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Experimental Study on the Effect of Emergency Braking without Anti-Lock Braking System to Vehicle Dynamics Behaviour

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Research Article

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INTRODUCTION

The World Health Organization's (WHO) Road Safety Report states that 25 fatalities per 100,000 people in Malaysia were caused by traffic accidents [1]. Additionally, from 2010 (RM5.94 billion loss) to 2014 (RM6.77 billion loss annually), Malaysia lost an average of RM6.45 billion due to these catastrophes [2]. In addition, the death toll from traffic accidents affects society's financial and emotional costs [3].
Road accidents are caused by a number of variables, including inexperience, lack of ability, and risk-taking behaviors [4]. According to W. Vanlaar and G. Yannis, the situational cues that influence driver behavior include the vehicle (such as size, brakes, and stability), the road (such as geometry, surface, and junctions), and the traffic (such as volume, speed, and gaps) [5]. The car is equipped with an advanced safety vehicle technology to improve road safety. A passive vehicle safety system (PVSS) and an active vehicle safety system (AVSS) make up this safety system. Airbags and seat belts are examples of PVSS that may lessen impact and minimize occupant injuries. However, by providing warning signs and even maneuvering the car if the driver ignores the warning, the AVSS, like the advanced driver assistance system (ADAS), may avert collisions [6].

Even though the active safety system is essential to the automobile, installing it may be costly, and some vehicles just have the bare minimum installed. The braking system is one of the fundamental safety features that every car must have. The braking force is produced at the wheel to slow down and stop the car when the driver depresses the brake pedal [7]. Tire lock up and the skidding phenomena may happen if excessive braking force is used [8]. Additionally, it will worsen while braking on a slick road.
In order to minimize wheel lockup and shorten stopping distances, airplanes were equipped with anti-lock braking systems (ABS) in 1930 [9]. Due to the speedy advancement of electronics, sensors, and microprocessors in the 1980s, ABS is rapidly becoming required for automobiles [10]. ABS may keep the automobile steerable and let the driver to maneuver it in a safe place in addition to preventing the wheel from locking [11].
An ABS controller is designed using the slip-friction graph's sweet spot. There is an ideal location where the tire can grip the road with the most friction based on the sweet spot [12]. The uncertainty characteristics of the cars and the road surface provide a problem in the development of an ABS controller. The slip-friction graph in Figure 1 illustrates how the friction coefficient peaks at a certain slip ratio before declining as wheel slip increases [13]. Additionally, the connection between the slip ratio and the friction coefficient is influenced by the road surface.

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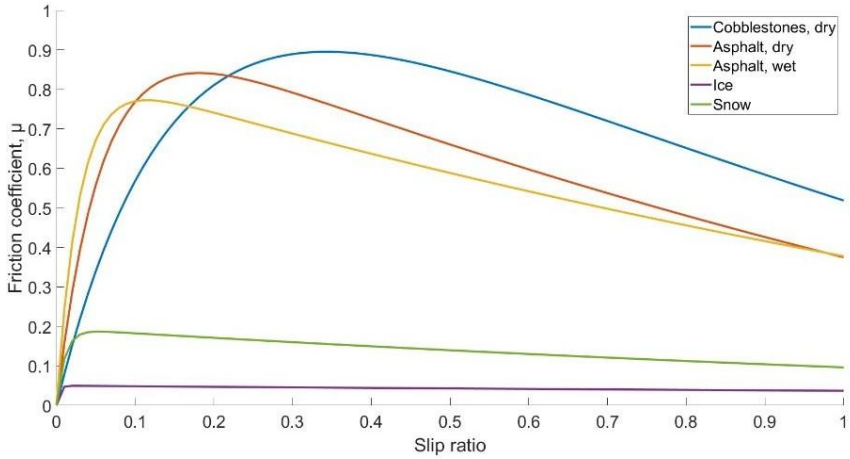


Figure 1. Slip-friction curve for different road surfaces at a linear speed of 10 m/s [12].

To counter the uncertainties, ABS requires a strong controller. The robust control mechanisms used in the ABS controller include sliding mode control, neural networks, and fuzzy control. According to a research by G. Fargione et al., fuzzy control optimization may prevent the brake pressure from exceeding the stable range. Genetic algorithms (GAs) are used to optimize the fuzzy approach so that it can create its own brake pressure control cycle. According to the simulation result, the braking pressure at any surface is close to the optimal brake pressure [14]. Additionally, A.B. Sharkawy has integrated genetic algorithms (GAs) with fuzzy algorithms. To address the impact of nonlinear dynamics (such as weight, road friction coefficient, and road inclination) on ABS performance, a self-tuning PID controller is implemented at the fuzzy and GAs. According to the simulation findings, a quick reaction with little overshoot and a short stopping distance is achieved by using the fuzzy self-tuning strategy with GAs [15].

The study of neural networks as a reliable controller for ABS has been suggested by Mirzaeinejad. In order to achieve strong robustness for the ABS controller, he invented the radial basis function neural network (RBFNN). The unknown parameter in the dynamics of the system may be found by using the Lyapunov function. RBFNN can lower the wheel slip tracking error, according to the simulation findings. Furthermore, RBFNN may function as an accuracy tracker and stop the brake torque from oscillating [11]. Neural networks are also used by Poursamad for the ABS controller. To get the required performance in a variety of driving situations, a hybrid controller for ABS based on adaptable neural networks is suggested. A feedback linearization controller and two feedforward neural networks make up the hybrid controller. The simulation results demonstrate how resilient the suggested controller is to outside perturbations [16].

Sliding mode control (SMC) is another reliable control method for ABS. Tang et al. claim that SMC is a better controller for ABS because of its resilience to changes in parameters and outside disruptions [13]. The impact of sliding surface design on SMC performance in ABS has been studied by Shim et al. They have simulated a different sliding surface design for an SMC using an 8-DoF nonlinear vehicle model. The suggested sliding surface design may enhance oscillation damping near the ideal slip ratio, according to the simulation findings [17].

According to Patil et al., it is costly and time-consuming to create and apply strong control systems on a vehicle. As a result, computer simulations are used by several researchers [9]. The dynamic behavior of the vehicle with ABS on and disabled under various road conditions has been analyzed using a simulation. The stopping distance is 28% greater when ABS is enabled or active than when it is not. Additionally, when the ABS is used on wet roads, the car does not slide [18]. Some studies use a laboratory ABS setup to verify the suggested control techniques and ABS algorithm. An ABS workbench has been established by Inteco Ltd., and the validation results for neural networks, sliding mode controllers, and fuzzy control are shown in [19–23].

It can be seen from the literature that computer simulation methods account for the majority of ABS research. The vehicle dynamics model may be developed using one of two methods: the simplified modeling technique or the multi-body method to create the equation of motion. According to a paper by Ahmad et al., unless the model is thoroughly tested using real vehicle data, the simulation's dependability is deemed impracticable [24]. As a

result, it is crucial to conduct a preliminary experiment to analyze the dynamics behavior of the vehicle without ABS. This investigation allows the researcher to confirm their modeling and ascertain the behavior of the automobile without ABS. The suggested ABS controller may be included into the modeling after validation, and the outcome is more dependable.

The dynamic behavior of an automobile during emergency braking on both wet and dry surfaces was examined in this research via an experiment. Even if there are a lot of research on ABS control, different vehicle kinds and driving abilities have an impact on several metrics including tire stiffness, suspension displacement, and braking force. This research aims to provide a thorough investigation of how emergency braking without ABS affects the responsiveness of the vehicle. Additionally, the study's conclusions greatly aid researchers and manufacturers in developing the vehicle's active safety system and ABS. The instrumented vehicle model is a sedan without an ABS.

VEHICLE DYNAMIC MOTION

In the analysis of the vehicle behaviour during braking, it is necessary to consider the load transfer at each wheel. The effect of the load transfer can be determined from the free body diagram of the car, as illustrated in Figure 2. Considering the force only acting on the longitudinal axis, the dynamic load at the front and rear tire can be derived as [25]:

$$F_{zf} = W\left(\frac{l_r}{l} - \frac{a_x}{g}\frac{h}{l}\right) \quad (1)$$

$$F_{zr} = W\left(\frac{l_f}{l} + \frac{a_x}{g}\frac{h}{l}\right) \quad (2)$$

where W, l, l_f, l_r, h, g and a_x are the weight of the car, wheelbase, length from the front/rear tire to the centre of gravity, height from the centre of gravity, gravitational acceleration and longitudinal acceleration, respectively. Referring to Eq.(1) and Eq. (2); the load is transferred from the front to the rear wheels due to the longitudinal acceleration, a_x. On the other hand, when the car decelerates, the load is transferred from the rear to the front wheels. In an emergency braking condition, the value of a_x will increase in a negative value abruptly. As a result, more load is shifted to the front wheel, and the car tends to pitch down. Therefore, the braking force at the front wheels must be larger than the rear wheels. Generally, passenger car employed disc brake at the front wheels and drum brake at the rear wheels. One of the advantages of disc brake is that the braking response is faster than drum brake. In addition, disc brake also provides more braking force compare to drum brake.

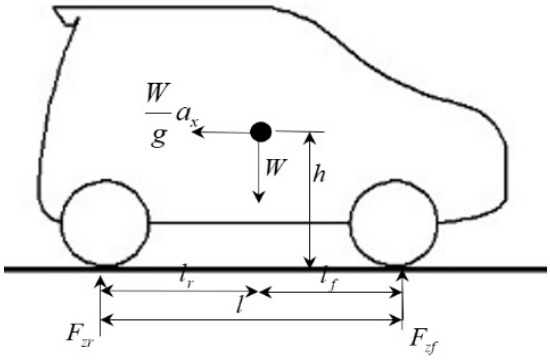


Figure 2. Free body diagram of the car on the level ground

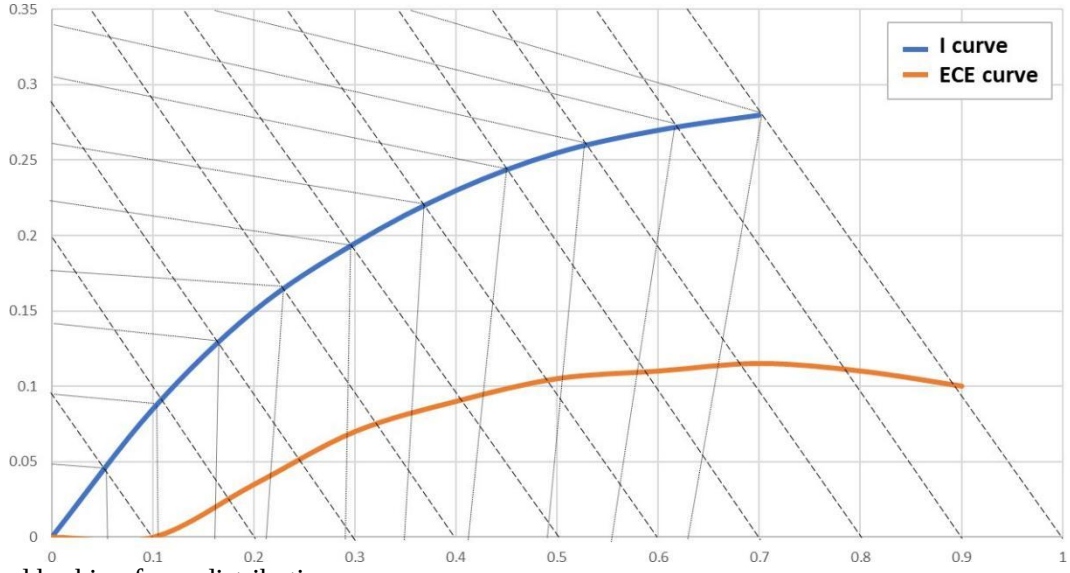


Figure 3. Ideal braking force distribution.

The relation of the front and rear braking force can be shown from the ideal braking force distribution curve, as shown in Figure 3. This curve, also known as *I*-curve, and is widely used as a reference in designing the braking control strategy. From Figure 3, the safe braking condition can be obtained when the total braking force is kept under the ideal braking curve [26, 27]. The best braking performance can be obtained if the front and rear wheels locked simultaneously. However, in reality, it is difficult to be performed. To maintain the direction and stability of the car, the front wheels can be locked earlier than the rear wheel.

EXPERIMENTATION

Experimental Vehicle and Instrumentations

The Malaysian national car, namely Proton Persona was used as the experimental vehicle model. The car is a sedan type with 1.6-litre engine capacity with a manual transmission. Several parts of the car have been modified to enable sensors, video and data acquisition system (DAS) to be attached at the vehicle. Figure 4 shows the experimental car and instrumentations. The general technical specifications of this instrumented car are shown in Table 1.

From Figure 4, it can be seen that the brake pedal force sensor is located at the back of the brake pedal. The build-in strain gauge is used in this sensor to measure the applied brake pedal force from the driver. The car is also equipped with a global positioning system (GPS) sensor, DEWE-VGPS-200C, to measure the velocity, distance and the course the car had travelled. The GPS is placed at the top of the car to detect the satellite as much as possible. To obtain consistent data, GPS must detect at least five satellites.

The tire angular speed is measured from the wheel pulse transducer. Kistler's wheel pulse transducer is used. This sensor is placed at the centre of the rim, which one rotation consists of 500 pulses. Then, by multiplying the tire angular speed with the tire radius, the linear velocity of the tire can be obtained.



Figure 4. Experimental vehicle and instrumentations.

Table 1. Main specifications of the vehicle.

Parameter	Value
Gross weight, *W*	1330 kg
Wheel-base, *l*	2.6 m
Front track, *df*	1.475 m
Rear track, *dr*	1.470 m
Height of centre of gravity, *h*	0.479 m
Wheel radius, *r*	0.297 m

Meanwhile, the tri-axial gyroscopic sensor is installed inside the car, and it is located at the car's centre of gravity. The model used in the experiment is MTi and MTx from Xsens Motion Technology. This sensor can provide the longitudinal, lateral and vertical acceleration or deceleration. Additionally, roll, pitch and yaw angles also can be measured from this sensor. During braking, the longitudinal deceleration and pitch angle are the desired data to be analysed because the longitudinal deceleration can pitch down the car.

The effect of the load transfer also can be seen from the displacement between the car's body and the lower arm. In order to measure the displacement, the wire potentiometer is tightening straight from the body to the lower arm. Wire potentiometer model SA-WP0225HQ-000 from 2D Debus & Diebold Meβsystem GmgH. If the load is transferred to the front, the wire potentiometer will be shortening and shows a negative value. In contrast, at the rear wheel, the wire potentiometer is extended and shows a positive value.

All the data from the sensors were acquired at frequency 500 Hz using the DAS from Dewetron. At this frequency, the DAS can capture the signal from the sensors at every 0.002 s. The DAS is integrated with the Dewesoft software for real-time data processing, display and recording.

Safety Precautions

The car is equipped with a basic passive and active safety system. The passive safety system of this car is the airbags and seat belts, while the active safety system is a hydraulic brake system. Without ABS, the safety of this car is considered low. Therefore, the experiment must be performed at the test track and under traffic control. Figure 5 shows the satellite view of the test track. From this figure, the total distance for the straight line is 288.18 m. The emergency braking experiment was performed at this lane. For the safety precautions, the track is closed for other vehicle, and it is controlled by the security officer.

The other safety precautions that have been considered are the driver. In the experiment, an expert driver from Automotive Engineering Center (AEC), Universiti Malaysia Pahang (UMP) drove the car. Two assistants at the rear seat recorded the data in the DAS. The assistant also reminds the driver when the car reaches the desired speed. Then, the driver maintained the speed for several seconds before stepping down the brake pedal firmly.



Figure 5. Satellite view of the test track.

Experimental Procedures

Before starting the experiment, the calibration is made in the DAS to set the initial value of each sensor. After calibration has been made, the driver starts driving the car. The experiment was performed after the rain stops to ensure the road is wet. The overview of the experimental procedures is shown in Figure 6. When the speed is approaching 60 km/h, the assistant in the rear seat starts recording the data and inform the driver to maintain the speed. The speed for the experiment was at 60 km/h, based on the limit for commercial vehicles on the federal state and state roads which is between 60 km/h to 80 km/h [28]. When the car reaches the initial braking point, the driver pushed the brake pedal firmly until the vehicle stops moving. The assistant checked all the acquired data and saved them in the DAS. The experiment was done three times to ensure the data acquired have a consistent result. Then, the raw data are filtered and denoised by using the Origin software. The smoothing method that has been used in this software is Savitzky-Golay.

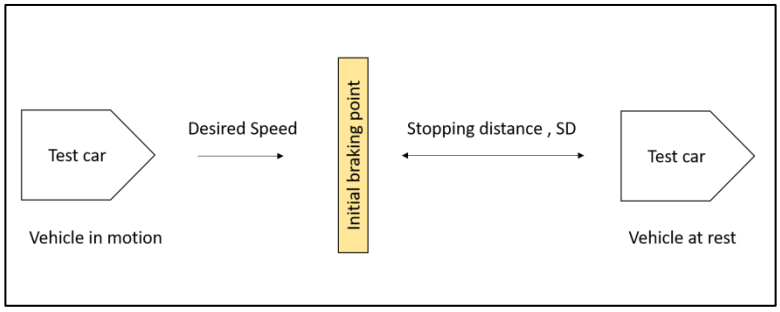
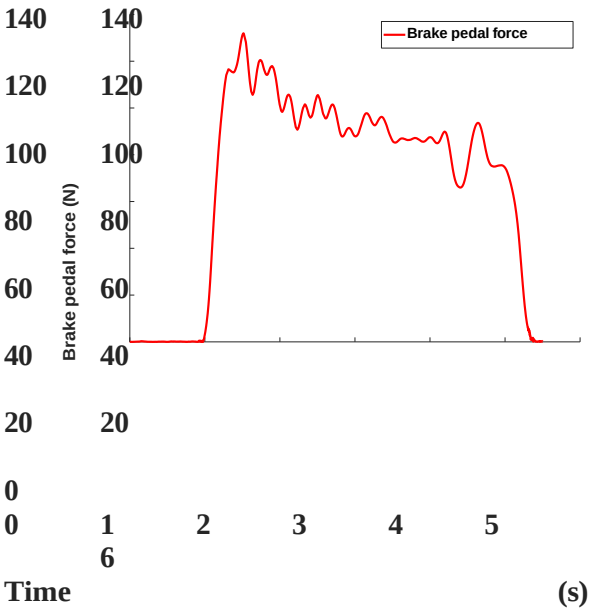


Figure 6. Overview of the experimental procedures.

RESULTS AND DISCUSSION

Effect of the Emergency Braking to the Brake Pedal Force

In this study, the brake pedal is input from the driver to the vehicle. The effect of the emergency braking on the brake pedal force for the wet and dry surfaces is shown in Figure 7(a) and 7(b) respectively. From Figure 7(a), it can be seen that the driver started to push the brake pedal firmly at 1 s. Due to the emergency braking, the brake pedal force increased rapidly to 135 N. From 2 s until 5 s the brake pedal force reduced gradually to 80 N. It is difficult to maintain the brake pedal force because the driver used his own feet to push the brake pedal. At 5 s, the driver started to release the brake pedal, and the brake pedal force decreased rapidly. Then, the brake force becomes 0 N at 5.5 s.


Brake pedal force
Brake pedal force (N)
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
Time (s)

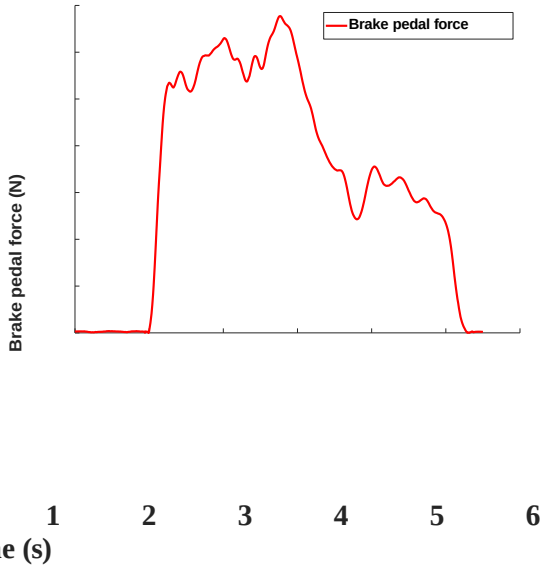

Brake pedal force
Brake pedal force (N)
0
0
1
2
3
4
5
6
Time (s)

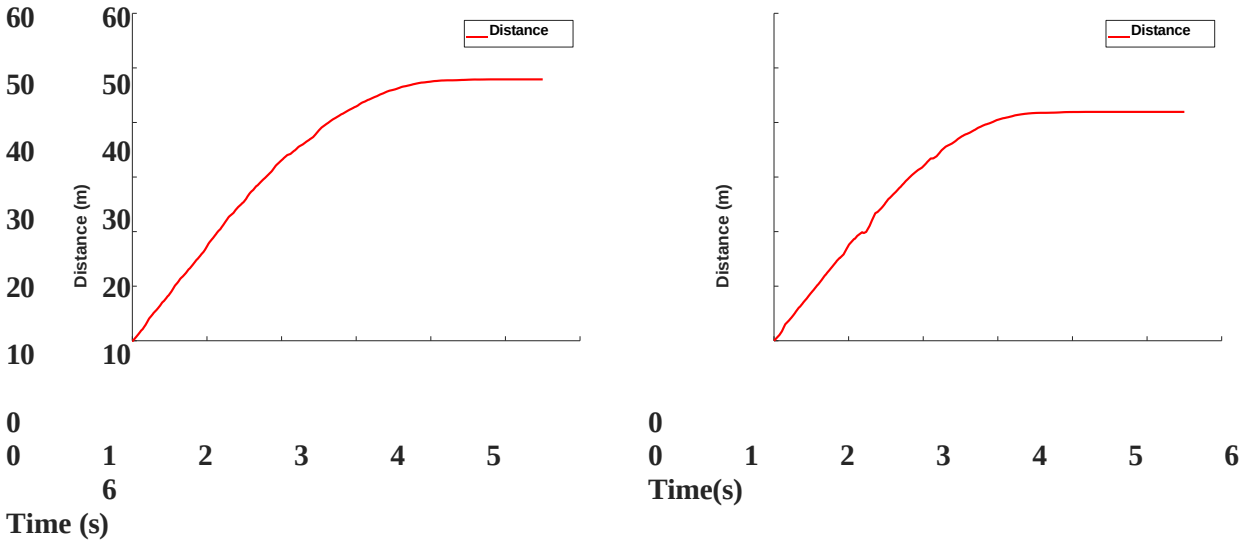
Figure 7. Braking pedal force during emergency braking for (a) wet surface and (b) dry surface condition.

The pattern of emergency braking on the dry surface is slightly different from the wet surface. In Figure 7(b), there are two peaks of the brake pedal. The first peak is when the driver starts to press the brake pedal at 1 s. At this moment, the brake pedal force increased rapidly to 110 N due to emergency braking applied by the driver. Then, the brake pedal force keeps increasing gradually to 140 N until 2.8 s. However, starting from 2.8 s until 3.8 s, the brake pedal force decreased from 140 N to 50 N. The amount of brake pedal force is based on the judgment by the driver. As a safety precaution, if the driver feels sudden changes in the vehicle dynamics motion, the driver released the brake pedal force. At 2.8 s, the driver released the brake pedal slightly to mitigate any collision. At 3.8 s, the brake pedal force increased again to 60 N and maintained at the range of 60 N to 50 N until 5 s. When the driver released the brake pedal at 5 s, the brake pedal force decreased rapidly to 0 N.

Effect of the Emergency Braking to the Vehicle Dynamics Behaviour

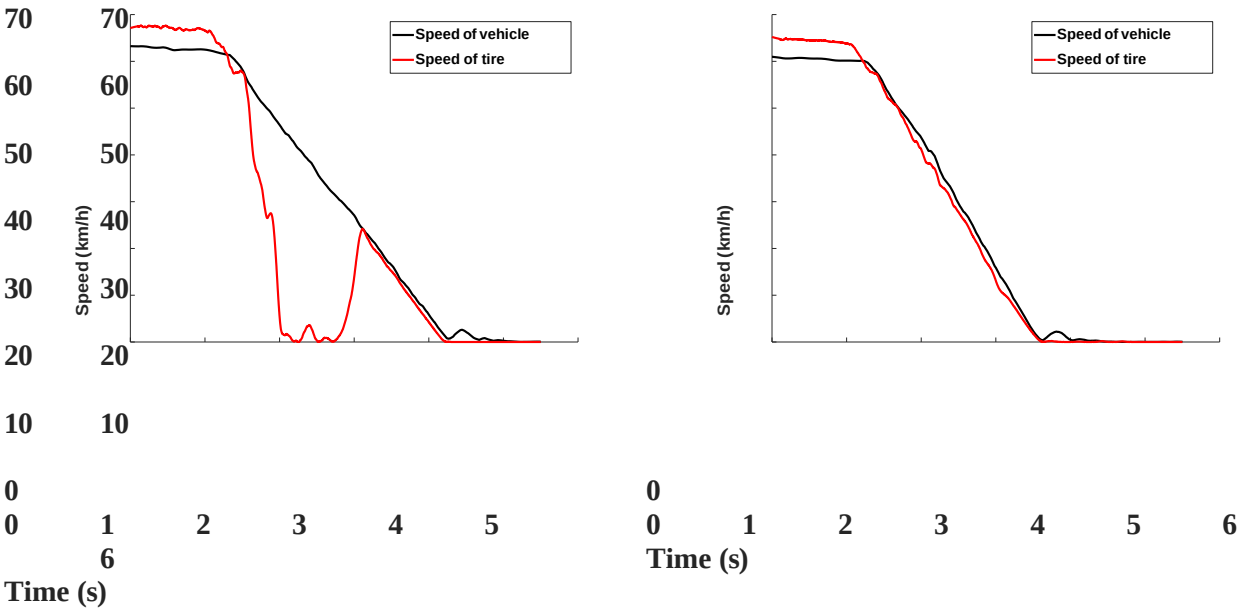
The travelled distance of the vehicle can be measured from the GPS sensor. In the analysis of stopping distance, the initial and final braking time needs to be identified. The date of brake pedal force in Figure 7(a) and 7(b) is used as a reference for applied braking time. From Figure 7(a), the initial and final braking time for wet road condition is at 1 s and 5 s respectively. Based on Figure 8(a), at time of 1 s, the travelled distance is 17 m, while at 5 s, the travelled distance is 48 m. Then, the stopping distance of the vehicle during emergency braking on a wet surface is 31 m.

For dry road condition, the initial and final applied braking time is taken based on Figure 7(b). The recorded initial and final braking time are at 1 s and 5 s respectively. From Figure 8(b), at time of 1 s, the travelled distance is 17 m, while at 5 s, the travelled distance is 41 m. The total braking distance for the dry road surface is 24 m, which is 7 m shorter than the wet surface. Due to the low friction coefficient on the wet surface, the capability of the tire to grip reduced [12]. As a result, when emergency braking applied on a wet surface, the possibility of the tire to lock-up increased. The effect of emergency braking to the wheel speed can be seen in Figure 9(a) and 9(b).



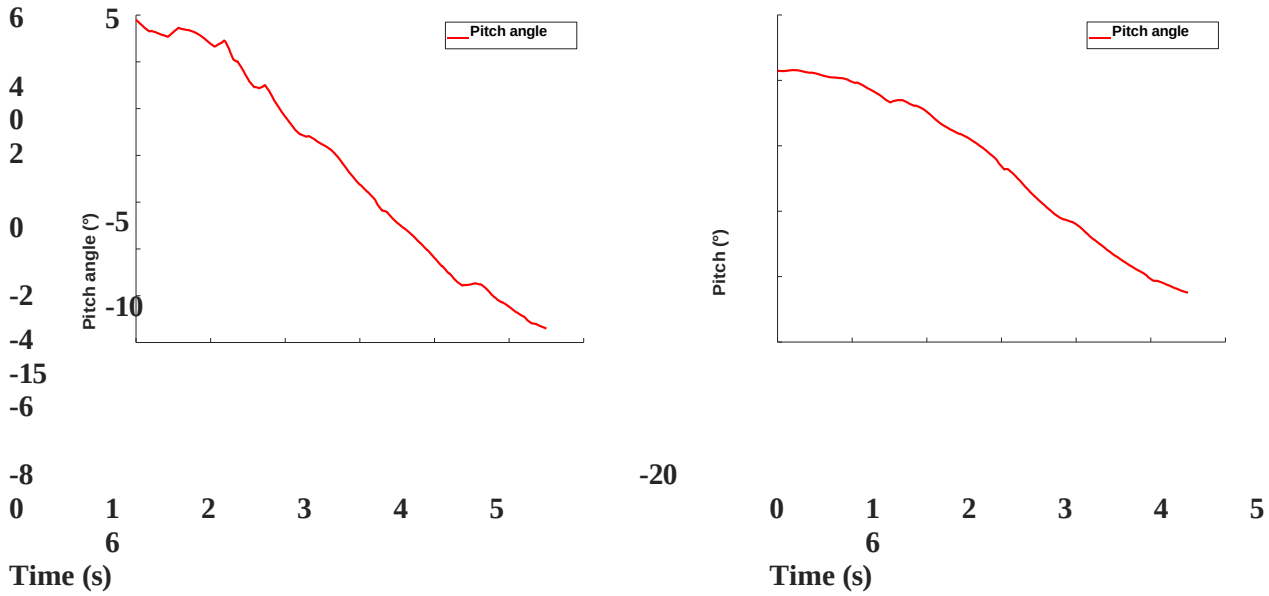
(a) (b)

Figure 8. Travelling distance by the car for (a) wet surface and (b) dry surface condition.



(a) (b)

Figure 9. Speed of the car and wheel during emergency braking for (a) wet surface and (b) dry surface condition. Figure 9(a) shows the velocity of the car and wheel during emergency braking on the wet surface. As illustrated in
Figure 9(a), before the driver pushes the brake pedal, the speed of the car maintained at 63 km/h, while the speed of the wheel was kept at 67 km/h. This is a traction phase when the speed of the wheel is larger than the speed of the car. Starting from 1 s, when the emergency braking is applied, the velocity of the car reduced gradually to 0 km/h. On the other hand, the speed of the wheel is decreased rapidly to almost 0 km/h at 2 s. The tire locked also can be observed from 2 s until
2.7 s. Then, from 2.7 s until 3.1 s, the wheel speed increased to 23 km/h and close to the speed of the car. After 3.1 s, the speed of the car and wheel decreased gradually. The results show when the driver applied emergency braking on wet surface condition, the tire locked-up and slipped. This phenomenon can reduce the stability of the vehicle and increase the risk of an accident [8].
On the other hand, for the dry road condition, the speed of the wheel and vehicle decreased gradually. Before the driver steps down to the brake pedal, the vehicle is in a driving condition. Due to the driving torque from the engine to the wheel, the speed of the wheel is greater than the speed of the vehicle. At 1 s, when the driver pushed the brake pedal, the wheel and vehicle's speed decreased gradually to 0 km/h. In this condition, the vehicle's speed is greater than the wheel's speed due to the braking torque applied at the wheel. Although emergency braking is applied to the vehicle, no tire slip phenomenon observed. Thus, emergency braking on a dry surface is safer than the wet surface.
In order to analyse the stability of the car during emergency braking, the data of pitch angle is plotted as in Figure 10. For wet surface condition in Figure 10(a), before braking, the pitch angle of the car decreased slightly from 5.8º to 4.7º. However, after 1 s, when the driver steps to the brake pedal firmly, the pitch angle decreased by 12º, which is from 4.7º to -7.3º. This result means that the car dived forward due to the longitudinal load transfer from the rear to the front wheels. The effect of pitch angle during emergency braking on a dry surface can be seen in Figure 10(b). Before the driver steps on the brake pedal, the pattern of pitch angle almost same to the wet surface. Due to the constant speed until 1 s, the pitch angle slightly decreased from 0.7º to -0.1º. However, after 1 s, when the driver steps on the brake pedal firmly, the pitch angle decreased by 16, which is from -0.1º to -16.1º. Although the tire on dry asphalt is not locked up, the pitch angle is greater than the wet surface due to the longitudinal acceleration. As discussed on the speed of the wheel and vehicle for wet and dry conditions in Figure 9(a) and 9(b), the stopping time for dry asphalt is shorter than the wet road surface. This is the reason for the acceleration on dry asphalt greater than the wet surface. When the acceleration is
increasing, more load is transferred to the front wheel and pitch angle increased [12, 22, 26].

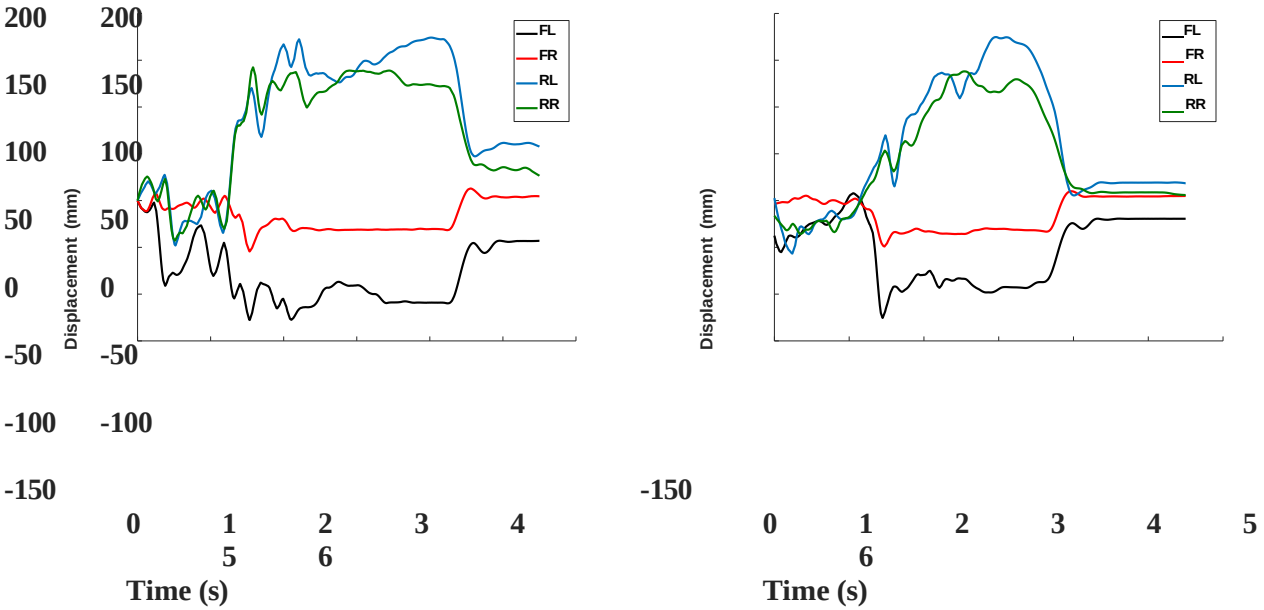


(a) (b)

Figure 10. Pitch angle of the vehicle during emergency braking for (a) wet surface and (b) dry surface condition.

By using the displacement sensor, the effect of the load transfers to the stability and ride comfort of the vehicle can be determined. This sensor used a wire potentiometer to measure the vertical displacement of the suspension. The wire potentiometer can be elongated or shortened based on the load transfer to the wheel. From Figure 11(a), for the wet surface, when the brake pedal force is applied at 1 s the displacement for both rear right and left suspension (*rr*, *rl*) increased rapidly to positive value; which is from 0 mm to 100 mm. Then, the displacement for both rear tires was maintained at 100 mm to 160 mm until the driver released the brake pedal at 4.5 s. In contradiction, the displacement for the front right and left suspension (*fr*, *fl*) decreased rapidly to the negative value, which is from 0 mm to -100 mm. The displacement then maintains at -130 mm to -40 mm until 4.5 s. From these results, the positive value means that the wire potentiometer elongated, while the negative value means the wire potentiometer shortened. From these results, it can be understood that during emergency braking, the load transfers to the front wheel.

For the dry surface, the effect of load transfer to the suspension is the same with the wet surface. As shown in Figure 11(b), when the braking force is applied at 1 s, the displacement of the rear wheel is increased from 0 mm to 125 mm. Then, the displacement is maintaining at 125 mm to 160 mm until the driver releases the brake pedal at 4 s. On the other hand, the displacement at the rear wheel decreased from 0 mm to -100 mm when a driver steps to the brake pedal at 1 s. Then, the displacement is maintained at -100 mm to -40 mm until the driver releases the brake pedal. From the displacement results at wet and dry asphalt, the displacement value for both road conditions is almost similar. Due to the load transfer from rear to the front wheels, the wire potentiometer at front wheels is shortened, while the rear wheels are elongated. Although the displacement for wet and dry asphalt is not too significant, the anti-dive suspension can be used to increase the stability and ride comfort of the vehicle [10].



(a) (b)

Figure 11. Displacement of each suspension during emergency braking for (a) wet surface and (b) dry surface condition.

CONCLUSION

The vehicle dynamics behavior during emergency braking on a wet surface without ABS was examined in this research. The vehicle's longitudinal, lateral, and vertical movements were all taken into account in the thorough examination. The car's velocity, tire rotational speed, and path traveled—which is 7 meters longer on the wet surface than the dry—all demonstrate how an emergency brake affects longitudinal motion. In the meanwhile, the influence at the lateral motion may be seen from the pitch angle, which indicates that the weight transfer from the rear to the front is more than 4º on the dry surface. The general motion used in the growth of the ABS is longitudinal and lateral. Nonetheless, this investigation also looked at how each wheel was affected by vertical motion. When braking in an emergency, the

The car's longitudinal deceleration quickly altered. The car moved forward as a consequence of the increased load being shifted from the back wheels to the front wheels. The impact of the load transfer may be readily seen by employing the displacement sensor at each lower arm. This research may aid in the development of anti-dive suspension in addition to analyzing vehicle behavior during emergency braking. The importance of ABS may be recognized from the thorough investigation of how emergency braking without ABS affects the dynamics behavior of the vehicle. Furthermore, the findings may serve as a basis for the validation of the whole vehicle model and aid in the advancement of anti-dive suspension.

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