# Modeling and Simulation of ABS through Different Types of Controllers Using Simulink

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# ABSTRACT

The ABS system is an abbreviation of the Anti-lock Brake System. Anti-lock brake system is the most important development in automotive technology for vehicle and traffic safety improvements. This system is used widely to ensure safe braking. Accident investigators have noticed that some of accidents happen and become a matter of concern, due to various human errors. But the most of traffic accidents occur because of faults in any mechanical system in vehicle, and/or bad condition of the roads. Bosch company was the leader in this field. It was the first company that invented and produced this system in 1978, and the brakes were designed in Anti-lock to implement the technique of braking technology automatically without the intervention of the vehicle driver. Through an electro-hydraulic control system, where an electronic control unit works to control the activation or non-activation of the hydraulic control system via the controlling of screw valves based on the signal sent from a number of sensors and switches. As the wheel speed sensors work to determine the speed and slowdown of the wheels. This signal is sent to the electronic control unit, if the wheels are slowing sharply, i.e. about to close, the control unit issues instructions to the hydraulic group. Then hydraulic group will reduce the brake pressure on these tires. And prevent the lock from occurring. When the driver continues to press the brake pedal, the pressure rises again. And this process is repeated several times until the vehicle stops completely.

In this thesis, the subsystems and dynamics of ABS will be explained. Then a model of ABS will be created in MATLAB/SIMULINK software. While simulation of ABS model achieved by applying different control strategies as: Bang-bang which acts as on/off, PID and PD controller, with a vehicle speed of 100km/hr moving in straight line. Simulation will analyze the behavior of vehicle under application of ABS and without implementation of ABS mode, through different road types.

**Keywords:** Anti-lock braking system (ABS), locking, slipping, PID controller, PD controller, simulation, vehicle dynamics.

# ÖZ

ABS sistemi, Kilitlenmeyi Önleyici Fren Sisteminin bir kısaltmasıdır ve kilitlenmeyi önleyici fren sistemi, araç ve trafik güvenliği iyileştirmeleri için otomotiv teknolojisindeki en önemli gelişmedir ve güvenli frenleme sağlar, Kaza müfettişleri, çeşitli insan hatalarından dolayı bazı kazaların meydana geldiğini fark etmiş ve endişe konusu haline gelmiştir, ancak trafik kazalarının çoğu araçtaki herhangi bir mekanik sistemdeki arızalar ve / veya yolların kötü durumundan kaynaklanmaktadır, Bosch firması bu alanda lider olmuş ve bu sistemi 1978 yılında icat eden ve üreten ilk firma olmuştur, ve frenler, araç sürücüsünün müdahalesi olmadan fren teknolojisi tekniğini otomatik olarak uygulamak için kilitlenmeyecek şekilde tasarlanmıştır. Bir elektronik kontrol ünitesi, bir dizi sensör ve anahtardan gönderilen sinyale bağlı olarak vidalı valflerin kontrolü yoluyla hidrolik kontrol sisteminin etkinleşmesini veya etkinleşmemesini kontrol etmek için bir elektro-hidrolik kontrol sistemi aracılığıyla sağlar. Tekerlek hız sensörleri tekerleklerin hızını ve yavaşlamasını belirlemeye çalıştığı için bu sinyal elektronik kontrol ünitesine gönderilir, tekerlekler keskin bir şekilde yavaşlıyorsa, yani kilitlenmek üzereyse, kontrol ünitesi, kilidin oluşmasını önlemek için bu lastikler üzerindeki fren basıncını azaltmak için hidrolik gruba talimatlar verir. Sürücü fren pedalına basmaya devam ettiğinde basınç tekrar yükselir ve bu işlem araç tamamen durana kadar birçok kez tekrarlanır.

Bu tezde ABS sisteminin alt sistemleri ve dinamikleri anlatılacak, ardından MATLAB/SIMULINK yazılımında bir ABS sistemi modeli oluşturulacak, ABS modelinin simülasyonu ise açma/kapama işlevi gören Bang-bang, PID ve PI denetleyici gibi farklı kontrol stratejileri araç 100 km/sa hızında doğrusal olarak hareket ederken uygulanarak elde edilmiştir. Simülasyon, ABS uygulaması altında ve ABS modu uygulanmadan, farklı yol türleri aracılığıyla aracın davranışını analiz edecektir.

**Anahtar Kelimeler**: Kilitlenmeyi önleyici fren sistemi (ABS), kilitleme, kayma, PID denetleyici, PD denetleyici, simülasyon, araç dinamiği.

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| | |
|---|---|
| ABS | Anti-locking Braking System |
| $C_1$ | The highest value in friction curve |
| $C_2$ | Shape of friction curve |
| $C_3$ | The difference between the highest value and the value when $\lambda = 1$ |
| $C_4$ | Characteristic aspect of road-wetness. |
| DSC | Dynamic Stability Control |
| EBD | Electronic Braking Distribution |
| F | Friction force of wheel [N] |
| $F_b$ | The braking force of wheel [N] |
| $F_N$ | Normal reaction of the ground [N] |
| GA | Genetic Algorithm |
| I | Inertia of vehicle [Kg.m$^2$] |
| K | Braking gain |
| $K_b$ | The braking factor |
| $K_d$ | Derivative Control |
| $K_i$ | Integral Control |
| $K_p$ | Proportional Control |
| M | Mass of quarter-vehicle [Kg] |
| $M_b$ | Braking torque [N.m] |
| P | Pressure of braking fluid |
| PD | Proportional-derivative |
| PID | Proportional-integral-derivative |
| R | Radius of wheel |

| | |
|---|---|
| $T_b$ | Braking torque [N.m] |
| TB | The inertia parameter of the solenoid valve |
| TCS | Traction Control System |
| V | Speed of vehicle [m/sec] |
| $\dot{v}$ | Acceleration of the vehicle |
| $v_x$ | Vehicle Linear velocity in a straight line [m/sec] |
| $V_w$ | Wheel angular speed without slip |
| W | Angular velocity of wheel [rad/sec] |
| $\lambda$ | Slip ratio of the wheel |
| $\mu$ | Coefficient of friction |
| $\dot{\omega}$ | Angular velocity of wheel [rad/sec] |

# Chapter 1

# INTRODUCTION

## 1.1 History and Development of ABS System

After the first motor-driven car launched in 1769, and the first vehicle accident occurred in 1770, since that time, safety of vehicles has become matter of concern, and automobiles manufacturers were motivated to eliminate driving injuries and reducing accidents as well as increasing road safety, through finding some active systems to increase safety[1]. Depending on a survey from the World Health Organization, about 1,35 million people dies each year from road traffic accidents[2], so Transportation and public safety are considered as one of the biggest challenges of the modern society, regarding to road crashes one of the world's causes of death.

In 1930, Vehicle scientists invented the first active system, called mechanical antilock braking system (ABS), it was applied in the aerospace field [3].

The first collection of ABS was inserted on a Boeing B-47 in 1945, to keep spinning tires without explosion or sliding and, afterward in the 1950s, ABS brakes were widely installed in all aircraft [4]. After that, high-end vehicles were built only with rear ABS in the 1960s, and with the fast development of computing technology, the phenomenon accelerated in the 1980's. Bosch company in 1978 developed the world's first ABS controller for passenger cars, with the primary purpose of avoiding vehicle slippage, lowering distance stoppage and increasing steer ability under braking [5].

In these days, ABS all wheels are present on most modern cars, automobiles and also on some specified motorcycles [6]. Several dynamic control systems implementations can be currently founded as active suspension, dynamic steering and traction control. Automobile manufacturers' majority concentrating on fitting the active and passive safety systems on their vehicles, especially ABS, systems can protect the vehicle from accident, can be defined active system, while systems can rescue lives of driver and passengers during collusion can be defined as passive systems [7].

ABS can be regarded as a significant addition to traffic and road safety, once it can preserve vehicle stable and steerable in case of suddenly or emergency braking, prevent slippage as a result of wheel blocking. It is known that driver will lose control of vehicle while driving on slippery or wet road throughout braking, or extreme braking. This typically triggers a long distance to stop, so vehicle may often lose its stability [8].

ABS aims to avoid the wheel slippage in order to achieve maximum friction between road and wheel, so steering stability and lateral stability will be increased. That would be, to makes sure that the vehicle stops in the nearest point on a route, during direction controlling. The perfect primary objective for the control system that controls the speed of the wheels, traction control system(TCS) technology and dynamic stability control (DSC), can be considered as applications of ABS technology.

ABS commonly composed of main subsystems in all vehicles as follows: normal physical brakes which divided to disk and drum brake, master cylinder, hydraulic modulator unit containing pump and valve for each wheels' line, speed sensor fitted with each wheel and the electronic control unit (ECU) as in Figure 1.

There are some specific sophisticated ABS containing an accelerometer for vehicle's deceleration estimation [9]. They aimed through their study to analyze and compare the behavior of vehicle with/without application of ABS by using MATLAB/SIMULINK software, in addition to compare different strategies of controllers through merging it with ABS model.

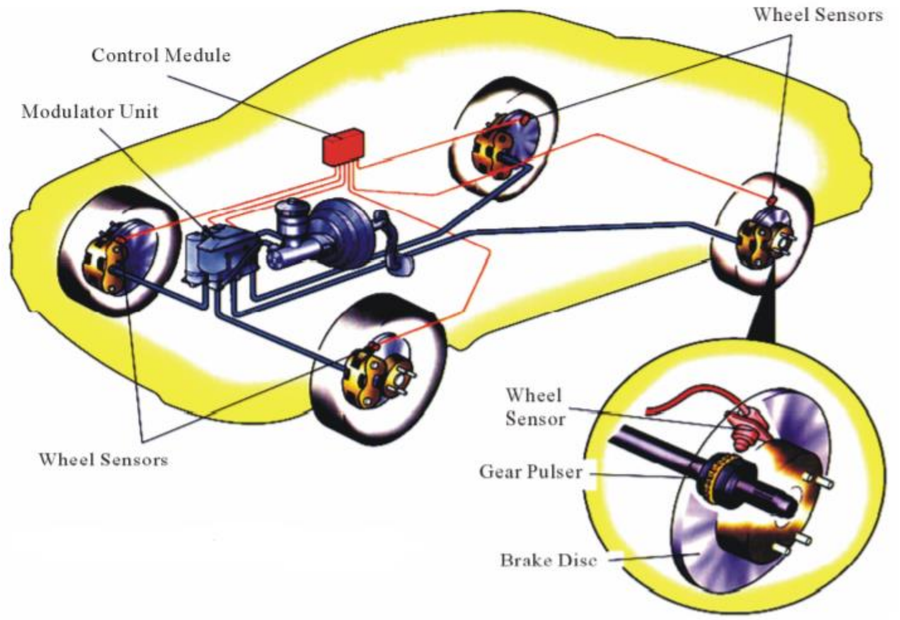


Figure 1. ABS subsystems [9]

## 1.2 Problem Formulation

There is an important relation between the coefficient of friction and the ratio of tire slipping, because it gives an indication of the ABS ability to preserve steer ability and stability of the vehicle, and also guarantee to ensure stopping in the least distance. Frictional coefficient is fluctuating very widely, because it based on several factors such as: road type and its condition if dry or wet, driving speed, the tire trademark, the slipping angle of tire while braking and the road-tire slipping ratio.

As shown in Figure 5 in chapter two, the frictional coefficient has its effective optimal value in a specific region on the curve of wheel slip ratio, this value is around 20%, although this value can be changing due to road type changing, as shown from the figure, for all types of roads the coefficient of friction has its optimal value which near to 20%, while its value is the worst at value of slip ratio 100% which means when tire locking occurs.

It is a scientific constant that if a lock occurs to the rear wheels when the brakes are used suddenly, this leads to instability of the vehicle and its rotates around its front axle, while if the front wheels are locked, this leads to the inability to control the vehicle's steering during braking and skidding.

So the aim of implementing the controller in ABS is to maintain and adjust the tires' slip ratio ($\lambda$) to the desired value of 20%, to ensure the coefficient of friction ($\mu$) is maximum regardless the road type.

## 1.3 Objectives of Applying Anti-Lock Braking System

### 1.3.1 Reducing the Stopping Distance

- Three factors are affecting on the stopping distance, these factors are: the vehicle's driving velocity ($V$), the vehicle's mass ($M$) and the force ($F_b$) affecting on pads while braking (braking force), however to forms of road surfaces.
- As the braking force increases, the stopping distance is decreased, provided other factors are constant.
- The best adhesion between the tire and road exists in a peak extent of friction coefficient.

- ABS can keep all of vehicle’s tires near to the peak region, this will obtain maximum of tire-road friction force and, thus, reducing stopping achieved.

### 1.3.2 Increasing in the Stability

- Since slowing and stopping the vehicle’s acceleration are a primary target of braking system, but in some cases, the friction force may not be maximum as desirable. For instance, if the driver driving on two different surfaces commonly called $\mu$-split surface, asphalt and sand or even asphalt and ice, in this case more brake force will applied by one side stronger than other.
- In case of $\mu$-split surface, The application of full braking force to the vehicle’s both sides, will lead to yield yaw moment, which when constantly increasing leads to drag the car to the high traction side, and react to car instability [10].
- Application of ABS in the vehicle, can keep the vehicle stable while braking on two different surfaces, maintaining the slipping on both sides less than the peak of coefficient of friction, this assist vehicle be more stable.

### 1.3.3 Increasing in the Steer Ability

- Effective controlling of the peak region of frictional force, is needed to attain acceptable lateral forces, and hence good steer ability.
- The importance of steer ability of vehicle during braking systems from the ability to avoid collision during braking and turning.

### 1.3.4 Reducing in Wheels Wearing

- The use of ABS, will lead to the maintenance of the surface of the wheels from wear, and preventing the appearance of undesired deformations or abnormality on a specific area on the surface of the tire, thus increasing the life of the tire, in addition to avoid mechanical vibrations.

## 1.4 Facts About ABS

1. When the brake pedal is depressed in vehicles with an anti-lock system, the brake pedal will vibrate, which will cause the steering wheel to vibrate, as well as the vehicle body.
2. Even if the vehicle has an anti-locking system, the vehicle still needs a space to stop between it and the vehicle in front of it, and this distance is called the stopping distance.
3. The anti-lock system does not prevent accidents caused by excessive speed, so the driver should slow down during turns.
4. On a rough road, gravel, or even snow, the system needs a longer distance to stop, so it is extremely important to slow down from the start.

# Chapter 2

# LITERATURE REVIEW

## 2.1 Recent Searches

An overview about antilock braking system and the different types of controllers used has been presented in this thesis, A Technical Review was a part of research according to Saudi Arabia road surfaces [9], Methods used to design ABS have been tested. They illustrated the key difficulties of their control strategies and summarized the more recent developments. Intelligent control mechanisms such as fuzzy control can be used in ABS control to imitate human intelligence qualitative aspects with many advantages such as robustness and universal approximation theorem. They concluded that because of the complicated relationship between its components and parameters ABS control is highly nonlinear control problem. Many of these methods need program models, and some of them are unable to achieve adequate performance when different road conditions are changing. The methods of soft computing such as Fuzzy control do not require an accurate model.

In a paper, [2], for an ABS braking system various models of wheel-road contact were simulated. To check the variations between the models used and the performance of the predicted controller, simulations were conducted across two loops, open loop and closed loop. A PID controller was projected using modified critical gain Ziegler Nichols method. Taking the generalized Burckhardt interaction model into account, the controller was modeled and modified according to Pacejka and Burckhardt formulas [11]. It was important to check that the predicted controller performed equally with each of the three models, maintaining tire deceleration near to the deceleration of vehicle, and reducing braking distance as opposed to the model simulation without the applied ABS.

For decreasing the chattering of traditional exponential approximation of law variables system control, a Fuzzy method law variable function controlling methodology is introduced [12], which is implemented to automotive ABS, and the structure is developed by merging the MATLAB Simulink software with the Fuzzy Control Toolbox. The controller developed by the Fuzzy Methodology can easily monitor the goal of slip ratio underneath single and salt road conditions and effectively avoid wheels from blocking, the process reaction time is high, lower in time of braking, and shorter in stopping distance.

A research paper [13] presents an innovative approach to implementing such a system. It has been shown that the use of anti-lock braking in vehicles can avoid locking mode in addition to avoiding slip. The machine model was developed in this regard on the basis of which mathematical equations were guided then those equations were implemented on Simulink. The machine model is still working, and tests are replicated in three different types of surfaces which are concrete / dry asphalt, snowy and ice surface while driving the vehicle. Another uniqueness of this work is Pacejka[13] magic formula was used. Through doing so, the system has acted extensively and the results affirm the engineered ABS status.

Another paper [14] investigated the possibility of using an inverse model of neural network to refine an embedded PID wheel slip system. The goal was to boost the controller's slip tracking capability. While both controllers registered the same stop distances, the control system shows a higher slip tracking efficiency. Potential research intents to test the device suggested for an advanced ABS test-rig.

ABS unit can essentially keep the tires from blocking, braking more quickly, relying on fuzzy control, as well as the rate of slip is therefore similar to the optimal slip ratio about 0.2 [15] due to using Matlab/Simulink software depending on fuzzy control strategy.

[16] has studied ABS efficiency with weight variance, road traction coefficient, road tilting, etc. A tuned PID controller scheme is built in order to resolve these effects through fuzzy GA; with a target goal to reduce the distance needed to stop while maintaining the wheel's slip ratio within the optimal range.

The Fuzzy Controller was used by [17], aiming to control the brake hydraulic modulator unit and thus the pressure of brakes. Controller output and the brake hydraulic modulator are tested in loop (HIL) tests using the hardware.

ABS model was tested; a car's Simulink-model regulating brakes loads was developed[18]. Comparison of stopping with ABS was carried out and without ABS. Research insight orientation is connected to the stability strategy and algorithms. The test looks at the car braking cycle at which blocking wheels' phenomena may occur, and as a consequence a vehicle may lose the stability and controlling.

Represented as a single-wheel model controlling system [19], the performance of ABS is evaluated, though the resulting results, it was found that the system able to regulate the wheel slip ratio well enough and maintain slip ratio of tires close to the desired slip ratio at all times, and will have the best braking performance. Based on the double-wheel model, the single-wheel braking in a straight line is simulated. The results indicate that the system can provide guarantee to ensure adhesion of the two wheels, and there is a certain optimal value for solving the locking difficulty for the saloon cars.

Two PID and Fuzzy Logic controllers were analyzed and compared ABS designing and developing [20], resulted that the suggested Fuzzy controller introduced exhibited greater and better efficiency than the PID controller, in addition that the Fuzzy controller provided faster convergent levels for slip management with no noticeable over-shoots, The controlling of deceleration was also accomplished with limited fluctuation and was the best braking distance than PID controller.

A practical test using test car while suddenly braking at three different speeds were achieved  [21], Matlab-Simulink was used to simulate the test car as a model, the simulator was performed to consider the vehicle's dynamic behavior, while pressing emergency braking under dry conditions, each speed of three initial speeds were simulated under using of ABS and without using of ABS, resulted that the tires is locked-up if ABS is not added to the car due to the unexpected and significant amount of braking torque, also stopping time and stopping distance is more long due to slipping. But when simulating while ABS was activated, the vehicle became more stable as a result of the value of the friction between the road and the wheel, slippage was very close to the desired value, the stopping distance was 28% less in the case of using ABS than in the absence of ABS.

## 2.2 Understanding Anti-Lock Braking System (ABS)

Nowadays, the majority of modern cars on the road are equipped with an anti-lock system that greatly reduces and prevents accidents. The majority of these accidents happen when the vehicle is out of control and is not able to steer while pressing the brake pedal. But with the availability of the ABS, the driver will be able to steer the vehicle and avoid obstacles in front of him if the brakes are suddenly and forcefully applied. In order to properly understand this system, one must first understand how braking and steering occurs. Initially, when the driver presses the brake pads, the brake pads located on both sides of the disc will move in effect by applying pressure on the disc from both sides, and thus friction will occur between the brake pads and the disc, causing the wheel to stop rotating. When pressing the brake pedal suddenly and strongly, this leads to the occurrence of the locking of the wheel, which in turn leads to the occurrence of a slip at the weakest point, which is between the wheel and the road, where the vehicle stops as a result of this friction. As for the understanding of the steering mechanism, it depends on a simple principle, which is to maintain the consistency of the wheel during braking with the ground, so the wheel is rolling during braking, and this means that the speed difference at the point of contact between the wheel and the ground is equal to zero.

There are two kinds of motion for the rotating wheels, they rotate on their axis and also they move along the direction of the car. Due to these two kinds of motion, two kinds of velocity will exist: translational and rotational. For non-slip rolling conditions, the summation of these two velocities at the contact point must be zero [22].

In all automobiles, all four wheels must roll all times in order to prevent the vehicle slipping. As a result of the force created by the friction between the pads and the disc, the wheel will stop rotating, Consequently, there will be no rotational speed at all for the wheel, in which case the car will continue to slide in the same direction in which it is traveling, regardless of the driver's orders regarding steering or turning, thus this will lead to an inevitable accident.

Apart from the driver's inability to steer the vehicle while braking, another big problem that cars that do not have an anti-lock system may face is braking on surfaces with different levels of traction, and applying pressure to the brakes in this case generates different friction forces on the wheels; This will produce torque at the edges of the car and thus enter the car into uncontrollable rotation. Simply put, the anti-lock braking system prevents the wheels from locking completely.

This system includes several sensors, so that each speed sensor is connected to one wheel only. These sensors continuously read the rotation speed of the wheels separately and then compare these speeds with each other to see if there is a wheel that has stopped or is about to stop, and when it is detected, the pressure modulator reduces the brake pressure on that wheel and releases the brake pad, and this process is repeated several times Every second until the vehicle comes to a complete stop without slipping.

In this way, the wheels are able to rotate intermittently while ensuring the ability to steer and control the car and not slip on the road in the event of sudden braking.

## 2.3 Components of ABS

Applying the brakes too hard or when driving on a slippery surface can lock the wheels, at which point the steering control of the vehicle is lost, and these situations result in an increase in the vehicle's stopping distance, the ABS braking system prevents wheels locking or skidding no matter how hard brakes are applied or how slippery the road surface, steering stays under control and stopping distances are generally reduced. It is generally composed of main subsystems in all vehicles as follows: brakes, a master cylinder, wheel speed sensors, the electronic control unit or ECU and a hydraulic control unit [10] also called a hydraulic modulator, these components were illustrated in Figure 3 below.

1. Brakes

- Mainly, there are two forms of brakes, disk and drum brakes, it is common in all vehicles, most vehicles have disk brakes in the front axle and drum brakes in the rear axle.
- Disk brake containing pads within a caliper pressed through force of wheel cylinder, force applied to each side of disk, and braking occurred as a result of frictional force between pads and disks surfaces, disk brakes is better than drum brakes in case of possibility of linear braking and less sensitivity to wearing.
- Drum brake consisting mainly of two shoes (leading and trailing) containing pads, and brake drum, and braking occurs due to frictional force between both surfaces of shoes and the inner side of drum, drum brakes is better than disk braking in case of high gain, but it is more sensitive to non-linear wearing.

2. Wheel-Speed Sensors

- The wheel speed sensor consists of Hall-effect pulse sensor has a notched or toothed rotor that attached to each wheel, and spins and sensing a pickup, as the wheel turns a small voltage pulse is induced into the pickup and sent to the electronic control unit. When the brakes are applied. Figure 2 illustrates the toothed wheel speed sensor.

- Voltage frequency and rotation of wheel have a proportional relation.

Figure 2. Toothed Wheel-Speed Sensor [23]

3. Hydraulic Control Unit

- It is working according to the received electrical signal, and intended to reduce, maintain and restore wheel brake pressure, via controlling the solenoid valves in the hydraulic system.
- It is the structure connected between master cylinder and wheel cylinder, to control the hydraulic pressure.
- It is connected by engine side to reduce the length of hydraulic lines, it consists of pump, accumulator and oil reservoir.

4. Electronic Control Unit (ECU)

- Wheel sensors send signals to ECU, these signals will be amplified then filtered in order to measuring wheel speed and acceleration, ECU can read the velocities of two opposed wheels to measure the vehicle speed.
- A reference speed has to be compared with speed of individual wheels to derive slipping.

- ECU can feel of any wheel locking by comparing signals of wheel acceleration and wheel slipping.
- ECU sends signal to hydraulic modulator to trigger pressure and valve opening to limit the braking pressure as well as braking force.
- ECU responds to a known fault or mistake by either flipping off the system's caused by a faulty component or turning off the whole ABS.

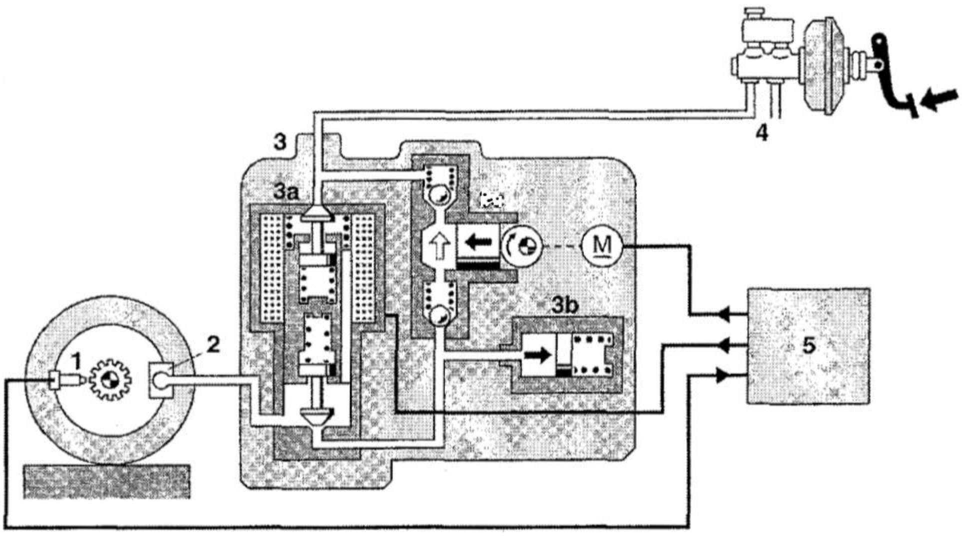


Figure 3. ABS components, 1. speed sensor, 2. braking cylinder, 3. Pressure/hydraulic modulator, 4. master cylinder, 5.ECU. [23]

# Chapter 3

# MATHEMATICAL MODELING OF ABS BASED ON MATLAB/SIMULINK

Modeling at first step, then simulation of ABS system can be considered as the most important step in development of the control system, Modeling of ABS is always a daunting challenge, taking in account dynamics of ABS are strongly nonlinear in addition to time varying.

In this part of this thesis, the dynamics of vehicles behavior while suddenly braking will be explained, the equations of motions, then modeling these equations by interacting with controller model in Matlab/Simulink software to achieve mathematical model of ABS, through considering some assumptions while process of modeling. This mathematical model defined as a single-tire model and can be repeated many times to build multi- tire model. The model consists of vehicle model, tire model, road-tire slipping model, in addition to braking and the controller models. Then the performance of ABS will be estimated, with and without application ABS mode.

## 3.1 ABS Models Based on Matlab

### 3.1.1 Tire Model

The real vehicle model must include all the dynamic aspects and simulation accuracy, that are too complex to be included in brake control designing. A classical model of tire including the basic elements with controller will be used. Figure 4 illustrates the classical tire and its characteristics. where;

$M$ = the mass of quarter-vehicle

$V$ = the speed of vehicle

$F$ = the friction of wheel

$R$ = the radius of wheel

$\omega$ = the angular velocity of wheel

$F_N$ = the normal reaction of the ground

$T_b$ = the braking torque

$F_b$ = the braking force

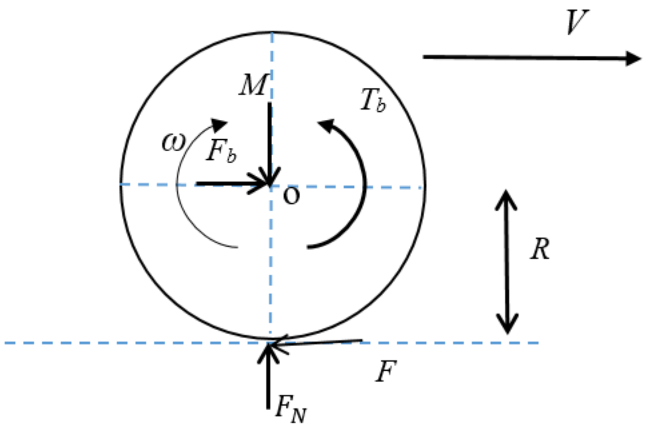

Figure 4. Classical tire model.

Tire model is separated to two types, theoretical and empirical model, the bi-linear tire model is used widely when analyzing the forces acting on the tire in physical applications [24].

### 3.1.2 Vehicle Model

#### 3.1.2.1 Single-Wheel Model (Quarter Vehicle Model)

Single-wheel model is primarily designed to test and analyze braking performance of the system, while double-wheel model is used to study the vehicle's braking behavior in a straight path, in addition to analyze braking performance. Mainly, the wheels have two forms of motion, they rotate on their axis and also they move along the direction of the travelling, due to these two kinds of motion, they have two types of velocities which are translational and rotational, which are resulted of newton's law differential equation[25].

So the vehicle's translational motion equation can be defined as Eq. (1) as follows:

$$M \,.\, \dot{v} = -F \tag{1}$$

While the wheel's rotational motion equation can be defined in Eq. (2):

$$I_o \,.\, \dot{\omega} = F \,.\, R - T_b \tag{2}$$

And the vehicle's linear friction equation can be illustrated as in Eq. (3):

$$F = \mu \,.\, F_N \tag{3}$$

**3.1.2.2 Coefficient of Friction (μ)**

- In perfect rolling conditions, the frictional coefficient value is close to zero. However, when the wheel is slipping at rate of 100%, the sliding friction plays its role. Because the rubber made of tires is a complex material and has strange properties during braking, the coefficient of friction between the tire and the road surface varies according to the slip, as illustrated in figure 5, coefficient of friction has its maximum value almost at 20% of slip ratio, and below and above this, the frictional coefficient reduces.

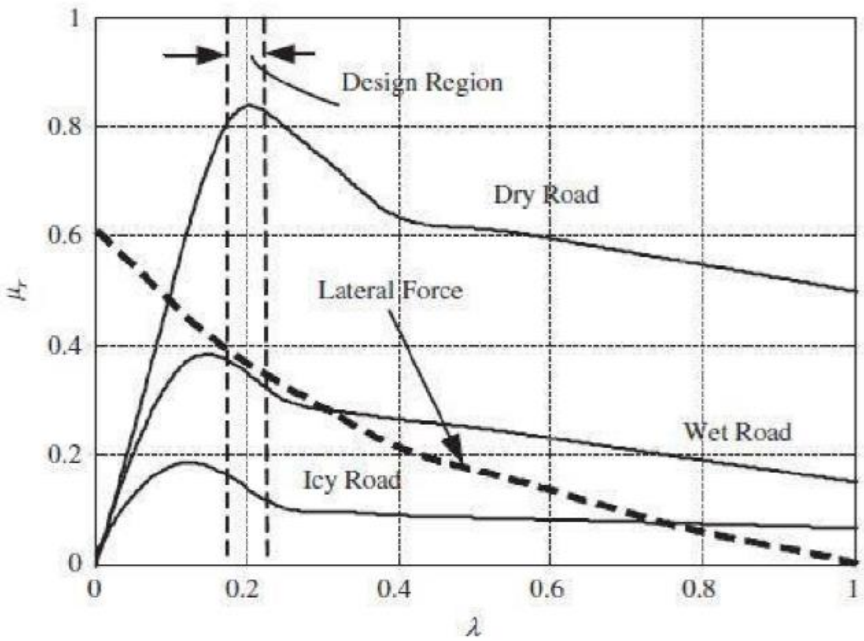

Figure 5. Curves of μ – λ for different types of roads[26]

- During braking with absence of ABS mode, the frictional coefficient that implemented is mostly due to the sliding friction. However, in ABS mode, the intelligent algorithms adjusting pressure of brakes to maintain the slipping ratio close to 20%, as the frictional value is at the maximum, and this greatly reduces the distance which needed to stop.
- Regarding the enormous instability on the roads of automobiles, there is an advanced system for electronic brake distribution (EBD) which is a subsystem of the modern ABS, thus this problem can be overcome very easily. An EBD system is measuring the vehicle’s yaw rate and the relative slip of each wheel. Just through reduction of braking pressure on the wheels while ensuring higher grip, then the needed frictional force affecting to these wheels can be produced. This will keep the yaw torque and the whole car under control.
- Coefficient of friction is regarded as a function that depending on the wheel rate of slippage and the vehicle’s linear velocity, there are many factors affecting on it such as: tire type according to material, tire characteristics according to (wearing,

aging, composition), road surface type (wet or dry), slipping angle of tire, driving velocity, wheel pattern, and the ratio of wheel and slip which changing during time.

- Coefficient of friction can be described by magic formula, called Burkhardt formula, this formula is used generally in all passenger and commercial cars, so the longitudinal friction of wheel and the slip curves can be represented, this formula has a different parameters values for each road type as shown in table 1, the dry asphalt road type is used in this thesis and simulation, the parameters values of dry asphalt were applied in the formula, then the resulted curve is plotted in an excel table, after that this table is logged and exported to the mu-slip curve, and became as lookup table in the simulation model. Burkhardt formula [27] is written in Eq. (4) below:

$$\mu(\lambda, vx) = [C1(1 - e^{-C2\lambda}) - C3\lambda]\, e^{-C4\lambda vx} \quad (4)$$

where:

$C_1$ = The highest point in the frictional curve

$C_2$ = Shape of curve

$C_3$ = The difference between the highest point and the point when $\lambda = 1$

$C_4$ = Characteristic aspect of road-wetness.

Table 1. Values of parameters of Road-Tire friction [27]

| Road type | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---|---|---|---|---|
| Asphalt (Dry) | 1.2801 | 23.99 | 0.52 | 0.03 |
| Asphalt (Wet) | 0.8570 | 33.822 | 0.347 | 0.04 |
| Concrete (Dry) | 0.19 | 94.12 | 0.06 | 0.04 |
| Snow | 0.1946 | 94.129 | 0.0646 | 0.04 |
| Ice | 0.05 | 306.39 | 0.001 | 0.04 |

### 3.1.3 Road-Tire Slip Model

When the car is running on the road normally without any external influences or forces on it, in this case the liner speed of the vehicle and the speed of rotation of the wheels are equal, but when any external force or braking force affecting on the vehicle, the slipping phenomena will appear.

Tire of vehicle have two kinds of slips, which are longitudinal and lateral slips, longitudinal slip is always affecting in the direction of motion of vehicle, while the lateral slip appears as a result of lateral forces affect to the vehicle body, both of those kind of slips yield the tire slip angle. In this thesis and through simulation, slipping angle of tire is zero, so the vehicle is running in a straight line and the slip is pure longitudinal slip.

In fact, tires have 100% grip with road in parking mode, and full tire gripping during driving is rare, while there is no tire gripping in case of hydroplaning so the slipping is 100%. When the driver of vehicle affects suddenly force on tire, gripping between tire and road will decrease. For instance, when driver want to accelerate the vehicle suddenly, tire rolling or skidding will occur, while when he wants to make sudden braking, slipping will occur.

When a hard braking occurring, the liner velocity of vehicle ($v_x$) will be greater than the linear speed of wheel, which equal to rotational speed ($\omega$) of wheel multiplied by wheel radius ($R$), and this indicates that there is slippage between road and tire.

Slip of wheel is equal to the linear speed of vehicle minus linear wheel speed, to the liner speed of vehicle, and slipping percentage of wheel can be calculated through Eq. (5) as follows:

$$\lambda = \frac{vx - \omega\ .\ R}{vx} * \ 100\% \qquad (5)$$

According to Eq. (5), slip equal to zero when the speed of vehicle and tire are equal, and slip equal 1 in case of wheel locking. During this work, the required slip was 0.2 meaning that the wheel is rotating in value of 0.8 from the real number of wheel rotation in normal running without braking with same speed of vehicle.

Slip rate model that based on the previous equation, is created in Simulink environment and used in the model of ABS, named relative slip and can be seen in Figure 6.

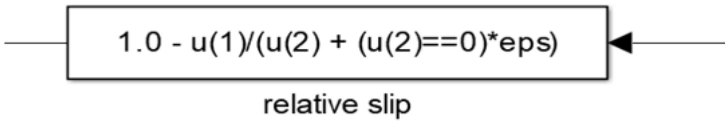


Figure 6. Relative slip model of ABS

### 3.1.4 Braking Model

Braking model is a subsystem of ABS model, which represents the connection and the relation between the hydraulic pressure when pressing on braking pedal that can be considered as the valve command, and the braking torque which produce braking force to ensure braking according to signals of wheel sensors and lag in hydraulic lines, it is worth noting that, there is a proportional relation between the braking pressure rate and the flowing fluid rate, and the flowing fluid rate has a proportion relation with opening the valves. Thus, braking pressure rate is consequently having a proportional relation with valves opening(Wang and Qiong Wang 2012).

To make the simulation study easier, the components of brake system were considered as ideal, and its non-linearity was considered as weak, and proposed the impact of lags of movable valves as ignored. Subsequently, the transfer expression of braking torque which affecting to the vehicle's wheel can be defined in Eq. (6):

$$M_b = K_b \quad P \tag{6}$$

where; $M_b$, $K_b$ and $P$ were referring to the braking torque, the braking factor, and the pressure of braking fluid, respectively.

Braking system in reality, consist of the brakes and the transmission system, and both of those components must to be imbedded in modeling, the transmission system modeling is basically referring to the hydraulic system modeling, which usually takes into consideration that, how braking force pressure regulator adjustments with the solenoid valve current. So the to make the system simple, the non-linearity of spring of solenoid valves and the hydraulic pressure delay were neglected, which resulted that the hydraulic part transformed to integral part inside modeling.

The hydraulic transmission receives the control signals as inputs, and regulate the fluid flow as output. The simplified hydraulic transmission function in Eq. (7) can be defined as the following;

$$G(S) = \frac{K}{(TB\,.\,S+1)} \tag{7}$$

The solenoid valve has a response time (*TB*) generally almost 10 milliseconds, thus the inertia parameter became 0.01, and (*K*), which is the brake gain, takes 1000. So that the hydraulic transmission function will be as Eq. (8) follows;

$$G(S) = \frac{1000}{(0.01\,S+1)} \tag{8}$$

So the braking subsystem model in simulation environment was built with the help of the previous two equations 6 and 8, this model receives the input signals from the controller, and the braking torque as its output. The braking subsystem simulation model is shown in Figure 7.

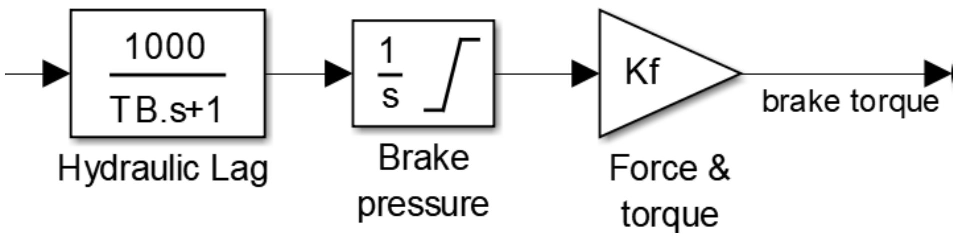

Figure 7. Braking subsystem model of ABS

### 3.1.5 Controller Model

In a closed loop control system, the system actuating the error signals, which is the difference between the input signals and the feedback signals, is fed to the controller so as to reduce the difference in error, and being the output of the system to a desired value. Block diagram of the classical closed loop control system is illustrated in Figure 8 as follows; in this simulation, three types of controllers were used which was:

1. Bang-bang controller
2. PD controller
3. PID controller

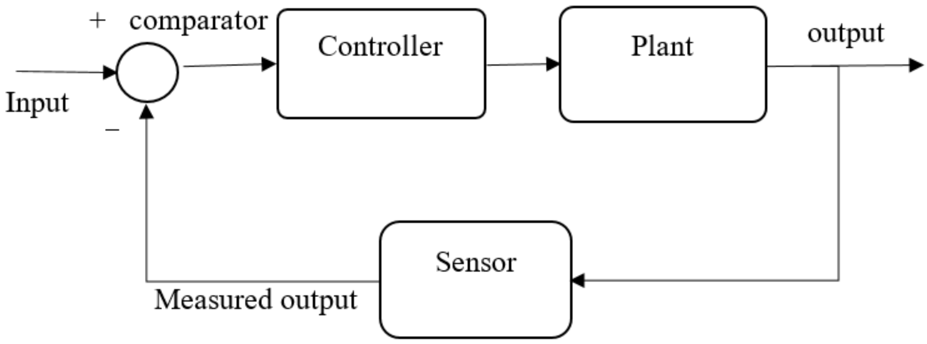

Figure 8. Block diagram of the classical closed loop control system

### 3.1.5.1 Bang-bang Controller

It works as on-off controller which is also called hysteresis controller, is applicable and usable in wide fields of industrial control systems, especially in homes applications, this controller also renowned as two step controller, it acts as feedback controller turns suddenly between two states which are upper and lower boundaries, and it works when a difference (error) become between the set point (desired value) and current values. This type of controllers can always be utilized in forms of every hysteresis-providing system, it is also used in operation of systems which deal with binary inputs. Bang-bang controller often takes place of the problem at least time, for example, if a car needs to be stopped at a certain location relatively far ahead of the vehicle, in addition to achieve the shortest amount of time, the approach is to apply maximum acceleration before the particular stopping point, and then adapt maximum force of braking to stop precisely in the required location. So, in certain cases, bang-bang controller is potentially ideal, but it is often used because it is easy or convening.

In this thesis, bang-bang controller of ABS works according to the continuous values of error which between the real slipping ratio and the required slipping ratio, in which, the value of the required slipping ratio is the value at which the curve of $\boldsymbol{\mu} - \boldsymbol{S}$ shows the highest value as shown before in Figure 5, and at this region of $\boldsymbol{\mu} - \boldsymbol{S}$ curve, the least stopping distance can be achieved.

Bang-bang has an output 1 if the input higher than 0, and has output -1 if the input is lower than 0, bang-bang controller is explained in Figure 9 as shown, and it was abbreviated to subsystem appearing in the model as shown in Figure 10.

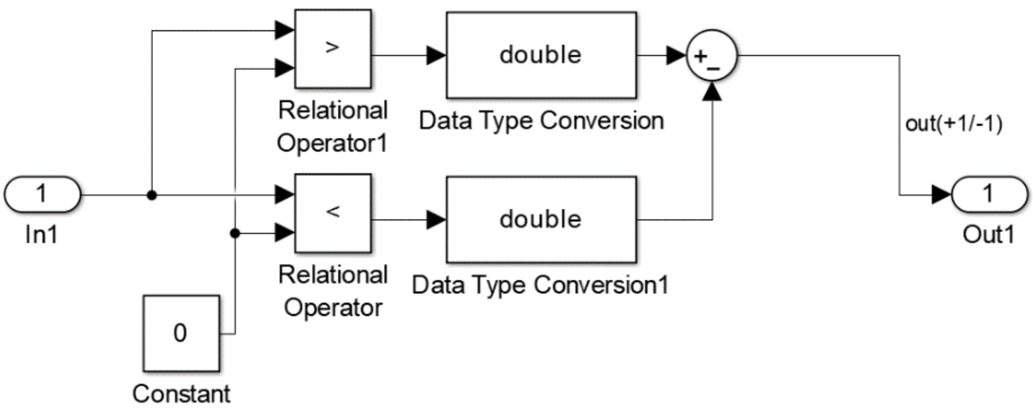

Figure 9. Bang-bang controller model

Figure 10. Abbreviated Bang-bang subsystem controller model

### 3.1.5.2 PID Controller

PID is an acronym that stands for proportional-integral-derivative. It is a mature technology used widely in industrial and home systems which contain close loops. It is an instrument used to keep something constant as pressure, temperature, cruise control, flow, and other process variables.

PID is an excellent choice for an automated process. Essentially, it uses a control loop feedback to ensure the wanted output to be gotten, so its job is measuring the conditions of process. Simply, some sittings are putting in the controller and the output will be kept constant based on feedback from some input, typically some kind of sensors or meters.

PIDs come in many different forms including standalone units and PLC programming software. PID controller has an advantages which are: it can be implemented easily and it has good effects in controlling.

In this thesis, the classical PID controller was used as controller in modeling of ABS, Figure 11 illustrated the simulation model of classical PID controller.

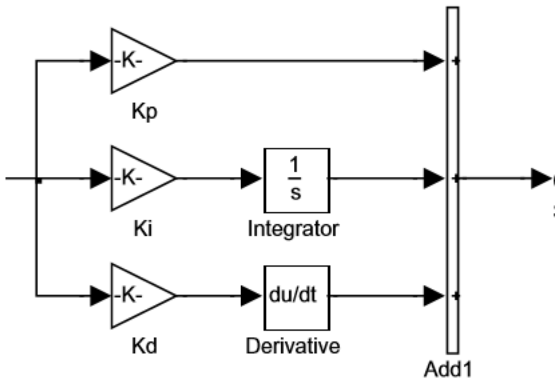


Figure 11. Classical PID controller model

The input of PID controller is the actuated signal and the output is the controller variable, where the input of this system is the combination of the calculated control actions, which are: proportional control $K_p$, integral control $K_i$ and derivative control $K_d$, and each control multiplied to the error signal. PID equation of controller is as Eq. (9):

$$U(t) = Kp\, e(t) + Ki \int e\, dt + Kd\, \frac{d}{dt} e(t) \tag{9}$$

### 3.1.5.3 PD Controller

PD controller is produces an output, which is the union of two types of controllers, proportional and derivative controllers, it can increase system stability and it will not affect the steady state error of the system.

Generally, for proportional controller, the output is proportional to error signal. While, for the derivative controller, the output is proportional to the derivative of error signal.

PD controller used only two types of control gain in parallel which are: proportional control (error gain) $K_p$, and derivative control (error derivative gain) $K_d$ to ensure the output to be the required value of the system. PD control equation is shown as the follows Eq. (10):

$$U(t) = Kp\, e(t) \;+\; Kd\, \frac{d}{dt}\, e(t) \tag{10}$$

## 3.2 Simulink Models

After discussing and analyzing the mathematical equations of motion and the vehicle dynamics properties, then it's time to convert those mathematical and dynamic equations into a model in Matlab/Simulink software environment, Figure 12 represents the map of modeling dynamic and mathematical equations of ABS of vehicle.

The model in Simulink environment can be created by collecting and connecting different blocks that corresponding to the mathematical and dynamic equations, then the model which created in Simulink inters the signals to the workspace window of Matlab environment, and then according to the model which implemented, Matlab will compute and analyze the equations and view the results in scope block in the Simulink environment.

In this work, a single-wheel of vehicle was modeled, and the speed of wheel and the vehicle were calculated and compared to result the actual slip, and then trying to adjust actual slip to the desired slip which equal to 0.2 by using different types of controllers, in Simulink environment the solver of ode45 is used, and then the model can be replicated to consist multi-wheel model.

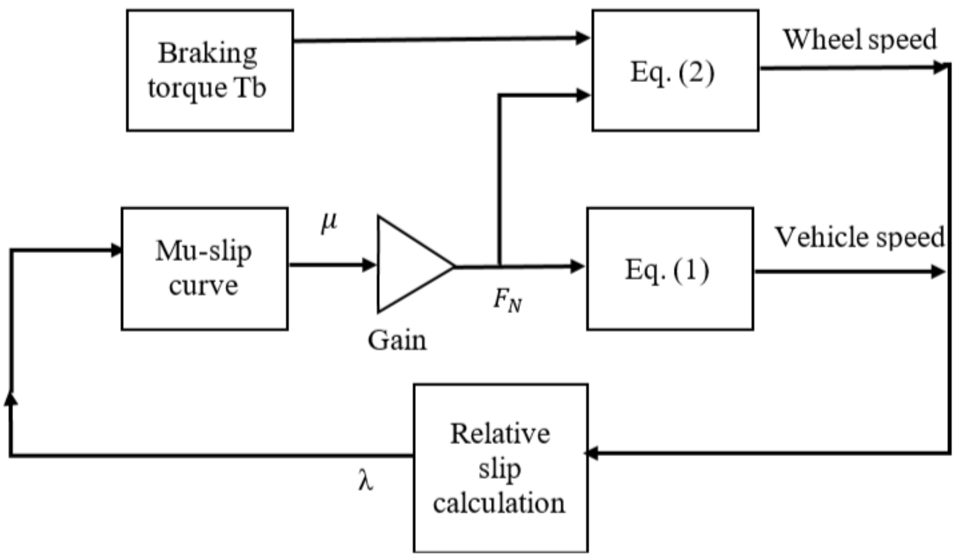


Figure 12. The map of modeling dynamic and mathematical equations of ABS of vehicle

## 3.3 Discussion of The Block Diagram Model of ABS

At first, according to the vehicle speed, the wheel has a rotation speed (angular velocity) before the application of brakes suddenly, and the friction coefficient which resulted from the formula and logged to Matlab is represented and named mu-slip curve block, which was between the tire and dry asphalt and archived in lookup table of Simulink. ABS model multiplied the value of mu by the weight of quarter vehicle which equal to the mass of quarter the vehicle (m), multiplied by the gravitational acceleration (g), to yield the frictional force, then the frictional force multiplied by the tire radius (R) to result the acceleration torque of the tire, in addition to divide frictional force to the mass of the vehicle to result the vehicle angular acceleration (deceleration), then the model integrate the angular acceleration (deceleration) to produce the vehicle velocity. Through vehicle velocity, stopping distance can be obtained by integration. Also through vehicle velocity, the vehicle angular speed ($V_w$) can be known.

On the other hand, there is a braking system which achieve the actions, and the model compute the difference between the desired and actual slip then logging it to the controller ,then the controller fed this signal to braking model to adjust the braking pressure according to the slip error, a delay in hydraulic lines of braking system was represented through first order function, and then integration of its value resulting the braking pressure in the hydraulic line of braking system, then the multiplication of the braking pressure by coefficient of friction of the braking pad will produce the wheel braking torque.

This will help to reach to an optimal slipping rate and ensuring the vehicle has the highest braking efficiency and lateral stability.

Now, there is tow torques, the torque which produced due to braking pressure and the tire torque, and the difference torque is divided by the inertia (I) of the vehicle to produce the wheel acceleration, and by integrating the wheel acceleration the wheel angular velocity ($W_w$), simulation implemented through limited integrations to ensure vehicle speed is positive.

After using tow separated blocks of integrators to find out the vehicle speed or wheel angular speed without slip ($V_w$) and the wheel angular speed ($W_w$), slipping calculation can be achieved through those tow speeds as expressed in equation 5 before, and the relative slip can be computed during time and feeding to the system continuously as closed loop till stopping simulation.

In this simulation, the simulation of ABS model is implemented under these conditions and assumptions; the vehicle was running in a straight line with speed of 100 km/hr, so there are no steering inputs during braking, and the braking action applied suddenly and hardly, five different road types were used, which are: dry asphalt, wet asphalt, dry concrete, snowy and icy roads, through the different controllers. Also the load transferring during braking and the hysteresis of the tire were neglected.

Simulating the model of ABS were applied through using three types of controllers which are: Bang-bang (on-off) controller, PID controller, and PD controller, the conventional braking system which is fitted in the majority of old vehicles and does not contains controller was simulated as well, the conventional braking system is considered as open loop system because there is no feedback in this model, but the other models of ABS are closed loops, and it has feedback logging to controller again during till reaching to stop. The Simulink model of conventional open loop braking system for quarter vehicle can be seen in Figure 13 below, and the ABS Simulink models of Bang-bang, PID, PD controllers also can be seen in Figures 14, 15, 16, respectively.

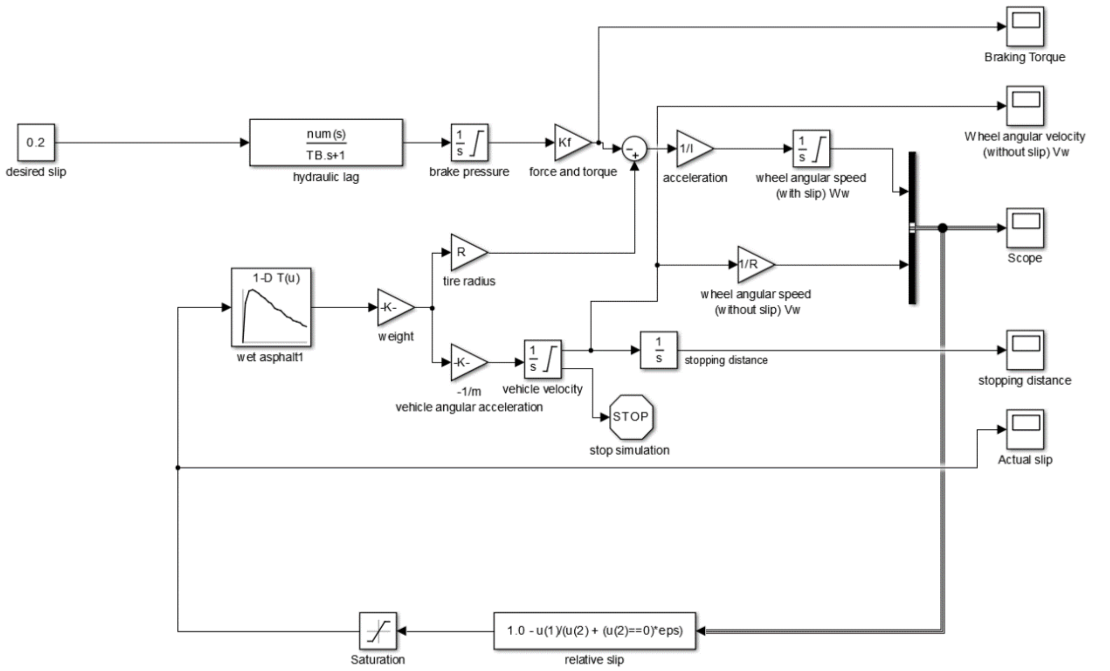


Figure 13. Simulink model of conventional open loop braking system for quarter vehicle

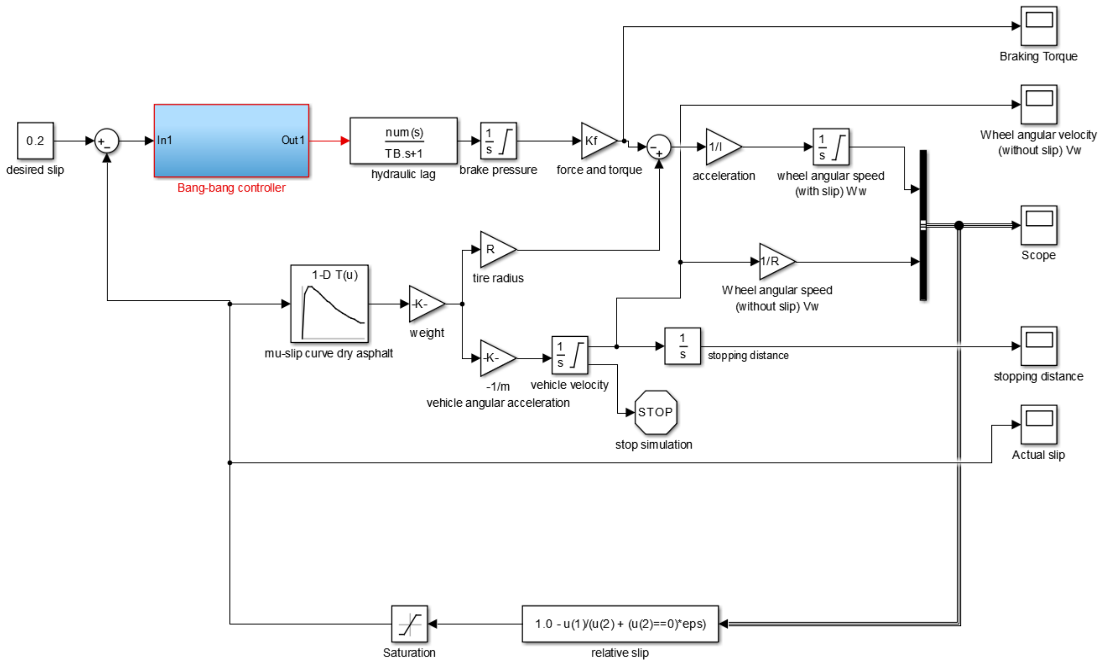


Figure 14. ABS Simulink model of Bang-bang controller

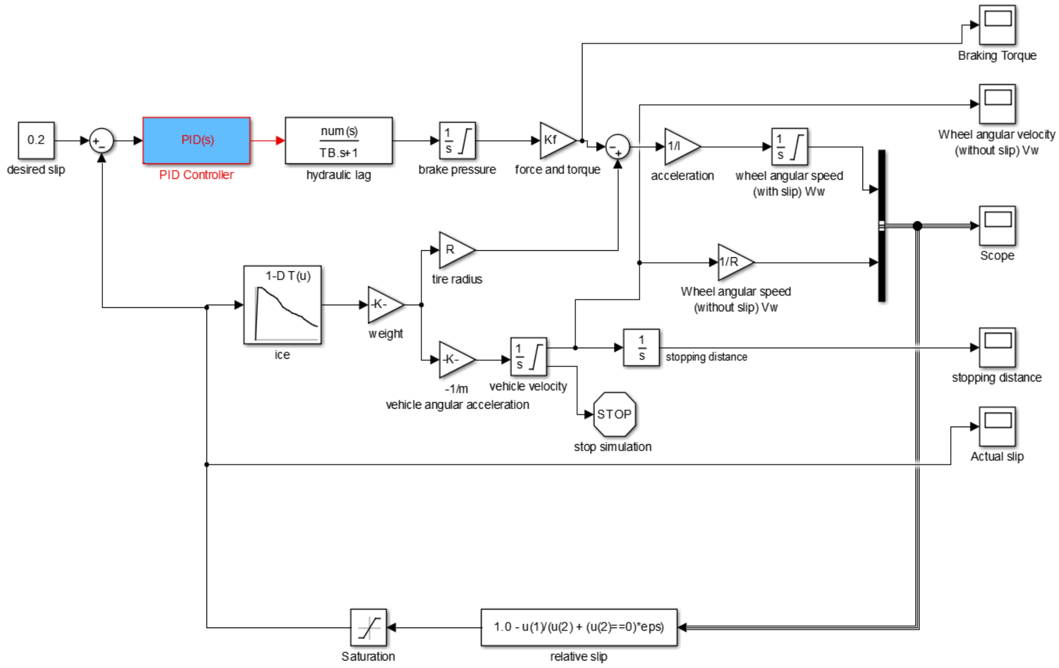


Figure 15. ABS Simulink model of PID controller

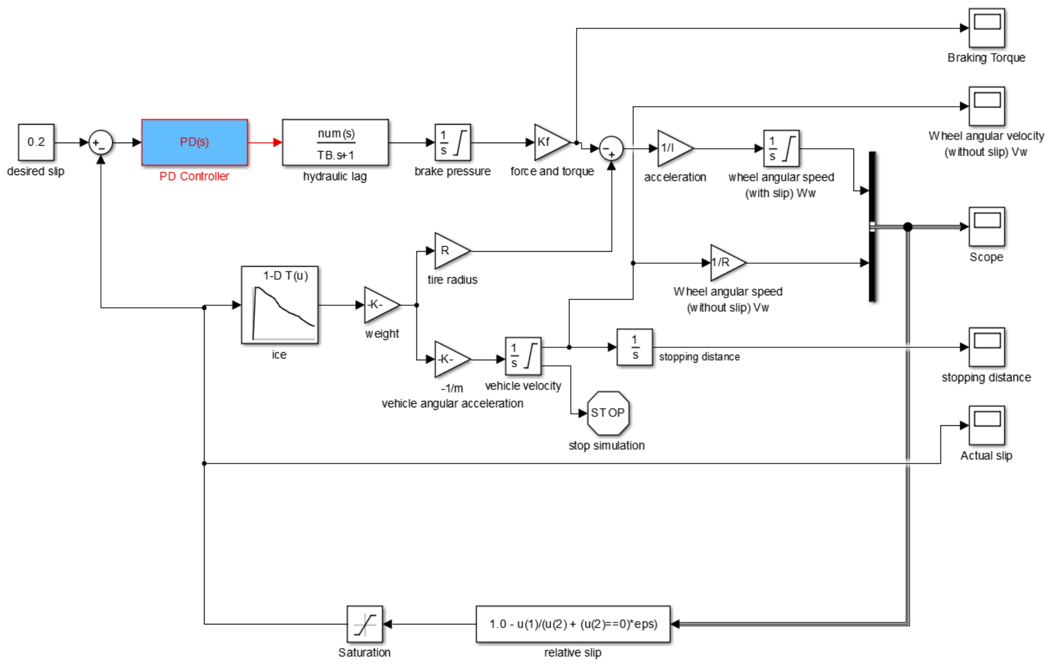


Figure 16. ABS Simulink model of PD controller

# Chapter 4

# RESULTS

In this chapter, the results and slipping response due to implementing different controllers were represented, in addition to compare the results with and without controllers and describing the differences between them.

## 4.1 Parameters Which Used in Simulation

The main parameters of vehicle dynamics which used as inputs to simulate quarter (single) wheel model in Simulink are illustrated in table 2 as shown below, these parameters were used to differentiate the vehicle's behavior, and the efficiency of ABS, which resulted from using different controllers and without control the model.

Table 2. Parameters used in system simulation

| **Parameter** | **M (kg)** | **V0 (m/sec)** | **R (m)** | **g (m/sec$^2$)** | **I (Kg.m$^2$)** |
|---|---|---|---|---|---|
| Value | 300 | 28 | 0.35 | 9.81 | 1 |
| **Parameter** | **Pbmax** | **TB** | **$K_p$** | **$K_i$** | **$K_d$** |
| Value | 1500 | 0.01 | 100 | 10 | 5 |

## 4.2 Results of Hard Braking Application on A Dry Asphalt Road Through Different Simulink Models

As can be seen from the plots below, the dynamics behavior of vehicle was illustrated due to hard braking in a straight line, Figure 17 showing the plots of stopping distance versus time which resulted from Simulink models in cases of absent controller, Bang-bang controller, PD and PID controller.

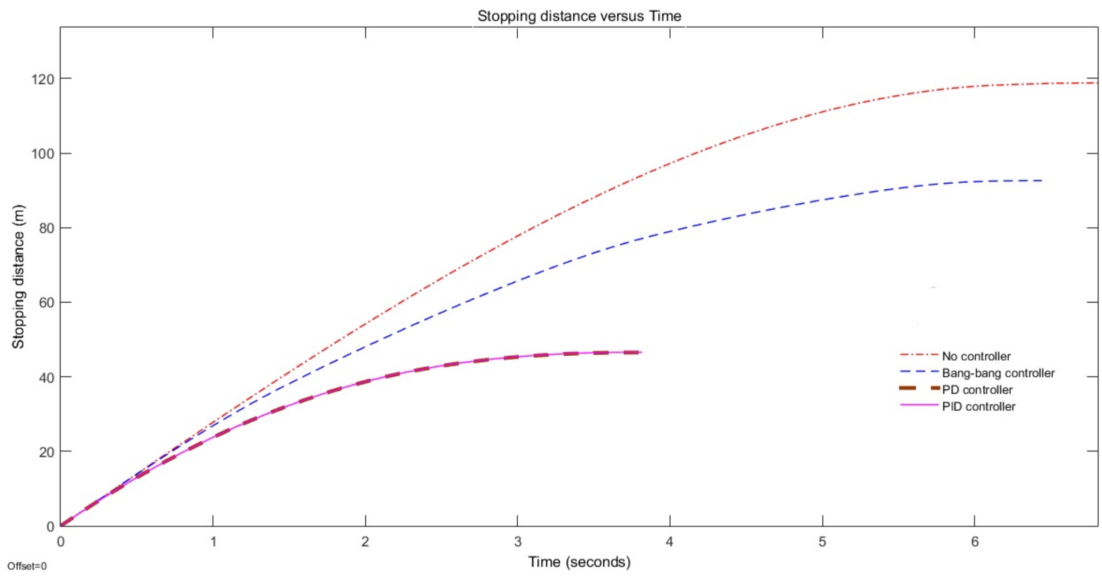


Figure 17. Stopping distance v/s time on a dry asphalt road

## 4.3 Results of Hard Braking Application on A Wet Asphalt Road Through Different Simulink Models

As Figure 18 below showing, the plots of Stopping distance versus time in case of wet asphalt road were obtained, through same Simulink models.

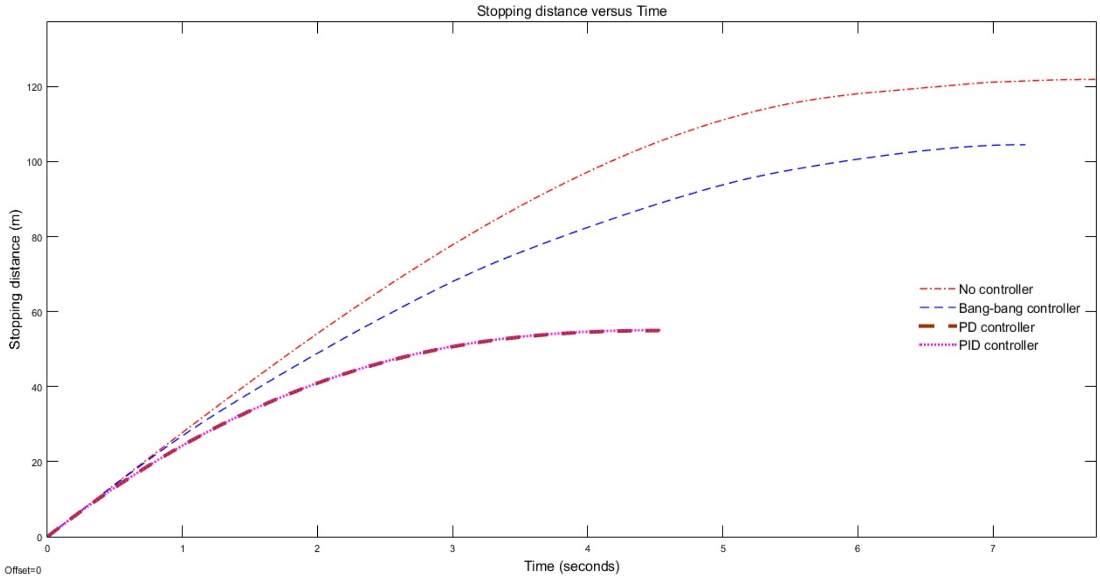


Figure 18. Stopping distance v/s time on a wet asphalt road

## 4.4 Results of Hard Braking Application on A Dry Concrete Road Through Simulink Models

Likewise, plots of stopping distance versus time were represented, in case of dry concrete road, through the Simulink models which had built, as obtained in Figure 19 below.

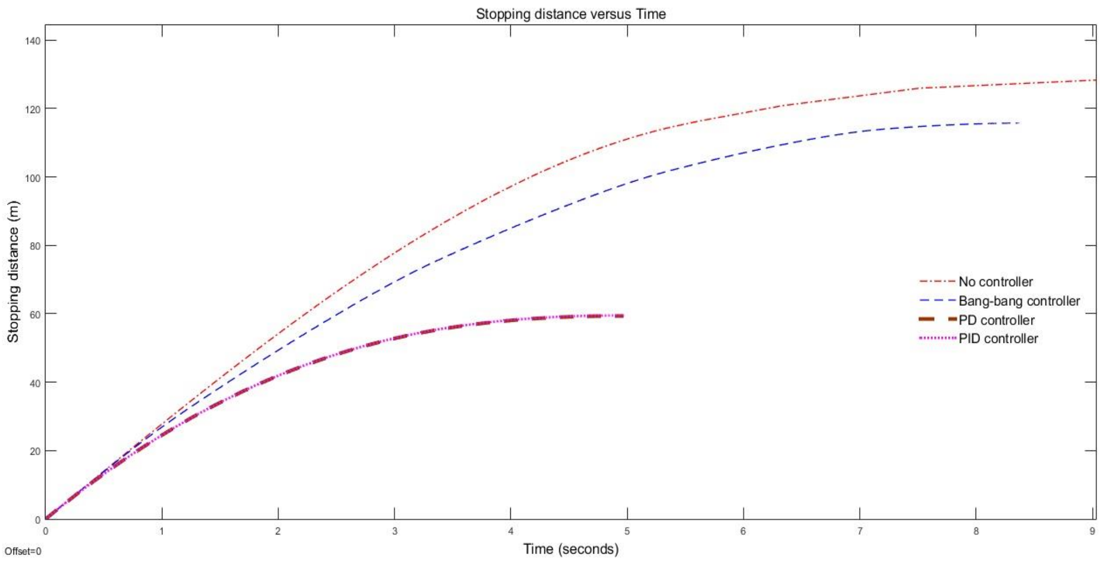


Figure 19. Stopping distance v/s time on a dry concrete road

## 4.5 Results of Hard Braking Application on A Snowy Road Through Simulink Models

Figure 20 show the plots of stopping distance of vehicle versus time, in case of braking on a snowy road, figure illustrates plots when absence controller, and when presence of controller as obtained.

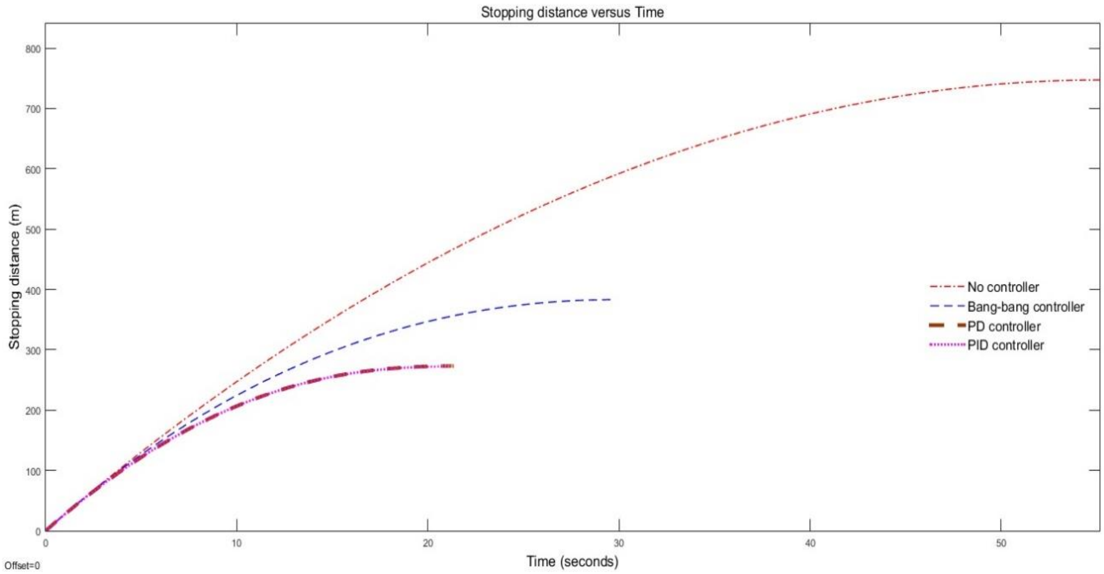


Figure 20. Stopping distance v/s time on a snowy road

## 4.6 Results of Hard Braking Application on An Icy Road Through Simulink Models

Eventually, the dynamics behavior of vehicle was illustrated due to hard braking in a straight line and on an icy road, and the plots of stopping distance versus time which resulted from simulation of Simulink models were combined and illustrated in Figure 21 below.

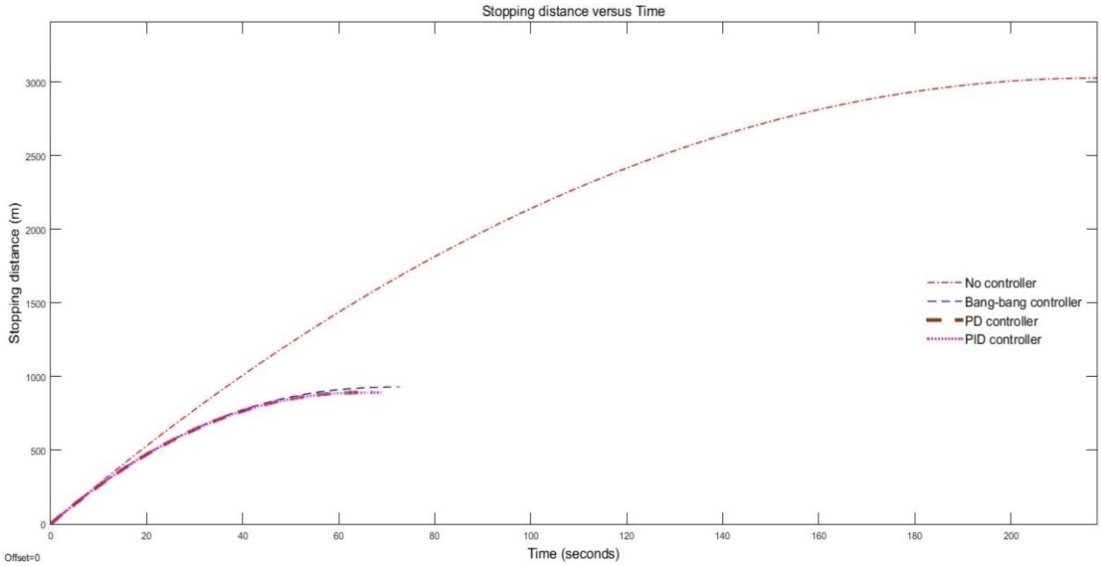


Figure 21. Stopping distance v/s time on an icy road

## 4.7 Results and Discussion

As is evident and apparently from all of the previous results of system simulation, the performance and effectiveness of the ABS is better when there is a controller in the system compared to the simulation without a controller. As can be seen in figure 17 before, the simulation results due to braking on a dry asphalt road through different controllers has various values, simulation of the system in the absence of a controller was given results of 118.8 m for the distance needed to stop, and 6.8 sec for time needed to stop the vehicle. While these values were decreased by the using the controllers in the system. When the Bang-bang controller was applied, the results of stopping distance and stopping time were reduced, so the results improved and it was 92.62 m and 6.44 sec respectively.  When the PD controller was used, better and more efficient results were obtained with respect to the stopping distance that was equal to 46.51 m and 3.8 sec with respect to time needed to stop, so these results is better than Bang-bang or absence of controller. When PID controller was applied, its results were almost similar as in case of PD controller, and better than when the controller is absent, distance needed to stop was 46.6 m and time needed to stop was 3.81 sec, so PD controller can be considered the best controller between these controllers in case of dry asphalt road type. Table 3 below showing the collected values of stopping time and distance related to dry asphalt road, which resulted through the simulation.

As resulted in figure 18, the simulation results due to braking on a wet asphalt road through different controllers has various values, simulation of the system in the absence of a controller was given results of 121.9 m for the distance needed to stop, and 7.76 sec for time needed to stop the vehicle, its higher than in case of dry asphalt. While these values were decreased by the using the controllers in the system. When the Bang-bang controller was applied, the results of stopping distance and stopping time were reduced, the results improved and it was 104.47 m and 7.24 sec respectively. When the PD controller was used, better and the best efficient results were obtained with respect to the stopping distance that was equal to 54.93 m and 4.52 sec with respect to time needed to stop, so these results is better than Bang-bang or absence of controller. When PID controller was applied, its results were almost similar as in case of PD controller, distance needed to stop was 55.04 m and time needed to stop was 4.54 sec, so PD controller can be considered the best controller between these controllers in case of wet asphalt road type. Table 4 below showing the collected values of stopping time and distance related to wet asphalt road, which resulted through the simulation.

According to plots in figure 19, the simulation results due to braking on a dry concrete road through different controllers seems similar to the previous dry and wet road type, simulation of the system in the absence of a controller was given results of 128.3 m for the distance needed to stop, and 9.02 sec for time needed to stop the vehicle. While these values were decreased by the using the controllers in the system. When the Bang-bang controller was applied, the results of stopping distance and stopping time were reduced, so the results improved and it was 115.7 m and 8.38 sec respectively. When the PD controller was used, better and more efficient results were obtained with respect to the stopping distance that was equal to 59.96 m and 4.96 sec with respect to time needed to stop. When PID controller was applied, its results were almost similar as in case of PD controller, and better than PD controller in stopping which was 59.5 m, but in stopping time it was 4.97 sec, so PD controller has the best stopping distance, and PID has the best stopping time in case of dry concrete road. Table 5 below showing the collected values of stopping time and distance related to dry concrete road, which resulted through the simulation.

Simulation results due to braking on a snowy road through different controllers has different values, simulation of the system in the absence of a controller was given results of 747.1 m for the stopping distance, and 55.14 sec for stopping time of the vehicle. While these values were decreased by the using the controllers in the system. When the Bang-bang controller was applied, the results of stopping distance and stopping time were reduced, and it was 383 m and 29.81 sec respectively. When the PD controller was used, better and more efficient results were obtained with respect to the stopping distance that was equal to 273 m and 21.38 sec with respect to stopping time, so these results is better than Bang-bang or absence of controller. When PID controller was applied, its results were almost similar as in case of PD controller, and better than when the controller is absent, distance needed to stop was 272.17 m and stopping time was 21.2 sec, so PID controller can be considered the best controller between these controllers in case of snowy road type. Table 6 below showing the collected values of stopping time and distance related to snowy road.

Finally, the simulation results due to braking on an icy road through different controllers has various values, simulation of the system in the absence of a controller was given results of 3028 m for the stopping distance, and 217.9 sec for stopping time. While these values were decreased by the using the controllers in the system. When the Bang-bang controller was applied, the results of stopping distance and stopping time were reduced, so the results improved and it was 930.5 m and 72.87 sec respectively. When the PD controller was used, better and more efficient results were obtained with respect to the stopping distance that was equal to 893.91 m and 67.09 sec with respect to stopping time, so these results is better than Bang-bang or absence of controller. When PID controller was applied, its results were almost similar as in case of PD controller, and better than when the controller is absent, distance needed to stop was 891.93 m and time needed to stop was 68.88 sec, so PD controller can be considered the best controller between these controllers regarding to stopping time, but PID is the best regarding to stopping distance in case of icy road. Table 7 below showing the collected values of stopping time and distance related to icy road.

Table 3. Simulation results of ABS models of different controllers through dry asphalt road

| System condition | Stopping distance (m) | Stopping time (sec) |
|---|---|---|
| System without controller | 118.8 | 6.8 |
| System with bang-bang controller | 92.62 | 6.44 |
| System with PD controller | 46.51 | 3.8 |
| System with PID controller | 46.6 | 3.81 |

Table 4. Simulation results of ABS models of different controllers through wet asphalt road

| System condition | Stopping distance (m) | Stopping time (sec) |
|---|---|---|
| System without controller | 121.9 | 7.76 |
| System with bang-bang controller | 104.47 | 7.24 |
| System with PD controller | 54.93 | 4.52 |
| System with PID controller | 55.04 | 4.54 |

Table 5. Simulation results of ABS models of different controllers through dry concrete road

| System condition | Stopping distance (m) | Stopping time (sec) |
|---|---|---|
| System without controller | 128.3 | 9.02 |
| System with bang-bang controller | 115.7 | 8.38 |
| System with PD controller | 59.96 | 4.96 |
| System with PID controller | 59.5 | 4.97 |

Table 6. Simulation results of ABS models of different controllers through snowy road

| System condition | Stopping distance (m) | Stopping time (sec) |
|---|---|---|
| System without controller | 747.1 | 55.14 |
| System with bang-bang controller | 383 | 29.81 |
| System with PD controller | 273 | 21.38 |
| System with PID controller | 272.17 | 21.2 |

Table 7. Simulation results of ABS models of different controllers through icy road

| System condition | Stopping distance (m) | Stopping time (sec) |
|---|---|---|
| System without controller | 3028 | 217.9 |
| System with bang-bang controller | 930.5 | 72.87 |
| System with PD controller | 893.91 | 67.09 |
| System with PID controller | 891.93 | 68.88 |

# Chapter 5

# CONCLUSION AND FUTURE SCOPE

## 5.1 Conclusion and Remarks

In this thesis, a simulation of ABS system of a passenger vehicle through Matlab/Simulink was achieved, the system is created by collecting and connecting blocks and modeled as a basic model without any type of feedback or controller, then this basic model is fitted with feedback and connected separately to different three styles of controllers, which are linear and became closed loop system, these controllers was simple controller as Bang-bang controller, and popular and widely used as PID and PD controller. Simulation was implemented with the goal of knowing the behavior and performance of ABS, in case of absence and presence of controller, during braking on different road types, in order to understand the best effective controller through the system.

The results of simulation regarding to the needed time and distance to stop were produced and plotted for each case of simulation. These results concluded clearly that the behavior of ABS is better in case of using controllers than absence of controller since the vehicle and wheel speed can be regulated simultaneously to prevent vehicle slippage, through different road types in case of hard braking. From simulation results, it is monitored that the least distance and time needed to ensure full stop of the vehicle is 46.6 m and 3.81 sec ‘respectively’ when braking on dry asphalt road, and system without controller.

On the other hand, all results which resulted from carrying out a simulation using the controller are results with approximately close values, with regarding to stopping distance, the distance has clearly reduced to 55.04 m, 59.5 m, 272.17 and 891.93 m which belonging to PID controller, in case of wet asphalt, dry concrete, snowy and icy road respectively. In addition to a significant decrease in stopping time than the other controllers, it was observed that the results, according to the outputs that resulted from the simulation, were approximately equal and it was 4.54 sec, 4.97 sec, 21.2 sec and 68.88 sec, respectively to the same road types. It is noted that the vehicle has the least values of stopping distance and time in case of hard braking when PD controller was used, so the most effective and the best performance of ABS was under application of PD controller.

## 5.2 Future Scope

Depending on which system is studied and which is a nonlinear system, and the controllers that were used with this system that are linear, so the efficiency of the controllers may be ineffective enough. In light of this and as a future vision, it is worth using a kind of robust controller so that it is operating in a specific situation of sliding mode. In fact, the controller system of the vehicle model must to be applied in the real time with the microcontrollers of the system of the vehicle model.

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