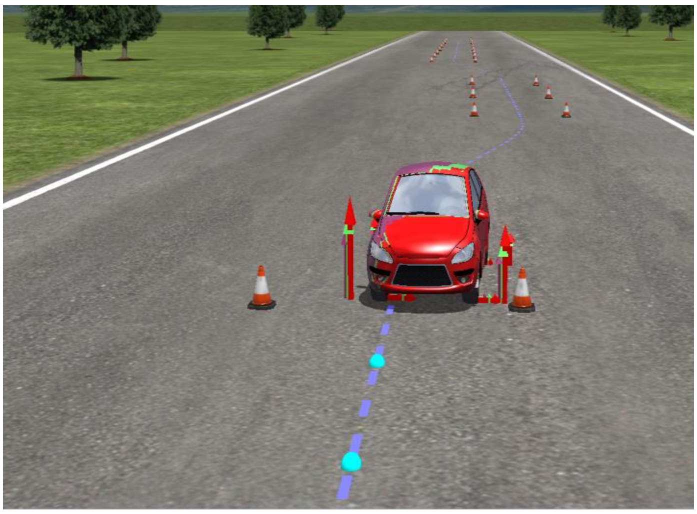

Figure 7: Animation on Double Lane Change Test at 110 km/h

3. Result and Discussion

The data obtained from this research is the result of the full simulation of the vehicle. The simulation data were divided into several parts that included vertical acceleration of the CG's (sprung mass), pitch and roll angle, longitudinal speed and vertical tire forces for the ride comfort test while the data were separated into lateral acceleration of the CG's, roll and yaw angle, vertical acceleration of the CG's and vertical tire forces for the handling test.

3.1 Result on Vehicle Ride Comfort Test

The result of the three-speed driving comfort test was shown. The simulated vehicle test was used to cross over a chassis twisted road profile with a fixed size for all simulations on a similar track to study driving performance. Highest peak shows that, at a given time, the simulated vehicle hit and crossed the twisted road profile of the chassis.

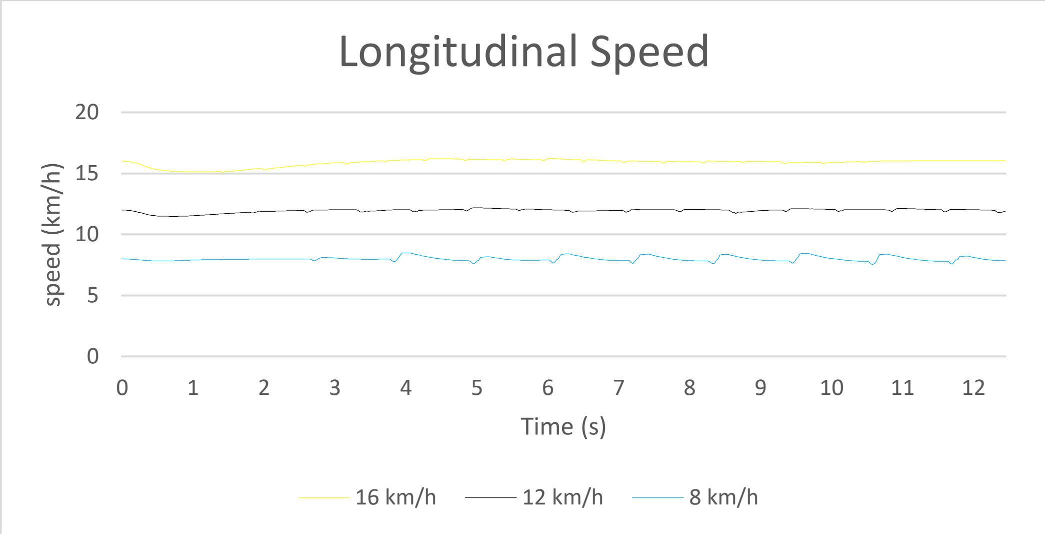

Figure 8: Longitudinal Speed

The difference in the simulation of the ride comfort is vehicle speed. The vehicle model was simulated at different vehicle speeds which are 8, 12 and 16 km/h. Figure 8 shows the longitudinal speed of the simulated vehicle models of which the yellow line represents the vehicle with a speed of 18 km/h, the black line represents the vehicle with a speed of 12 km/h and the blue line represents the vehicle with a speed of 8 km/h. All simulated vehicle was simulated on different target constant speed whereby referring to the bumpy road specification.

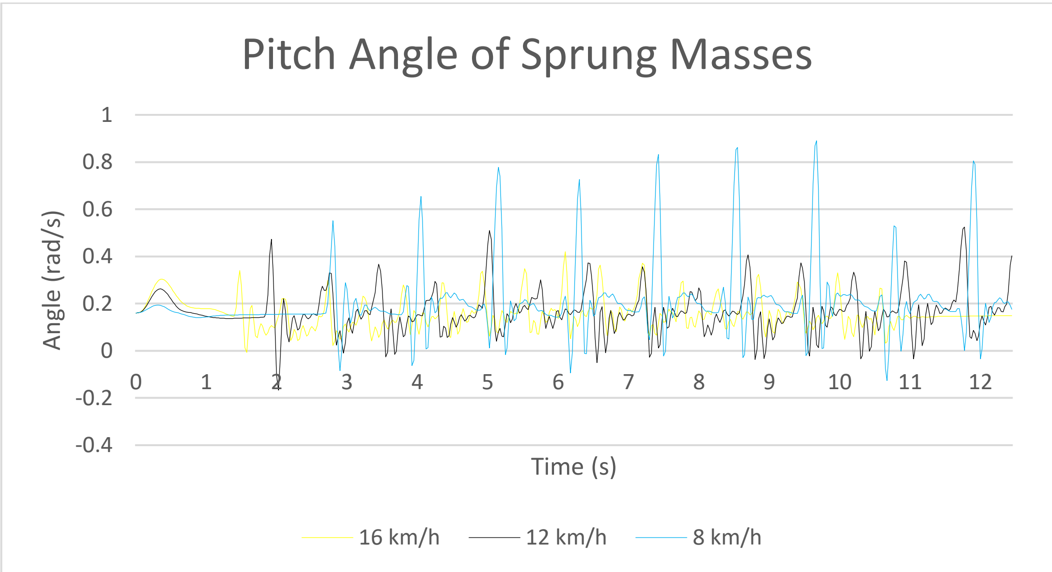

Figure 9: Pitch Angle of Sprung Mass

Figure 9 shows the pitch angle of the body of the vehicle (sprung mass). The blue line represents a speed of 8 km/h with a maximum vehicle angle of 0.89 rad/s. For the black line, the speed is 12 km/h, the maximum angle of the vehicle is 0.52 rad/s. The maximum angle of the vehicle is 0.42 rad/s for a speed of 16 km/h. It shows that the speed of 16 km/h achieved a lower pitch angle compared to the lowest speed of 8 km/h. This is because the speed of 8 km/h provides a lower centre of gravity (CG) than the speed of 16 km/h in which the pitch angle of the simulated vehicle with respect to gravity is measured using the gyro sensor inclination.

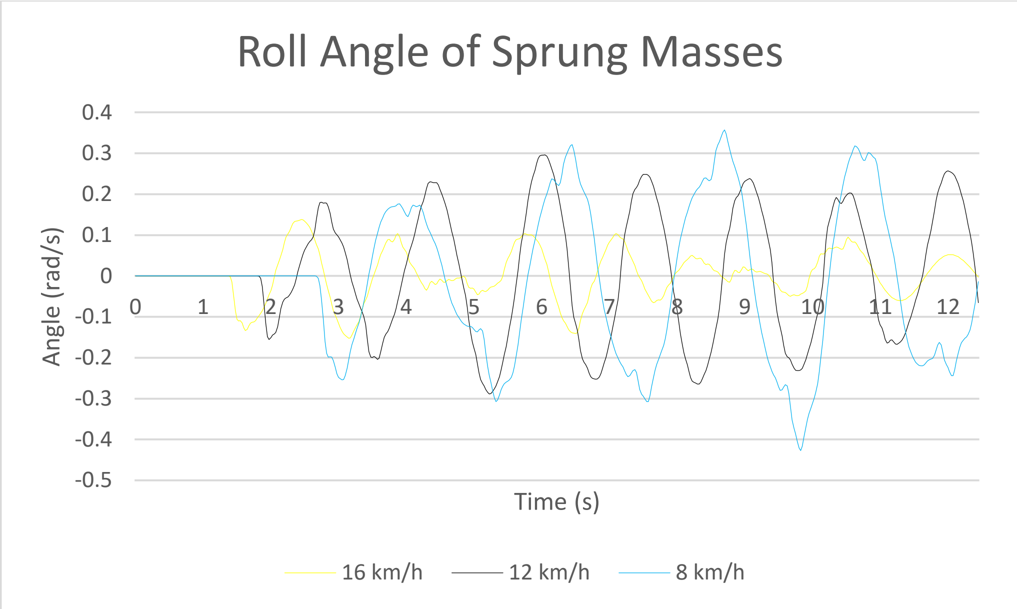

Figure 10: Roll Angle of Sprung Mass

Figure 10 shows the roll angle of the vehicle body for the simulation of ride comfort. The blue line represents a speed of 8 km/h with a maximum roll angle of 0.42 rad/s. In the case of a black line representing a speed of 12 km/h, the maximum roll angle of the simulated vehicle is 0.30 rad/s. For the yellow line which represents a speed of 16 km/h, which is the highest speed for the simulation, the maximum roll angle is 0.14 rad/s. It shows that the speed of 16 km/h was lower in roll angle compared to the speed of 8 km/h. It's because the speed of 8 km/h has lower roll stability control systems, as the roll angle is one of the most important variables that have been used to construct a feedback pressure command to counter the detected roll instability.

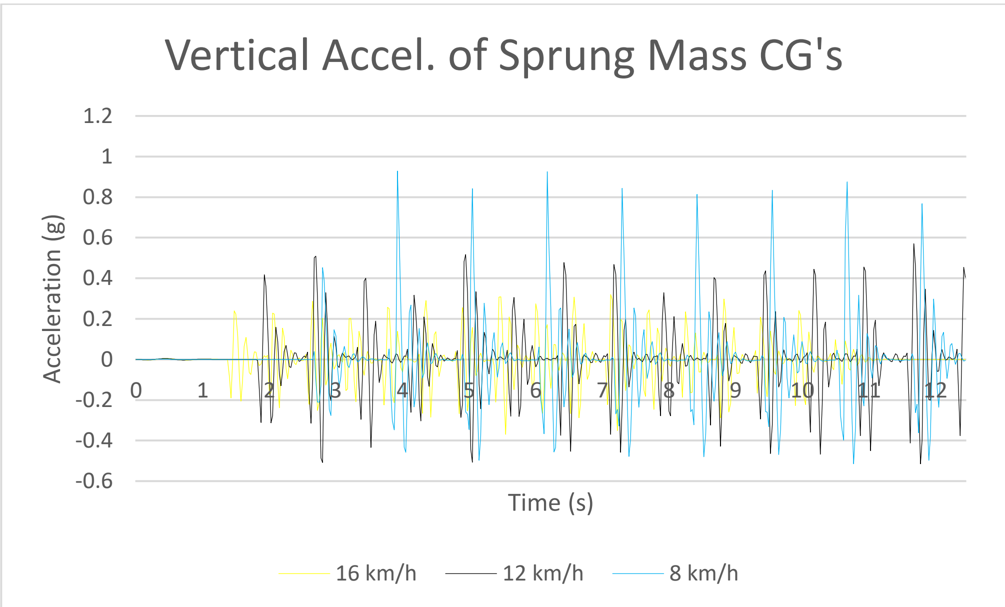

Figure 11: Vertical Acceleration of Sprung Mass CG’s

Figure 11 shows a comparison of CG's vertical acceleration for sprung masses with three different vehicle speeds. The blue line represents a speed of 8 km/h with a maximum acceleration of 0.93 g. The black line represents a speed of 12 km/h at which the maximum acceleration is 0.57 g and the yellow line represents a speed of 16 km/h at which the maximum acceleration is 0.32 g. The relationship between vertical acceleration and speed is the highest vertical acceleration, the lower the speed. The vertical acceleration measured in the centre of gravity must be taken into account. Other than that, the vertical acceleration is influenced by the moment in which the rear axle enters the bump.

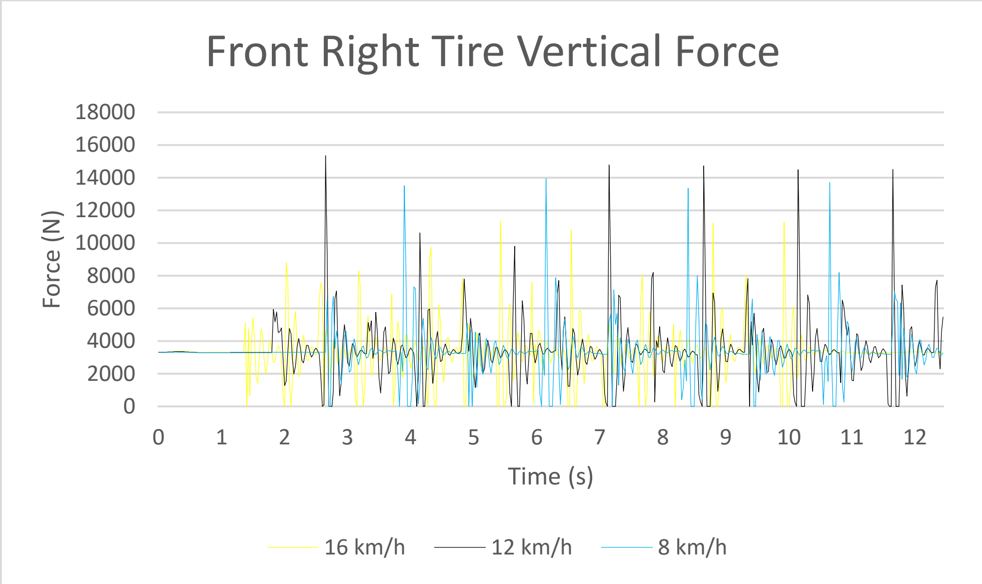

Figure 12: Front Right Tire Vertical Force

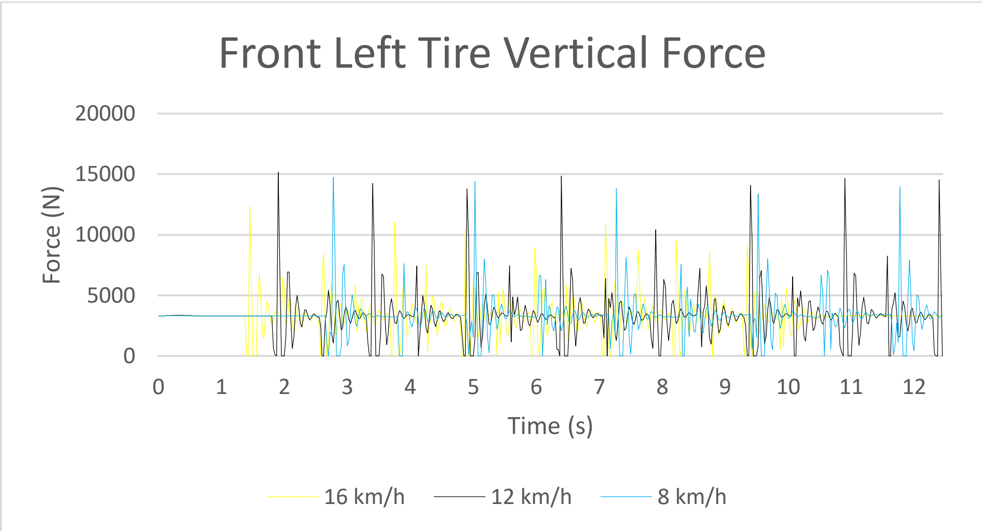

Figure 13: Front Left Tire Vertical Force

Figure 12 and 13 show the comparison of vertical forces of the front tires for both left and right side with three different speeds. In Figure 12, yellow line representing speed 16 km/h with a maximum force of 11.3 kN. Black line representing speed 12 km/h with a maximum force of 15.3 kN and blue line representing speed 8 km/h with a maximum force of 13.9 kN. Then for Figure 13, yellow line representing speed 16 km/h with a maximum force of 12.3 kN. Black line representing speed 12 km/h with a maximum force of 15.2 kN and blue line representing speed 8 km/h with a maximum force of 14.8 kN. Both Figures 12 and 13 show the same trend where for the graph of front right and front left tire vertical forces, the blue line representing cars with speed 8 km/h has higher vertical forces than cars with speed 16 km/h but it has lower forces than a car with a speed of 12 km/h. Also, both Figure 12 and 13 did not show negative value during the simulation.

3.2 Result on Vehicle Handling Test

The result of the three-load handling test was shown. The simulated vehicle test was used to negotiate with double lane change maneuver at 110 km/h in order to observe the lateral acceleration of the vehicle, yaw and roll angle and the tire vertical forces.

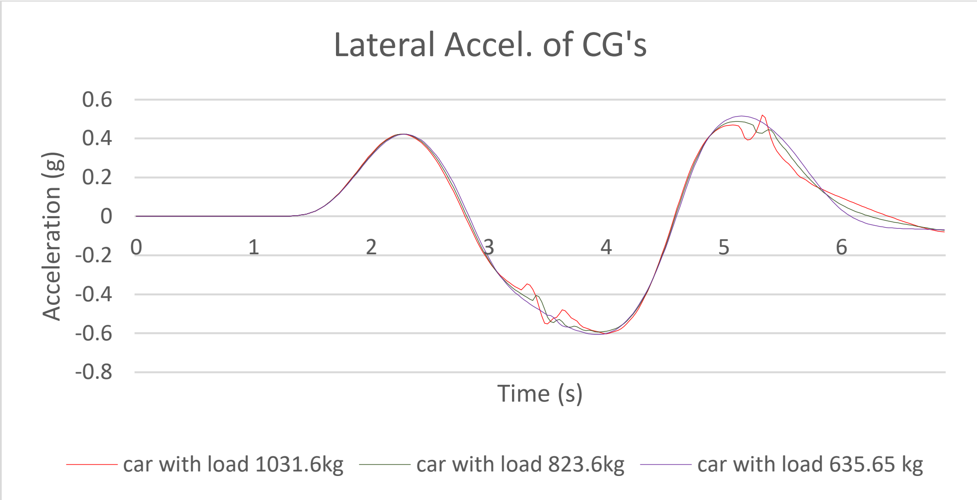

Figure 14: Lateral Acceleration of CG's

A comparison of lateral acceleration of center gravity (CG's) with three different vehicle loads is shown in Figure 14. From the graph, red line representing a car with a load of 1031.6 kg with a maximum lateral acceleration of 0.4218 g. The green line represents the car with a load of 823.6 kg with a maximum lateral acceleration of 0.4222 g and the purple line represents the car with a load of 635.65 kg with a maximum acceleration of 0.4223 g. From this graph clearly shows the lower the vehicle load of a vehicle, the higher the resulting lateral acceleration.

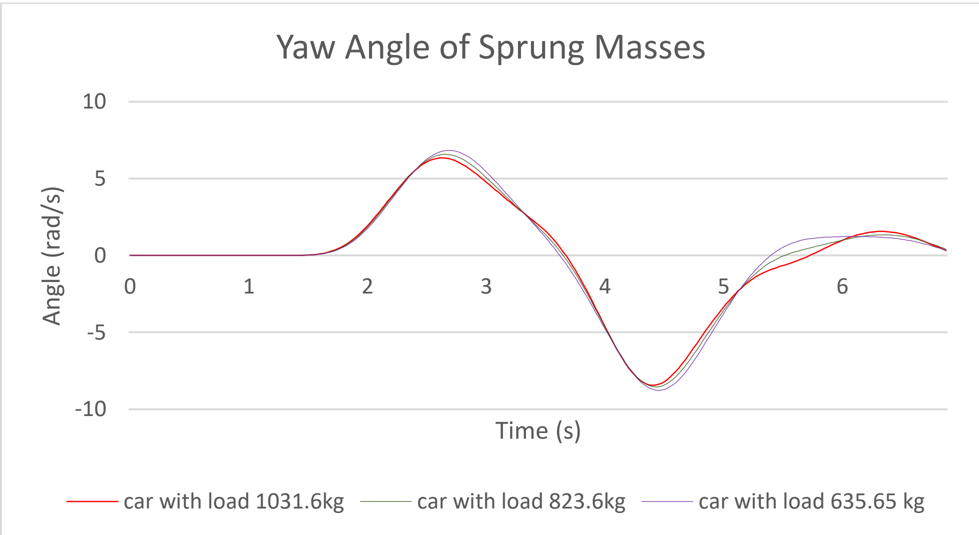

Figure 15: Yaw Angle of Sprung Masses

Figure 15 shows a comparison of yaw angle of sprung masses with three different vehicle loads. From the graph, red line representing a car with a load of 1031.6 kg with a maximum yaw angle of 6.34 rad/s. Green line representing a car with a load of 823.6 kg with a maximum angle of 6.58 rad/s and a purple line representing a car with a load of 635.65 kg with a maximum angle of 6.83 rad/s. This shows that the higher the vehicle load of a vehicle, the lower the yaw angle of sprung masses.

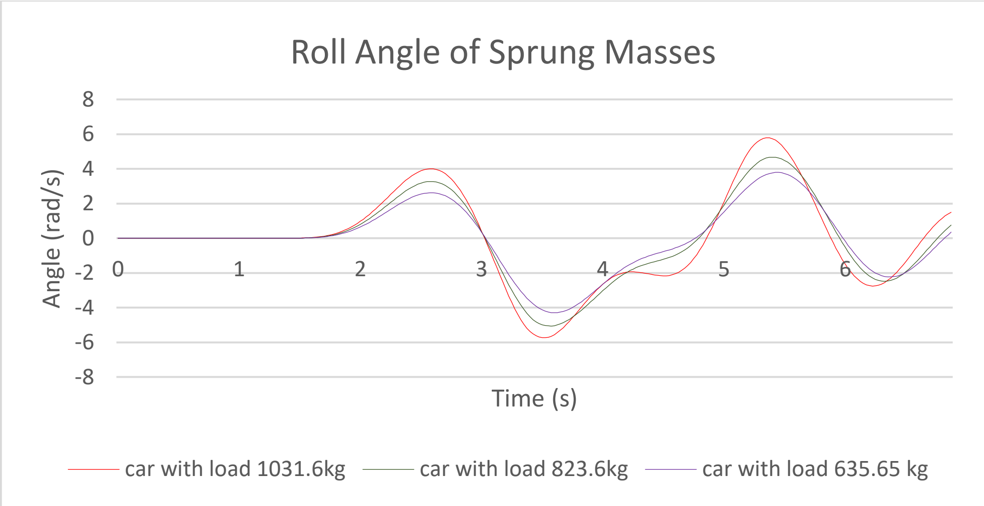

Figure 16: Roll Angle of Sprung Masses

Figure 16 shows a comparison of roll angle of sprung masses with three different vehicle loads. From the graph, red line representing a car with a load of 1031.6 kg with a maximum roll angle of 5.79 rad/s. Green line representing a car with a load of 823.6 kg with a maximum angle of 4.68 rad/s and a purple line representing a car with a load of 635.65 kg with a maximum angle of 3.80 rad/s. When a heavy vehicle does cornering or lane change, it will produce a high roll angle because of the centripetal force is proportional increase with the vehicle mass.

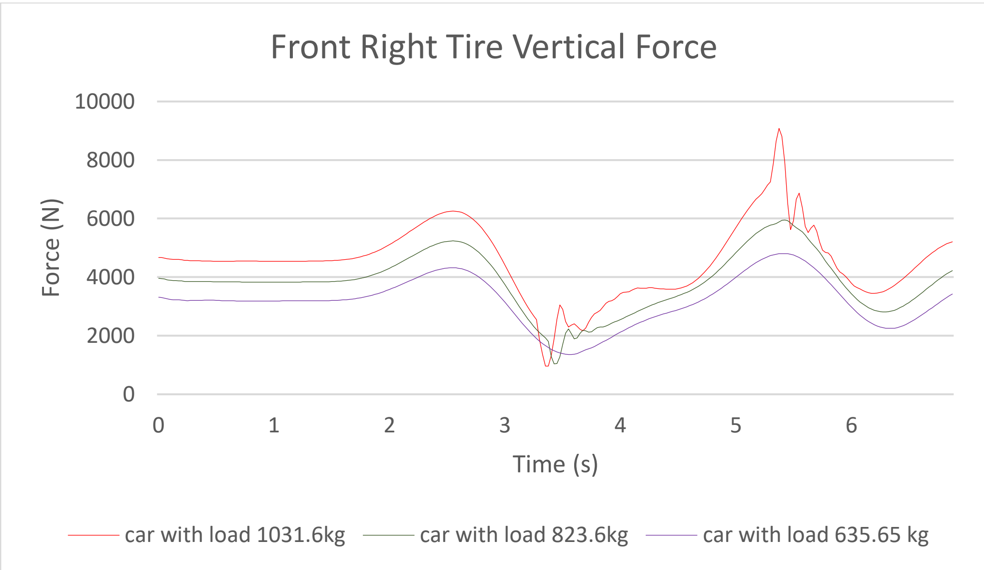

Figure 17: Front Right Tire Vertical Force

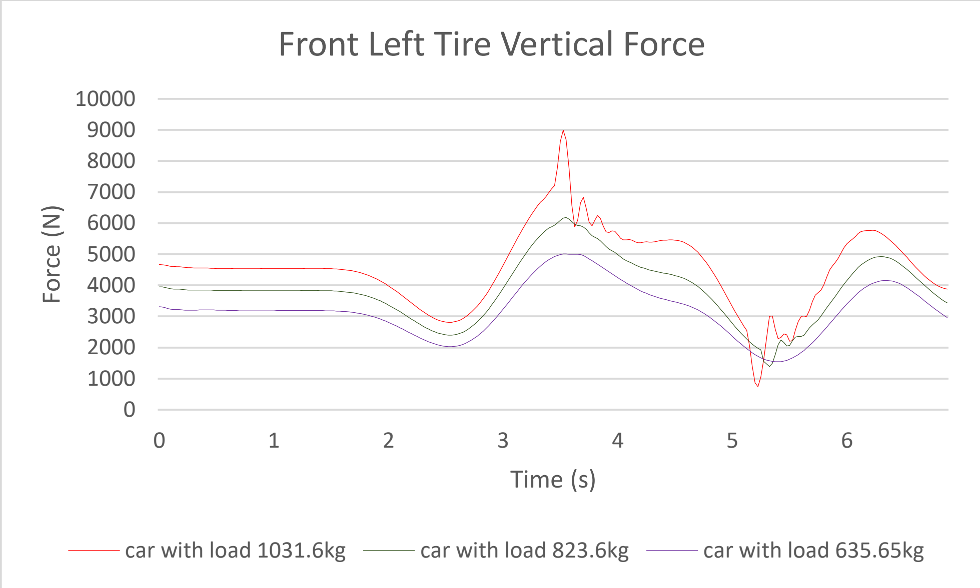

Figure 18: Front Left Tire Vertical Force

Figure 17 and 18 show comparison of both front tire vertical force with three different vehicle load. In Figure 17, the red line represents a car with a vehicle load of 1031.6 kg with a maximum force of 9.1 kN. The green line represents a car with a vehicle load of 823.6 kg with a maximum force of 6.0 kN and the purple line represents a car with a vehicle load as much as 635.65 kg with a maximum force of 4.8 kN. As for Figure 18, the red line represents the car with a vehicle load of 1031.6 kg with a maximum force of 9.0 kN. The green line represents the car with a vehicle load of 823.6 kg with a maximum force of 6.2 kN and the purple line represents the car with vehicle load of 635.65 kg with a maximum force of 5.0 kN. Based on Figures 17 and 18, both graphs have the same trend where the higher the vehicle load, the higher the resulting tire vertical forces.

3.3 Discussion on Vehicle Ride Comfort Test

Root mean square (RMS) was used to define the vehicle ride performance since the data obtained from ride simulation is a variable quantity (consecutive positive and negative). Table 3 shows RMS value for vehicle ride test. Table 4 shows the criteria of discomfort levels as suggested by ISO 2631-1 (1997). The subjective ride comfort criteria have overlapping RMS value. Vehicle ride comfort is assessed based on Table 4.

Table 3: RMS Value for Vehicle Ride Test (Chassis Twisted Road Profile Test)

Parameter	8 km/h	12 km/h	16 km/h
Longitudinal Speed (km/h)	7.99	11.95	15.88
Vertical Acceleration. of Sprung Mass CG's (g)	0.25	0.17	0.11
Pitch Rate of Sprung Masses (rad/s)	0.36	0.21	0.17
Roll Rate of Sprung Masses (rad/s)	0.26	0.17	0.06
Front Right Tire Vertical Force (N)	5156.79	4435.37	3687.74
Front Left Tire Vertical Force (N)	5172.66	4373.36	3682.53

Table 4: Subjective Ride Comfort Criteria Based on RMS Value [13]

RMS Value (m/s^2)	Subjective Indication
< 0.315	Not uncomfortable
0.315 – 0.63	A little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25 – 2.5	Very uncomfortable
> 2.0	Extremely uncomfortable

The longitudinal speed for the three different speeds approaches the speed value set for this test which is 7.99 km/h approaching 8 km/h, 11.95 km/h approaching 12 km/h and 15.88 km/h approaching 16 km/h. This is because the value that has been set is the maximum value, therefore, the resulting longitudinal speed value will only approach the set speed value. The approximate value is the result of the mathematical equation for the model in CarSim® software. This software is able to simulate a vehicle in a situation of actual vehicle based on mathematical model that seems real. Therefore, the resulting longitudinal speed value is not able to reach the maximum speed set due to factors such as friction, engine and tires that can affect the simulated vehicle model [14].

For the vertical acceleration of sprung mass, data shows that vertical acceleration will not increase when the vehicle speed increases. The vertical acceleration based on RMS value for 8 km/h is 0.25 g which is equal to 2.45 m/s^2. Based on subjective ride comfort criteria, 2.45 m/s^2 of vertical acceleration indicates very uncomfortable experience for the driver and passengers in the vehicle when hitting the bump. Other than that, it should be taken into account that vehicle vertical acceleration factor is measured in the center of gravity. Therefore, for the same road profile or bump (such as in this test is chassis twisted road profile) in which vertical acceleration is influenced, the vertical acceleration is measured when the rear axle enters and hits the bump. When the vehicle is moving at high speed, the longitudinal movement or longitudinal acceleration is higher than the vertical acceleration [15].

For vertical tire forces, slower the vehicle, vertical tire forces become higher. This is due to the high compression and rebound factor by the suspension system [16]. This will be resulted in the body of the vehicle not having time to go down completely because after that it will hit another bump and so on because the vehicle suspension not able to full compress and renounce. High vertical tire forces will have a high vibration effect on the passenger which in turn will lead to a high level of discomfort while driving.

For pitch angle of sprung masses, slower the vehicle, the pitch angle become higher. Pitch is the rotation of a vehicle about transverse axis. Pitch is also a shift in the vehicle's weight between front and rear vehicle. During low vehicle speed and when it hits the bump, high vertical acceleration will have occurred. This will result in the damper where in a dynamic state, will slowly absorb the resulting force when hit the bump [17]. This will make the vehicle easier to shift in the vehicle’s weight forward or backward and will increase the discomfort level to the driver and passengers in the vehicle.

For roll angle of sprung masses, the lower the speed of a vehicle, the higher the roll angle. Roll is the rotation of a vehicle about longitudinal axis. Body roll occurs when a vehicle hits the half of a bump, its weight is thrown to the outside of the corner, causing the vehicle tend to roll in that direction. When the vehicle moves at low speed and hits the bump, high vertical acceleration will be produced, and this will result in the damper in a dynamic state, will slowly absorb the resulting force when hit the bump. This will affect the vehicle body to roll to the left or to the right side of the vehicle. This situation occurred because of the slow bounce and renounce from the suspension, the suspension able to received full vertical displacement from the bump and transfer to the vehicle body [18]. Based on this results, high vehicle roll angle will cause discomfort to the driver and passenger during riding because it able to increase the driver fatigue.

3.4 Discussion on Vehicle Handling Test

RMS value was also used to discuss related data resulting from vehicle handling simulation since almost all the data obtained is a variable quantity (consecutive positive and negative). Table 5 shows the RMS value for vehicle handling test (double lane change at 110 km/h). The purpose of this discussion is to identify which vehicle have better handling performance with carriable load condition.

Table 5: RMS Value for Vehicle Handling Test (Double Lane Change at 110 km/h)

Parameter	Vehicle with load 635.65 kg	Vehicle with load 823.6 kg	Vehicle with load 1031.6 kg
Lateral Acceleration of CG's (g)	0.31	0.30	0.29
Yaw Rate of Sprung Masses (rad/s)	3.70	3.58	3.50
Roll Rate of Sprung Masses (rad/s)	1.94	2.32	2.66
Front Right Tire Vertical Force (N)	3282.96	3955.68	4716.17
Front Left Tire Vertical Force (N)	3311.93	3970.45	4710.08

Lateral acceleration increase if the vehicle load decreases. This situation shows that the unladen vehicle have a better handling performance compared with full load vehicle. High lateral acceleration will result when a vehicle passes cornering or changes lanes that tends to push a vehicle sideways. This situation cause by the centrifugal force, the vehicle is pushed outward [19]. High lateral acceleration is indicative of high cornering capability and good handling characteristics.

Yaw angle increase if the vehicle load decreases. Yaw is a motion of vehicle rotation in the vertical axis and it is regularly known as understeer and oversteer. Based on this simulation, unladen vehicle tend to produce higher yaw rate compared with vehicle will fully loaded. Therefore, unladen vehicle able to kept the direction of the vehicle is pointing changing at a constant rate [20]. High vehicle yaw rate also indicates that a vehicle has high handling capability.

Roll angle decrease if the vehicle load decreases. Based on RMS simulation results, vehicle with low vehicle load, shown a good vehicle roll stability (low roll rate) as the roll rate is define as a stability of the vehicle to control its side motion from roll over. When the vehicle fully laden, once the vehicle starts to rolled, it is easy to turn over because of the Newton's First Law which followed by gravity motion. Motion sickness is proportionally increased with roll, yaw and pitch rate, so by that means, motion sickness also increased because those motion [21].

For tire vertical forces, vehicles with high vehicle load will produce high vertical forces. This happens because a high normal force will result when the vehicle is heavy. The normal force of the road on the tire on the contact patch is produced in vertical direction in the contact coordinates. The resulting normal force will affect the tire and suspension system which in turn will affect the handling performance of a vehicle [22]. Low tire vertical force is indicating good vehicle handling characteristics.

Conclusion

The simulated model with passive suspension system consists of 7 DOF was defined in CarSim® Software. These models were simulated at different speeds and vehicle loads, with different simulation procedures being chassis twist road profile procedure for ride comfort test and double lane change procedure for handling test. The simulations were designed to compared variable vehicle loads and speeds. The simulation recorded sprung mass acceleration graph, unsprung mass acceleration, tire forces, pitch, roll and yaw angle. Simulation results show similar trends at different vehicle speeds and loads, but different in magnitude. Also, the results from the simulation show that high vehicle speed will improve vehicle ride comfort performance when the vehicle hits the continuous road bump while vehicle with low amount of load will improve vehicle handling performance when the vehicle passes cornering or changes lane. Last but not least, similar trends in CarSim® at various speeds and vehicle loads indicate that the CarSim® model can be used to further investigate as to study the performance of vehicle ride and handling.

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