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Implementation of four-wheel antilock braking system for commercial vehicle using bang-bang controller

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Abstract
The need for safety equipment that can prevent the wheels of a vehicle from locking up under emergency or harsh braking conditions has prompted the need for the Anti-Lock Braking System (ABS). However, The Anti-Lock Braking System helps the driver to maintain steering ability and also to avoid skidding while braking. This paper proposes an implementation of a four-wheel antilock braking system (ABS) for vehicle speed estimation using a Bang-bang controller. This will provide greater vehicle stability and control during lock-up to the drivers, reduce stopping distance, and most importantly reduce the collision rate to a lower percentage. The simulation was carried out using MATLAB/SIMULINK to achieve the desired slip ratio with the control scheme using the Bang-Bang controller. Graphs of velocity speed, rotational speed, stopping distance, braking torque for a system without an anti-lock braking system and Bang-bang controller was plotted and compared with each other. The performance of vehicle braking Bang-Bang controller was analysed with Bang-Bang controller mode and the result shows that the ABS with Bang-Bang controller will significantly help the driver to steer while braking heavily and could prove to be lifesaving.

Keywords: Anti-Lock braking system, bang-bang controller, Simulink, wheel slip

Introduction

The advancement in technology has led to an increase in the number of vehicles and automobile users daily. This prompted the need for an efficient braking system to prevent accidents. Skidding of the tires during braking input and cornering is regarded as the main cause of automobile accidents [1]. However, the implementation of an efficient antilock braking system cannot be possible without sufficient knowledge about vehicle dynamics and the relationship between the coefficient of frictional force between the road surface and the tire. Consequently, the anti-lock braking system is a safety system in cars and other automobiles that keeps their wheels from locking up and helps the drivers to maintain steering control [2]. Anti-Lock Braking System is a piece of safety equipment that prevents the wheels of a vehicle from locking up under emergency, panic, or harsh braking conditions. The brain of the anti-lock braking system consists of Electronic Control Unit (ECU), brake master cylinder, wheel speed sensor, and hydraulic modulator with pump and valve [3, 4].

It should be recalled that the first motor-driven vehicle was developed in 1769, a year after the first accident was recorded [5]. This led to the invention of a mechanical ABS that can prevent vehicle accidents, it is alarming that despite the advancement in vehicle safety technology, automobile accidents continue to rise globally [6]. World Health Organization [7] stated in their report that a total of 1.35 million automobile accidents occurred every year.

This paper intends to explain the physics behind the modeling of an antilock braking system with germane information on the Simulink block component that will aid the modeling on MATLAB. Though the phenomenal obey laws of motion, however, many empirical constants/relations make the work technical.

The Antilock Braking System (ABS) was introduced in the 1950s to minimise the stopping distance and also enhance the ability to steer the vehicle and has become conventional equipment for all latest automobiles in many nations [8, 9, 10], and the first ABS set implemented in an airplane was on a Boeing B47 to prevents spinouts and tires from blowing, while the two major types of control strategies in ABS are Acceleration control based and the Slip control based [11, 12]. Hence, the acceleration control base indirectly controls the slip using wheel deceleration/acceleration computed from the wheel angular velocity measurements, which its major drawback is the vibrations experienced during braking. While the slip control-based method involves keeping the actual slip rate on optimal target slip using continuous control during braking [13]. Various researchers have suggested different control approaches for designing the ABS controller. Most of the current mass production ABS controllers are rule-based as ABS has been acclaimed as providing significant improvement to overall vehicle safety. To prevent wheel lock-up, ABS helps the driver to maintain steering control during emergency braking and can also reduce stopping distances on some slippery surfaces. The braking system is a critical safety component of a vehicle [14]. However, the Bang-bang controller also known as a hysteresis controller is a feedback controller that switches abruptly between two states. Most common residential thermostats are bang–bang controllers. Fig. 1. Displayed the block diagram of the antilock braking system which shows the relationship between modulator, dynamics, and controller.

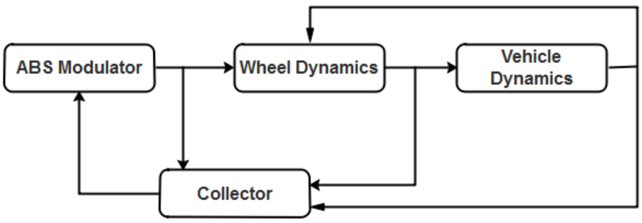

Fig 1: Block Diagram of Antilock Braking System

Methodology

The focus of this design set out to examine the effectiveness of ABS in reducing commercial vehicle occupant injury risk and severity by using a Bang-bang controller to enhance the braking performance of ABS In commercial vehicles [15]. The design examined the dynamic solution of the quarter car vehicle model to obtain the time-varying vehicle velocity and wheel.

A. System Model

If the vehicle in Fig. 2 is moving in a straight direction under braking conditions, equations of equilibrium can be deduced as follows:

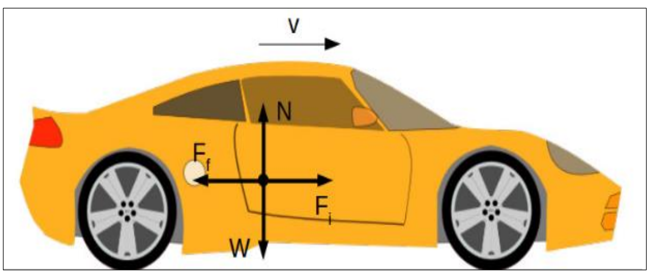

Fig. 2: Acting forces during vehicle braking [16]

Let Fr be a Frictional force
Fi be an inertial force
Mv be mass of the Vehicle
N be the normal reaction
W be the weight of the car

$$F_r = \mu * N \quad (1)$$
$$N = W = M_v * g \quad (2)$$
$$F_r = \mu * M_v * g \quad (3)$$

Where

$$F_r = F_i \text{and } F_i = M_v * a_v \quad (4)$$

$$\text{Hence, } M_v * a_v = \mu * M_v * g \quad (5)$$

$$M_v * \frac{dV_v}{dt} = \mu * M_v * g \quad (6)$$
$$\frac{dV_v}{dt} = \frac{1}{M_v} \mu * M_v * g \quad (7)$$

Meanwhile, we can also define a variable called the angular velocity of the vehicle, though the vehicle is not moving in a circular as;

$$V_w = \frac{V_v}{r_w} \quad (8)$$
$$thus \frac{dV_w}{dt} = \frac{1}{r_w} * \frac{1}{M_v} \mu * M_v * g \quad (9)$$

This means if we know the frictional force on the vehicle, the equation above will tell us the velocity of the vehicle.

Equation during application of braking

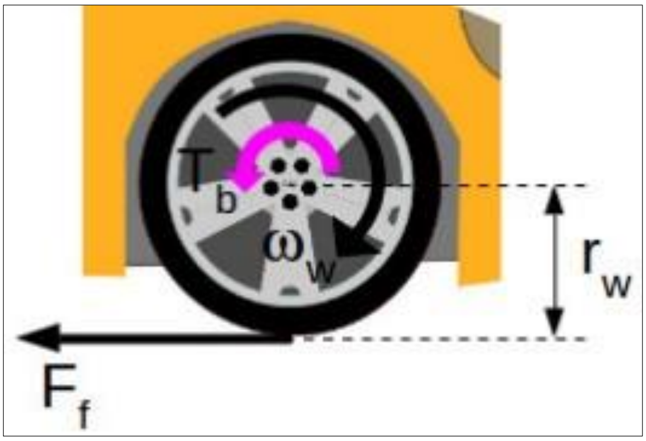

Fig 3: Acting forces during wheel braking [16]

Also, we can derive the equation of motion of the vehicle during braking, keeping in mind that, the inertial force (which is equal but in opposite direction to the frictional force) will have a moment about the center of the wheel (tire) and will tend to move the vehicle forward while the braking torque from the hydraulic will act in opposite direction. During braking, the driver applies a braking torque T_b to the wheels, while the friction force F_f [N] between the wheel and road creates an opposite torque with the wheel radius r_w [m] [17]. For true braking (i.e reduction in speed that can bring the vehicle to stop), the braking torque must exceed the friction torque. Taking moment about the center of the wheel, we can write the following equations and derive the wheel's angular acceleration and velocity.

$$T_{net} = T_b - T_f \quad (10)$$

However, since $T_b > T_f$, we can simply write and we have already taken the positive direction to be in that of the braking torque,

$$T_{net} = T_b - F_r * r_w \quad (11)$$
$$T_{net} = T_b - \mu * M_v * g * r_w \quad (12)$$
$$T_{net} = j * a_w \quad (13)$$
$$j * a_w = T_b - \mu * M_v * g * r_w \quad (14)$$
$$a_w = \frac{1}{j}\{T_b - \mu * M_v * g * r_w\} \quad (15)$$
$$\frac{dw_w}{dt} = \frac{1}{j}\{T_b - \mu * M_v * g * r_w\} \quad (16)$$

Equations 1 and 2 above are the fundamental equation of the vehicle and they show that the vehicle velocity and wheel velocity are two independent quantities that are not function of one another, the two are separately determined by the coefficient of friction. However, an important property of a car during braking is called slip rate S, which is defined to measure the degree of loss of velocity between the vehicle and the wheel introduce either intentionally by the braking system or unintentionally by the environmental condition.

$$S = \frac{\text{velocity loss}}{\text{normal velocity}}$$

$$S = \frac{\Delta v}{\Delta V_O} \quad (17)$$
$$S = \frac{(w_v - w_w)}{w_v} \quad (18)$$
$$S = 1 - \frac{w_w}{w_v} \quad (19)$$

B. System Illustration

The friction (μ) between the tire and the road is equal when created by relative movement between their two surfaces, i.e. difference in surface speeds, and this is called 'slip' (λ), which is normally expressed as a percentage of 0% slip means that the surface speed of the tyre and the road are equal. 100% slip braking means that the wheel has stopped rotating.

The level of friction depends on the condition of the tyre and the road surface and the percentage of 'slip' between the tire and the road.

Fig 3 shows how the friction available for cornering falls dramatically when the wheel starts to lock due to braking. The inability of a wheel on a steering axle to transmit lateral (cornering) force means that the vehicle will no longer be under the full directional control of the driver. The wheels must be prevented at all times from locking under braking conditions to maintain the stability of the vehicle.

C. MATLAB / Simulink Modelling

Fig. 4 shows the block diagram of a Simulink model of a bang-bang controller for an antilock braking system. Where a bang-bang controller uses the slip error signal as input to know the required brake force needed to minimise excessive slip and also avoid locking of the wheels.

These controllers switch between the minimum and maximum value when a certain set point is reached whereas Fig. 5 and Fig. 6 showed the Simulink model for wheel dynamics and vehicle dynamics respectively.

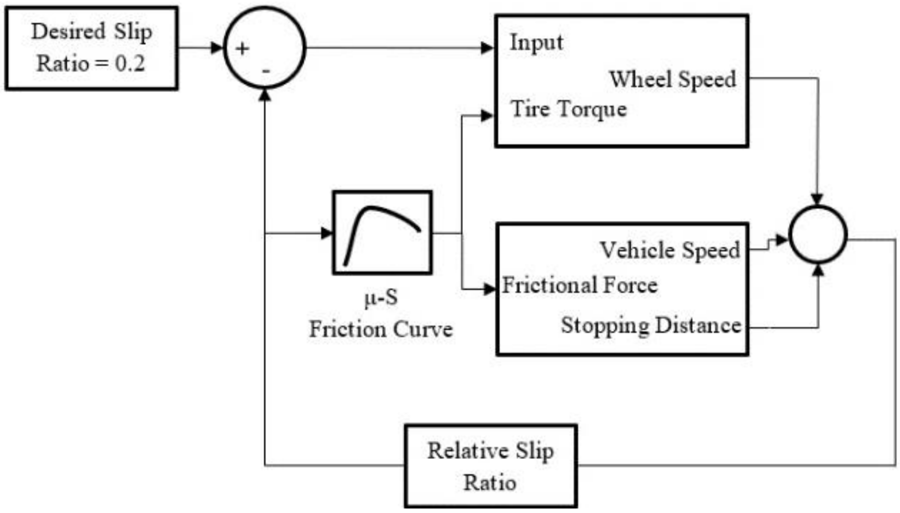

Fig 4: Block diagram of Bang-Bang Controller for Antilock Braking System

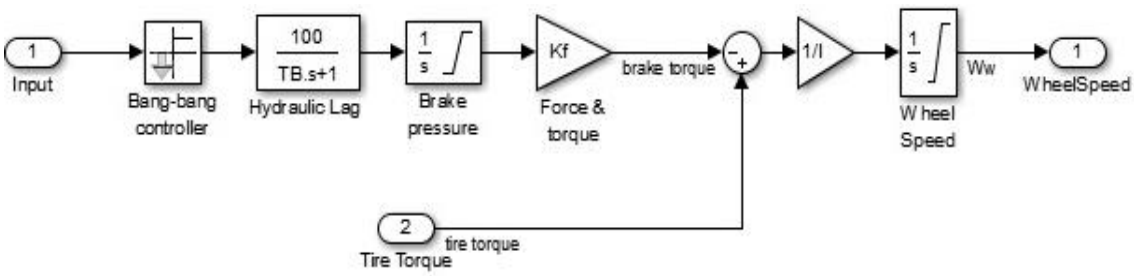

Fig 5: Block diagram of Simulink Model for Wheel Dynamics

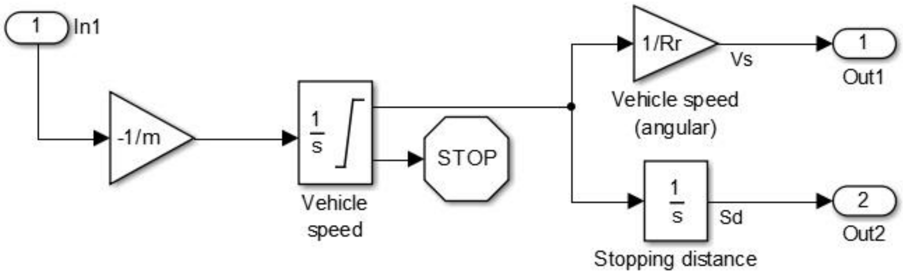

Fig 6: Block diagram of Simulink Model for Vehicle Dynamics

The bang-bang control is based upon the error between actual slip and desired slip, and the area of interest are acceleration, ride, braking, and turning. A list of variables and simulation parameters used in this model is given in Table 1.

Table 1: Simulation Parameters Used for Development of Bang-Bang Controller

Parameter	Description	Value (Unit)
M	Quarter Car Mass	300 kg
V_0	Initial Vehicle Velocity	70 (m/sec)
W_0	Initial Wheel Velocity	120 (Rad/Sec)
R	Wheel Radius	1.25 m
G	Gravitational Constant	9.81(m/s^2)
J	Moment of Inertia of Wheel	1.6 kg-m^2
FZ	Normal Force	50 N
Tb_{max}	Maximum Braking Torque	1200 Nm
AD	Desired Slip	0.2
K	Gain	100

Results and Discussion

The performance of the vehicle without an Antilock braking system and using a Bang-Bang controller is shown in Fig. 7 to Fig. 13. The graphs below are obtained from the various scopes of the model.

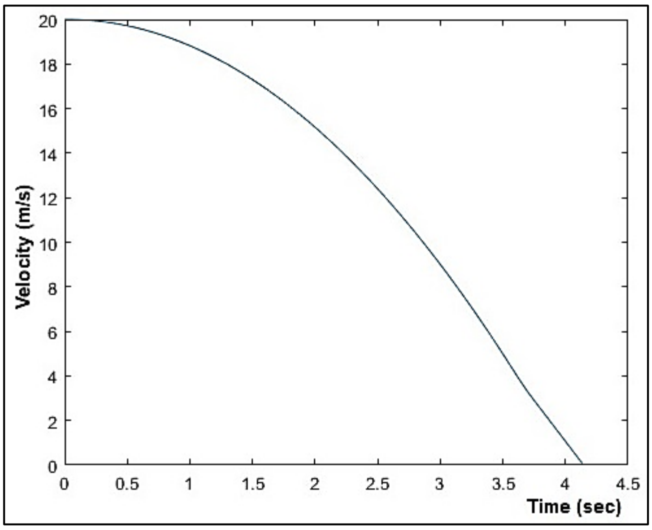

Fig 7: velocity speed without Antilock braking system

Where Fig. 7 displayed the velocity speed without any Antilock braking system which starts at 20 m/s with an inward decrease from 0 seconds to 4.1 seconds before a steady state is reached, which is extremely high within a shorter time.

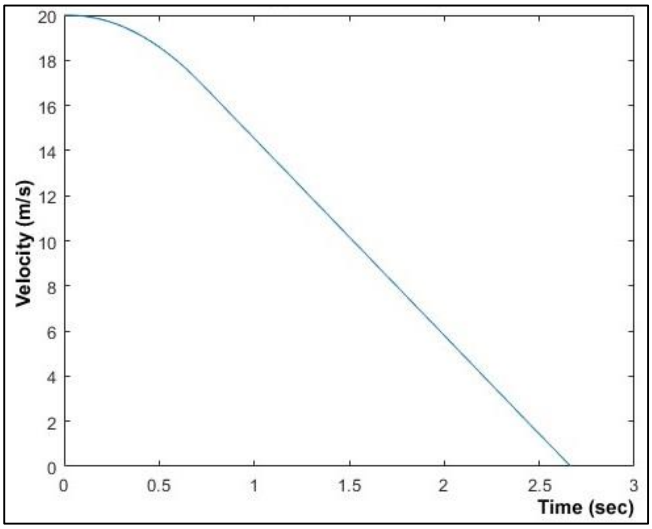

Fig 8: velocity speed using the bang-bang controller.

Fig. 8 displayed the velocity speed using the bang-bang controller which starts at 20 m/s with an inward decrease from 0 seconds to 2.7 seconds before a steady state is reached, which when compared to the graph plotted in Fig. 7, the time required is shorter.

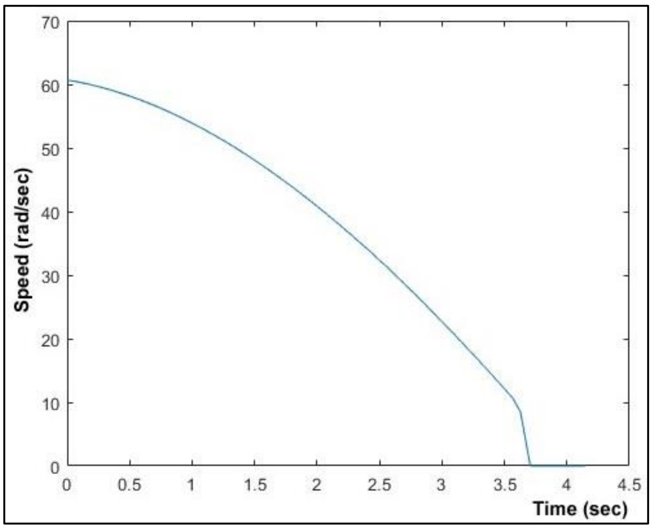

Fig 9: Wheel Rotational speed without Antilock braking system

Where Fig. 9 displayed the wheel rotational speed without any Antilock braking system which starts at a speed of 61 rad/sec with an inward decrease from 0 seconds to 3.7 seconds before a steady state is reached, which is extremely high within a shorter time.

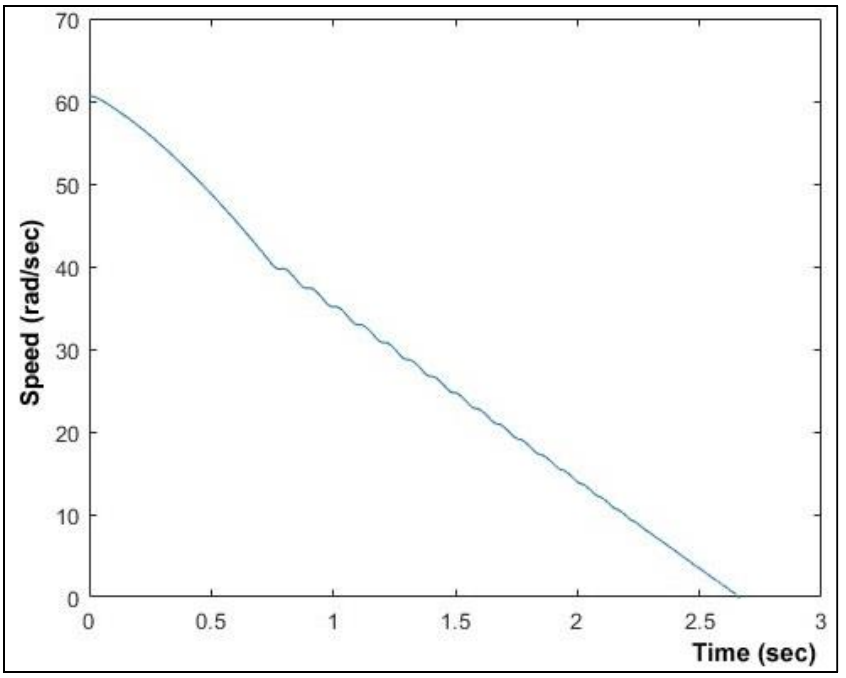

Fig 10: Rotational speed using the bang-bang controller.

Where Fig. 10 displayed the rotational speed using the bang-bang controller which starts at a speed of 61 rad/sec with a linear decrease from 0 seconds to 2.7 seconds before a steady state is reached when compared to the graph plotted in Fig. 9, the time required is shorter.

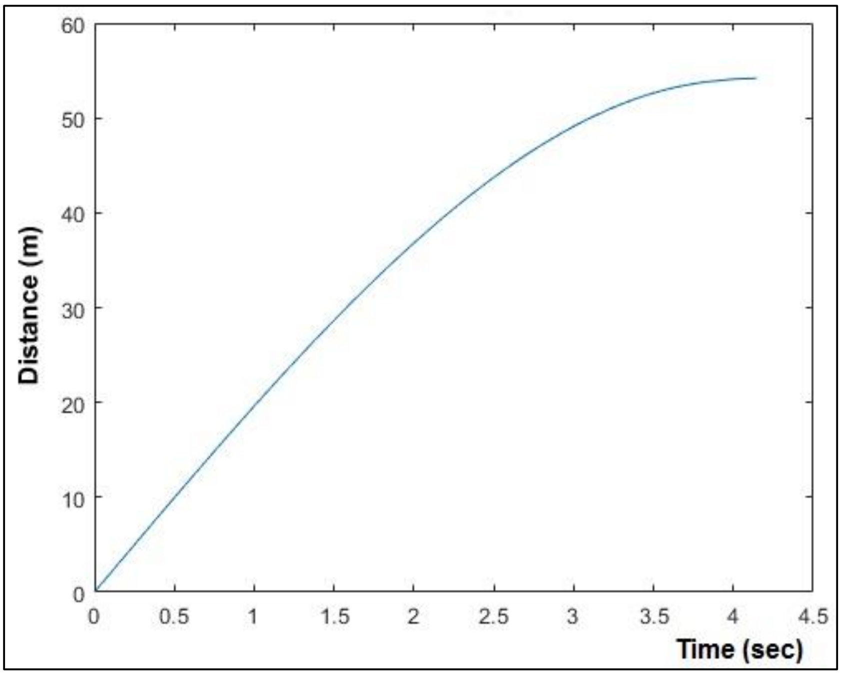

Fig 11: Stopping distance without Antilock braking system

Fig. 11 displayed the stopping distance without any Antilock braking system which starts at the origin with an upward increase to about 55 m from 0 seconds to 4.1 seconds before a steady state is reached, which is extremely high within a shorter time.

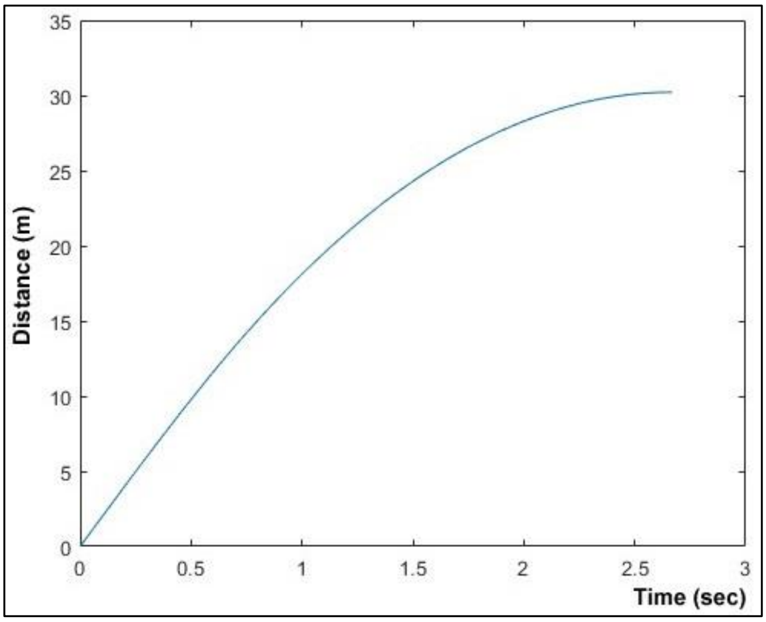

Fig 12: Stopping distance with the bang-bang controller.

Fig. 12 displayed the stopping distance using the bang-bang controller which starts at the origin with an upward increase to 31 m at 2.67 seconds in a straight line braking condition.

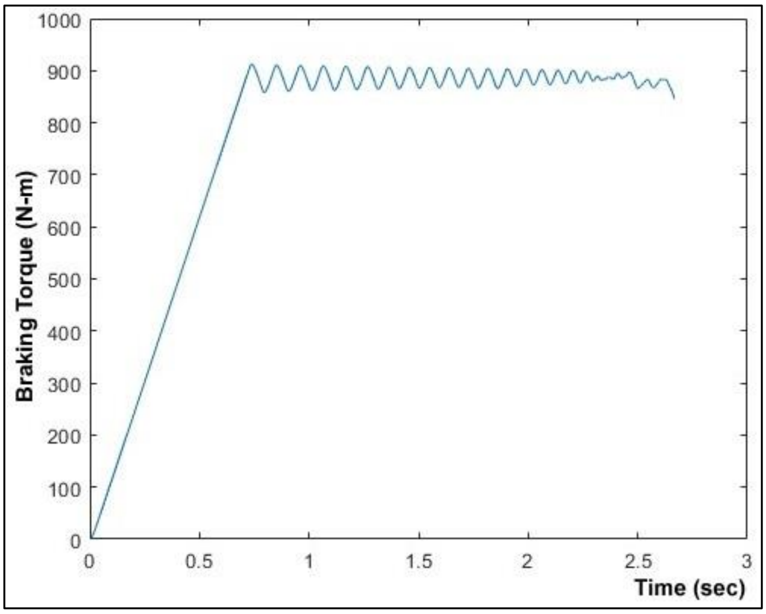

Fig 13: Braking Torque for bang-bang controller.

Fig. 13 describes and plots the braking torque using a bang-bang controller, it is evident from the graph plotted that by using the Bang-Bang controller the stopping distance was reduced when compared to a system without any Antilock braking system.

Conclusion

The paper compared and analysed the effectiveness of the Anti-Lock Braking System with and without a Bang-bang controller to improve vehicle stability control system on vehicle occupant injury. The results show that a vehicle without Anti-Lock Braking System takes a long time to come to stop when compared with a system with a Bang-bang controller. The performance of the wheel speed, slip distance, velocity speed, and control signal was plotted. The Anti-lock Braking System with a Bang-Bang controller has better braking performance because the wheel speed and the vehicle speed is been controlled at the same time. To avoid vehicle skidding during panic braking, the ABS with Bang-Bang controller will help the driver to steer while braking heavily and could prove to be lifesaving.

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