INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 17, ISSUE 1, 7832 – 7841
DOI: https://doi.org/10.15282/ijame.17.2.2020.02.0583

ORIGINAL ARTICLE

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

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ABSTRACT – An anti-lock braking system (ABS) is a basic skid control system that can prevent the tire from locking up. In an emergency braking situation, a high possibility that the skidding phenomenon can occur without ABS. This incident become worse when an emergency braking is applied either on wet or dry surfaces. Although ABS is crucial to prevent the collision, some vehicles still do not have ABS. This study is aimed to analyse the vehicle's dynamic behaviour during emergency braking on wet and dry surface condition. The experimental vehicle model is a Malaysian sedan car namely Proton Persona. This instrumented car is equipped with sensors, video camera and data acquisition systems to determine the vehicle's motion. In the experiment, when the vehicle reached a maximum speed of 60 km/h, the driver push the brake pedal firmly until the car stop. From the experimental results, the effect of emergency braking without ABS is clearly seen at the wheel speed. The tire locked up can be observed when emergency braking was applied on the wet surface. However, for the emergency braking on the dry surface, the tire decreased gradually. This finding shows that without ABS, the vehicle is unsafe and accident can occur. The experimental data from this study also can be used as a guideline to a researcher and manufacturer in the development of ABS and safety system of the vehicle.

ARTICLE HISTORY
Revised: 26th Feb 2020
Accepted: 28th Mar 2020

KEYWORDS
Anti-lock braking system (ABS).
Emergency braking,
Vehicle dynamics,
Slip ratio, Safety system

INTRODUCTION

According to the Road Safety Report by the World Health Organization (WHO), road accidents in Malaysia contributed to 25 deaths per 100,000 populations [1]. Besides, these accidents also caused an economic impact when Malaysia lost an average of RM6.45 billion from 2010 (RM5.94 billion loss) to 2014 (RM6.77 billion loss per year) [2]. Besides that, the fatalities in the road collision also impact the emotional and financial burden on society [3].

Several factors cause road accidents such as risk-taking behaviours, inexperience and lack of skill [4]. W. Vanlaar and G. Yannis stated that vehicle (e.g. size, brakes, stability), road (e.g. geometry, surface, intersections) and traffic (e.g. volume, speed, gaps) are the situational stimuli to the driver behaviour [5]. In order to enhance road safety, the advanced safety vehicle system is introduced to the vehicle. This safety system consists of two parts; a passive vehicle safety system (PVSS) and an active vehicle safety system (AVSS). The PVSS, such as seat belts and airbags, can reduce the impact and minimise injury to the occupant. While the AVSS, like advanced driver assistant system (ADAS), can prevent crashes by giving warning signals and even manoeuver the vehicle if the driver does not respond to the warning [6].

Although the active safety system is crucial for the vehicle, the cost to install is expensive and some of the cars just equipped with the minimum active safety system. One of the basic safety systems and mandatory for any vehicles is the braking system. When the driver steps down the braking pedal, the braking force is created at the wheel to reduce the speed and stop the vehicle [7]. If too much braking force is applied, the tire lock up and the skidding phenomenon can occur [8]. Moreover, it will become more severe when braking on the slippery road surface.

An anti-lock braking system (ABS) is introduced for aircraft in 1930 to prevent the wheel lock up and to reduce the stopping distance [9]. In the 1980s, due to the rapid development of electronics, sensors and microprocessors, the ABS is quickly becoming compulsory for cars [10]. Besides preventing the wheel from locking, ABS also can keep the car steerable and allow the driver to manoeuver the car in the safe area [11].

The sweet-spot in the slip-friction graph is used in the designing of an ABS controller. Based on the sweet-spot, there is an optimum point where the maximum friction for the tire to grip on the road can be obtained [12]. The challenge of developing an ABS controller is the uncertainties parameters of the vehicles as well as the road surface. As can be seen from the slip-friction graph in Figure 1, the friction coefficient reaches a maximum value at a certain slip ratio, then decreases with the increase of the wheel slip [13]. Furthermore, the road surface also affects the relationship between the slip ratio and the friction coefficient.

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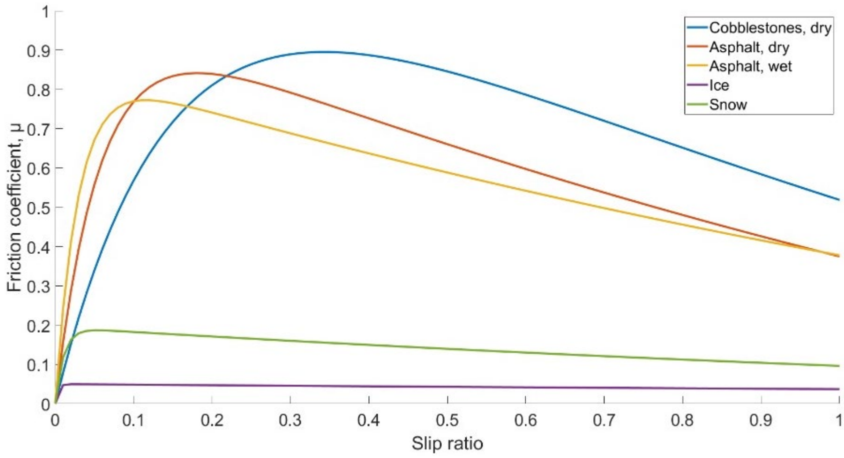


Figure 1. Slip-friction curve for different road surfaces at a linear speed of 10 m/s [12].

A robust controller for ABS is necessary to overcome the uncertainties. Fuzzy control method, neural network and sliding mode control are the robust control strategies that had been implemented in the ABS controller. A study from G. Fargione et al. have proved that the optimisation of the Fuzzy control can avoid the braking pressure from going over the stable region. The Fuzzy strategy is optimised with the genetic algorithms (GAs) to build its own braking pressure control cycle. The simulation result shows that the braking pressure is near to the ideal braking pressure at any surface [14]. A.B Sharkawy also has combined the Fuzzy with genetic algorithms (GAs). A self-tuning PID controller is added at the Fuzzy and GAs to deal with the effect of the nonlinear dynamics (e.g. weight, the friction coefficient of the road, road inclination) to the performance of ABS. From the simulation results, by using the Fuzzy self-tuning scheme with GAs, the fast response with low overshoot and short stopping distance are obtained [15].

Mirzaeinejad has proposed the study of the neural network as a robust controller for ABS. He has designed the radial basis function neural network (RBFNN) to obtain good robustness for ABS controller. By using the Lyapunov function, the unknown parameter in the system dynamics can be determined. The simulation results show that RBFNN can reduce the wheel slip tracking error. In addition, RBFNN also can perform as an accuracy tracker and prevent the oscillation of the braking torque [11]. Poursamad also using neural network for the ABS controller. An adaptive neural network-based hybrid controller for ABS is proposed to achieve the desired performance under various road conditions. The hybrid controller consists of a feedback linearisation controller and two feedforwards neural network. The simulation results show the robustness of the proposed controller to the external disturbances [16].

The other robust control strategy for ABS is a sliding mode control (SMC). According to Tang et al., SMC is a preferable controller for ABS due to its robustness against parameter variations and external disturbances [13]. Shim et al. have investigated the effect of sliding surface design on the performance of SMC in ABS. By using 8 degrees of freedom (8-DoF) nonlinear vehicle model, they have simulated an alternative sliding surface design for an SMC. The simulation results show that the proposed sliding surface design can improve the oscillation damping around the optimum slip ratio [17].

Patil et al. have reported that designing and implementing robust control strategies on a vehicle is both expensive and time-consuming. Therefore, many researchers work on computer simulations [9]. A simulation has been done in order to analyse the dynamic behaviour of the vehicle with ABS enable and disable on different road conditions. With ABS enable or active, the stopping distance is improved by 28% compared to without ABS. The vehicle also not experiencing skidding with the ABS enable on wet road condition [18]. In order to validate the proposed control strategies and ABS algorithm, some of the researchers take the approach on a laboratory ABS setup. Inteco Ltd. has set up an ABS workbench, and the validation results for Fuzzy control, neural network and sliding mode controller are seen in [19-23].

From the literature, it may be noted that most of the work on ABS is done in computer simulation techniques. There are two approaches to develop the vehicle dynamics model; first is known as the multi-body method to generate the equation of motion, and the second approach is known as the simplified modelling. A report from Ahmad et al. stated that the reliability of the result from the simulation is considered impractical until the model is fully validated using the actual vehicle data [24]. Therefore, the preliminary experiment to analyse the vehicle dynamics behaviour without ABS is essential. From this study, the researcher can determine the response of the car without ABS and validate their modelling. After validation, the proposed ABS controller can be added in the modelling, and the result is more reliable.

In this paper, an experiment was conducted to analyse the dynamic behaviour of a car during emergency braking on wet and dry surfaces. Although there is a considerable number of studies on ABS control, certain parameters such as braking force, suspension displacement and tire stiffness are influenced by the types of the car and the individual driving skill. The objective of this study is to provide a detailed analysis of the effect of emergency braking without ABS on the vehicle response. In addition, the findings from this study also significantly contribute as a guideline to the researcher and manufacturer in the development of ABS and active safety system of the vehicle. The instrumented vehicle model is a sedan car that is not equipped with 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]:

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

$$Fr = W\left(\frac{l_f}{l} + \frac{a_x}{g}\frac{h}{l}\right) \tag{2}$$

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.

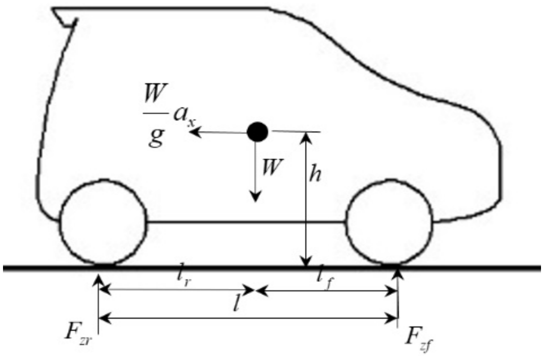


Figure 2. Free body diagram of the car on the level ground

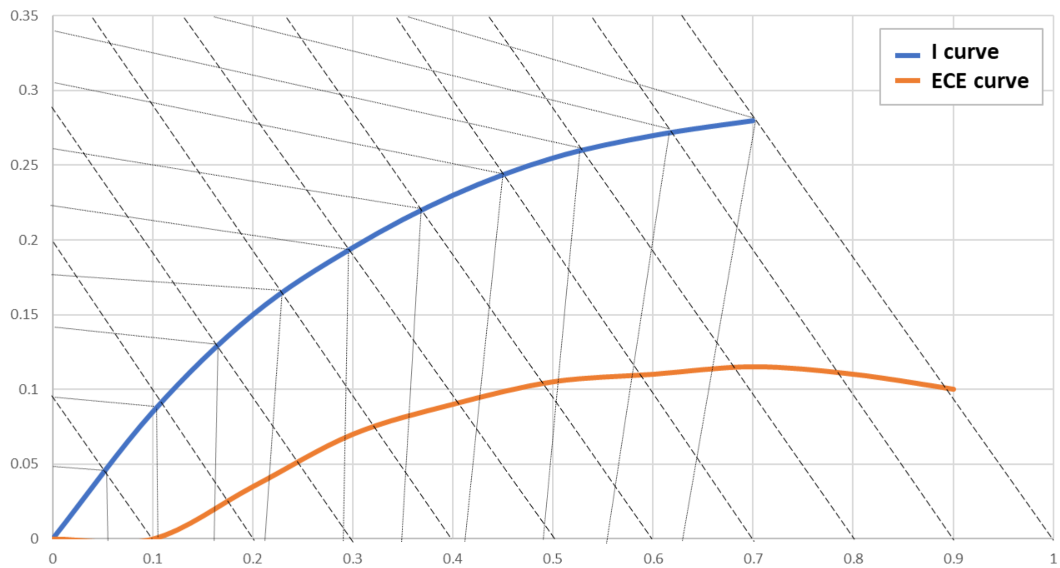


Figure 3. Ideal braking force distribution.

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, d_f	1.475 m
Rear track, d_r	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.

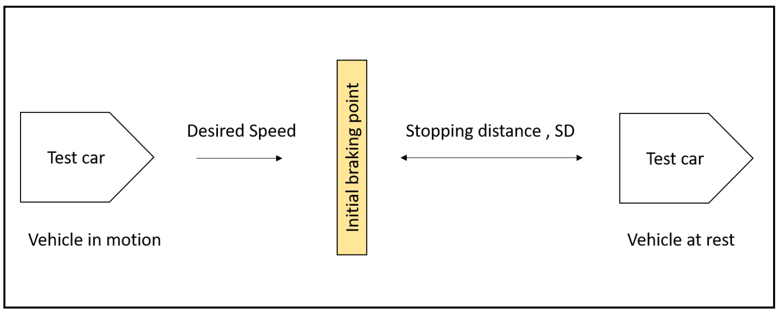


Figure 6. Overview of the experimental procedures.

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.

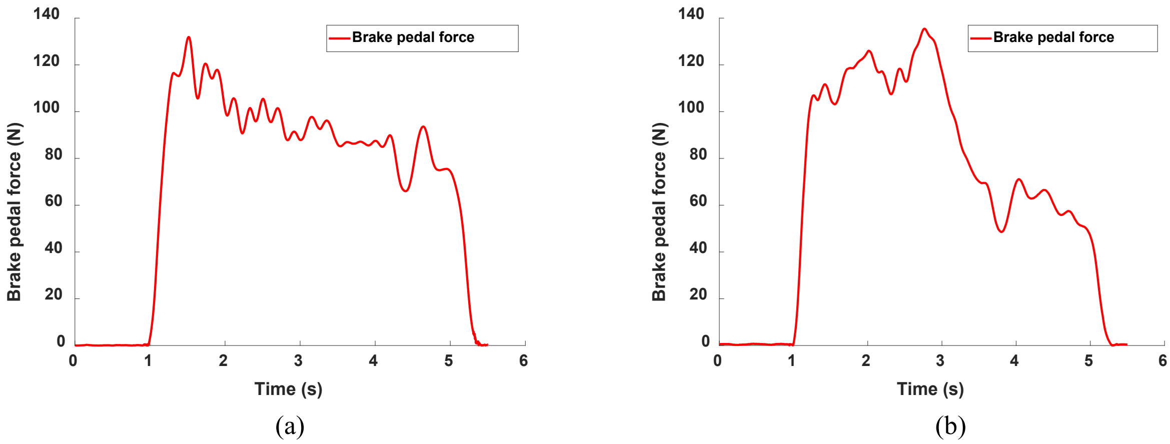


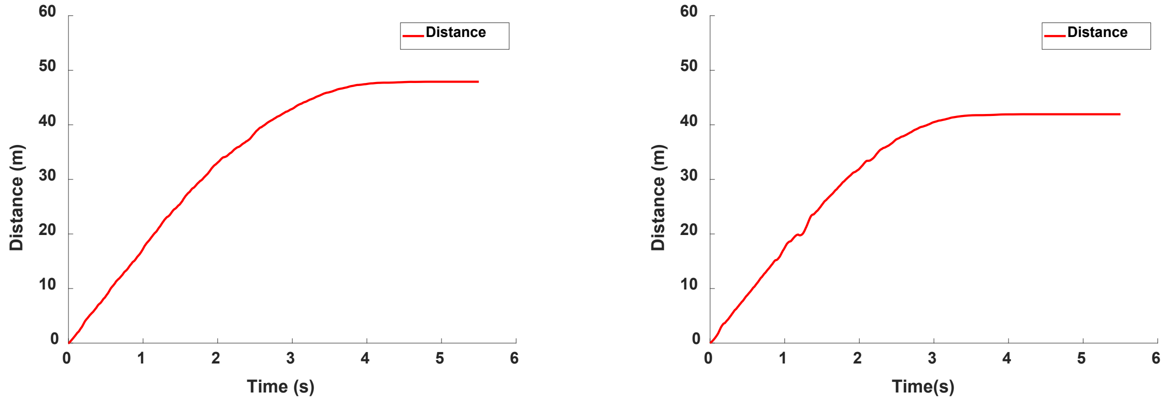
Figure 7. Braking pedal force during emergency braking for (a) wet surface and (b) dry surface condition.

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

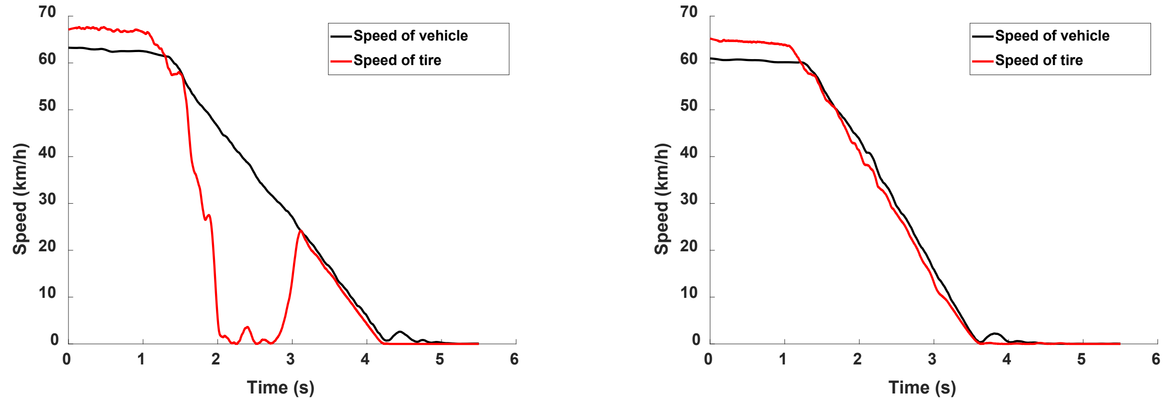
The travelled distance of the vehicle can be measured from the GPS sensor. In the analysis of stopping distance, the initial and final braking time needs to be identified. The date of brake pedal force in Figure 7(a) and 7(b) is used as a reference for applied braking time. From Figure 7(a), the initial 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)

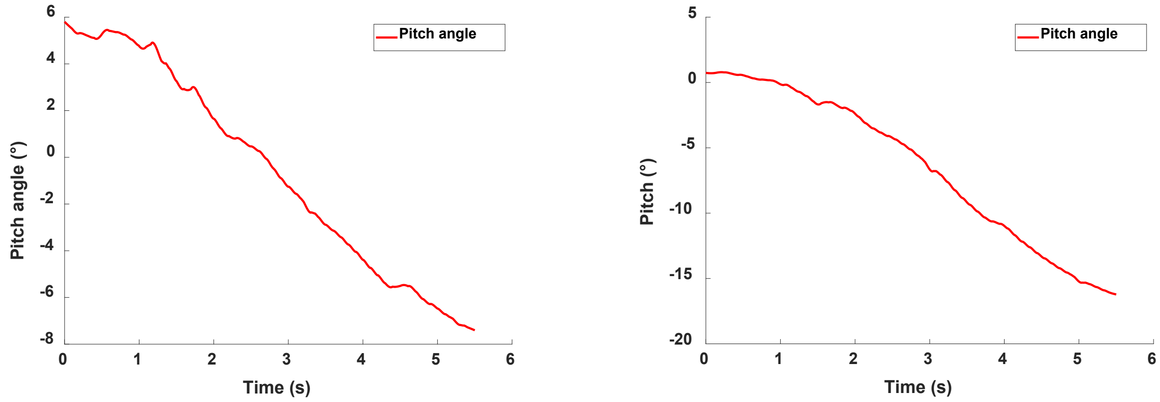
Figure 9. Speed of the car and wheel during emergency braking for (a) wet surface and (b) dry surface condition.

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].

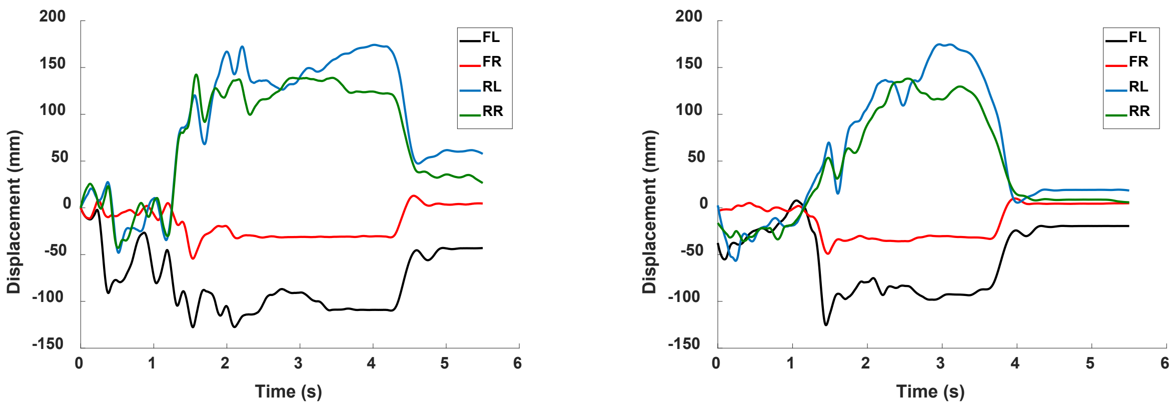


(a) (b)

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

In this study, we analysed the vehicle dynamics behaviour during emergency braking on the wet surface without ABS. The comprehensive analysis considered the longitudinal, lateral and vertical motions of the vehicle. The effect of an emergency braking to the longitudinal motion can be seen from the car's velocity, the tire rotational speed and course travelled that is 7 m longer on the wet surface compared to the dry surface. Meanwhile, the effect at the lateral motion can be seen from the pitch angle which shows that on the dry surface, the load transfer from the rear to front is more 4° than on the wet surface. The longitudinal and lateral motions are the general motion that is used in the development of the ABS. However, this study extended to the effect at the vertical motion on each wheel. During emergency braking, the longitudinal deceleration of the car changed abruptly. As a result, more load is transferred from rear wheels to the front wheels, which caused the vehicle to drive forward. By using the displacement sensor at each lower arm, the effect of the load transfer can be seen clearly. Besides analysis of vehicle behaviour during emergency braking, this study can contribute to the development of anti-dive suspension. From the comprehensive study on the effect of the emergency braking without ABS to the vehicle dynamics behaviour, the essential of ABS can be acknowledged. In addition, the results also can be as a guideline for the validation of the full vehicle model and contribute to the development of anti-dive suspension.

ACKNOWLEDGEMENT

The authors would like to thank the Ministry of Higher Education Malaysia for financial support through the Fundamental Research Grant Scheme FRGS/1/2016/TK03/UMP/02/2, RDU160138. Special thanks to Automotive Engineering Center, Universiti Malaysia Pahang (www.ump.edy.my) for providing test car and technical support.

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