Mechanical Engineering Final Year Project

MODELLING MOTORCYCLE ANTI-LOCK BRAKING SYSTEM

Name: Jack Waghorne

Student Number: 18066921

Project Supervisor: Denise Morrey

Word Count: 8903

Preface

The aim of this project was to design and produce a virtual model that simulates an anti-lock braking system (ABS). The first stage in this was to gather information surrounding ABS to determine their critical function and gain an understanding of where they are most necessary. The exploration of existing models was key in determining deficiencies and deciding areas which can be further developed. Further research was then carried out exploring topics such as the ABS purpose and function, vehicle & tyre dynamics and methods of control. These topics were selected as they are all crucial to the function of an ABS. This information was then condensed down and displayed in the form of a literature review.

A mathematical model was created using the researched areas mentioned above. This model is what connects the control method the dynamic system. The approach of the project was then planned out to have a clear, achievable, desired product. A design criterion was then specified to establish a minimum standard that the model must meet before completion.

A simple initial model was then created in MATLAB using a basic method on control known as 'bang-bang' control. This was then developed by transferring it from MATLAB to SIMULINK and implementing a more advanced methods of control such as PID and fuzzy logic. The results of these simulations were then validated by comparing the results from other simulation. Once it was determined that the controllers worked to an acceptable level they were then simulated against practical experiments carried out on motorcycles.

The comparison between the real experiments and the simulations results is what determines how effective the model is. The results found were that the model performs much more reliably under lower masses at slower speeds. At higher speeds the model is seen to overestimate results. There reason for this is likely found in the assumptions use, specifically, the neglect of the rolling resistance present on a motorcycle at it moves. The model did perform to a satisfactory degree but must be selective about its use if precise results are critical. While this model does function as intended with the limited scope of this project there are still certainly improvements that can be made to increase the accuracy of results.

Contents

List of Figures

List of Tables

Table of Abbreviations

Word or Phrase	Abbreviation
Anti-Lock Braking System	ABS
Free Body Diagram	FBD
Proportional Integral Derivative	PID
Metres	m
Seconds	s
Federal Motor Vehicle Safety Standards	FMVSS
Millisecond	ms
Very Small	vs
Small	s
Zero	zr
Large	l
Very Large	vl
medium	m
Negative	n
Error	e
Derivative Error	de

List of Appendices

1.0 Introduction

1.1 Background

Motorcyclists are extremely vulnerable road users and exhibit the most fatalities on road compared than any other road user. As figure 1 shows a motorcyclist is 60x more like to be in a fatal accident compared to a car user or more likely than the to be in fatal incident than the 6 main other road user types combined (Department of transportation, 2016b). These harrowing statistics are a clear indicator that more research and work must be completed to improve the safety of motorcyclists. An effective method of improving safety is to implement control system to minimise the effect of human error in dangerous situations. Brakes are a vital component in vehicle safety and stability. When used improperly however can lead to ineffectiveness and the potential to aggravate a situation even more. For example, an inexperienced rider may see an upcoming hazard and have the instinctual thought to apply the brakes as much as possible to stop faster. This method of braking, as will be discussed in depth later in the report, is inefficient and can lead to prolonged stopping distances and less control over the motorcycle. Braking has an even greater hold on stability if lean angles and steering input are incorporated into the situation as excessive braking during cornering can lead to a "sliding crash" (Rizzi *et al*, 2016). Wheel lock-up during corning would almost certainly lead to one of these accidents, as Zellner (1989) states "locked front wheel tends to result in the rapid capsize of two wheelers, even under straight line braking conditions".

.

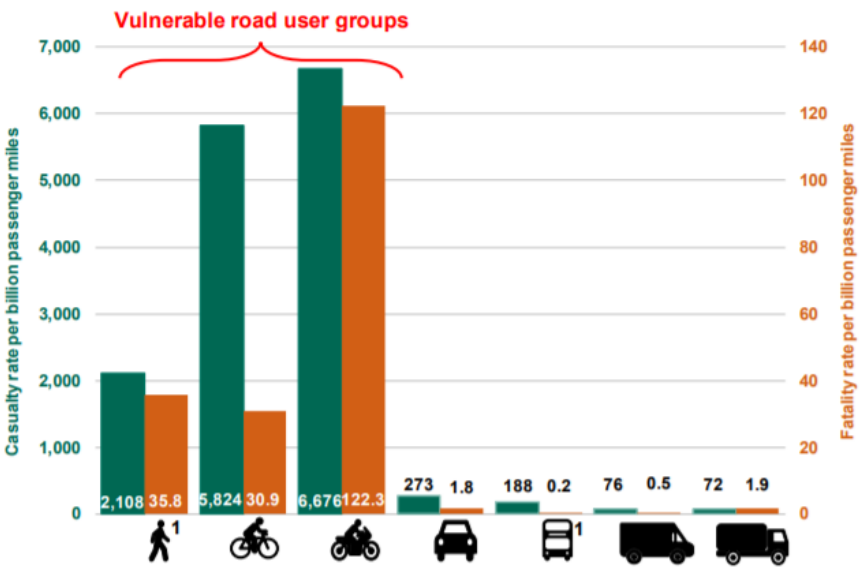

Figure 1- Motorcycle Casualty Statistics

Antilock braking systems (ABS) are a tried and tested solution to this issue surrounding wheel lock up during excessive braking. As the name implies an ABS prevents the brakes from bringing the wheel from coming to a complete stop or ‘locking’ while the vehicle is still moving. How exactly this is accomplished will be discussed in greater detail in section 2.2, but in brief, the brakes are rapidly applied and released to ensure that it is impossible for wheel to come to a full stop. ABS as a product was first introduced in the 1930’s know as ‘anti-skid system’ at the time (Johnson, 2001). ABS was originally designed for aircraft brakes as these needed to be rapidly decelerated in a safe manner upon landing. As research progressed ABS eventually made their way into other modes of transportation, most notably being commercially available in cars for the first time in 1966 (Johnson, 2001); produced by Dunlop. Large issues arose from scaling down a brake system designed for an aircraft into a much smaller car. This explains why the implementation of ABS into passenger road vehicles took a considerable amount of time. Along with being expensive all early ABS systems of the time faced problems with performance, vibration and steerability.

A large shift for ABS came during the 1970’s when electromechanical became more accessible, helped in large part by the advancement of microprocessors. Whilst many of the large automotive manufacturers rejected this shift as electronics in mechanical systems had the reputation of being ‘unreliable’ (Johnson, 2001). Despite this the company Robert Bosch set out to develop a system “providing closed loop control of the wheel slip rates at one or several wheels during braking manoeuvres.” (Bosch, 1995). Bosch aimed that their system would improve steerability, stability, and reduced stopping distances and did not allow it to become commercially available until all these goals had been achieved (Johnson, 2001). Bosch released a fully electromechanical ABS in 1978 and set a strong precedent for all those that followed. Similarly, from change of aircraft to automobile, ABS production for motorcycles was delayed even after Bosch produced his product “due to a variety of technical and practical factors” (Zellner, 1989). The first motorcycle ABS was an adapted car ABS, however this had difficulties as motorcycle brakes function very different to car brakes, being controller by two independent levers. Along with this motorcycle component safety requirements were more stringent due to the more severe consequences of their failure. Though the cost of an ABS is a fraction of the cost it was back then, building and testing physical braking system still cost a significant amount, disincentivising companies to test. Therefore, the development of more advanced, accurate and robust anti-lock braking systems is therefore essential to safety of motorcycle users everywhere.

1.2 Aims and Objectives

Project Aim:

To create a virtual anti-lock braking system control model, capable of storing and displaying data for analysis, of a motorcycle during excessive braking in MATLAB to improve the safety and stability.

Project Objectives:

1. To research a minimum of ten academic and technical documents to build a firm understanding of the dynamics processes taking place when a vehicle undergoes braking and to examine pre-existing control methods used in modern ABS. Condensing this research down into an in-depth literature review that can be referred to throughout the duration of the project. To be completed by the 19th October 2020

2. To design and produce a numerical model of a motorcycle undergoing heavy braking, as if in an emergency stop manoeuvre. Interpreting the numerical model to create a list of all factors whilst doing so. To be completed by 30th October 2020

3. To convert the numerical model into MATLAB. Implementing a closed-loop feedback controller that monitors and adjusts brake pressure applied to attain a desired slip value which corresponds to optimal tyre traction. The model must also contain features, such as arrays and plots, which can be inspected for analysis. To be completed by 18th November 2020

4. To evaluate and contrast results derived from this produced model to those derived from pre-existing models. These results can either be from practical investigations of physical anti-lock braking systems or similar virtual brakes system models. The outcome of these investigations will be what determines if the results achieved by this model are valid or not. To be completed by 23rd November 2020.

5. To create an advanced model of the initial system. This will be accomplished by implementing additional features or advanced control methods, such as a Fuzzy logic and Proportional-Integral-Derivative (PID). To be completed by the 7th January 2021

1.3 Research Justification

The popularity of motorcycles has been annulling increasing for decades, with the number of licensed motorcycles within the UK increasing by almost 75% since the mid 1990's as figure 2 shows, taking it to roughly 1,300,000 in 2019 (Department of vehicle statistics, 2020). The increase in popularity can be partly attributed to their lower upfront cost both to purchase and operate. This accompanied with being more versatile and a faster method of getting from getting to one destination to another. A recent survey by the Department of Transportation (2016a) states that "For the period 2002-2016, over half of all motorcycle trips were for commuting or business purposes". This indicates that motorcycles users are riding more frequently now more than ever. With more motorcycles in use this means that there are more riders that have a chance of getting in dangerous and potentially fatal incidents. The Royal Society for the Prevention of Accidents (2017) stated that "Although motorcyclists only account for 1% of total road traffic, they account for around 18% of deaths on the road". This alarming statistic further demonstrates that even though motorcycles may be becoming more frequent they are still a vast minority and extremely vulnerable.

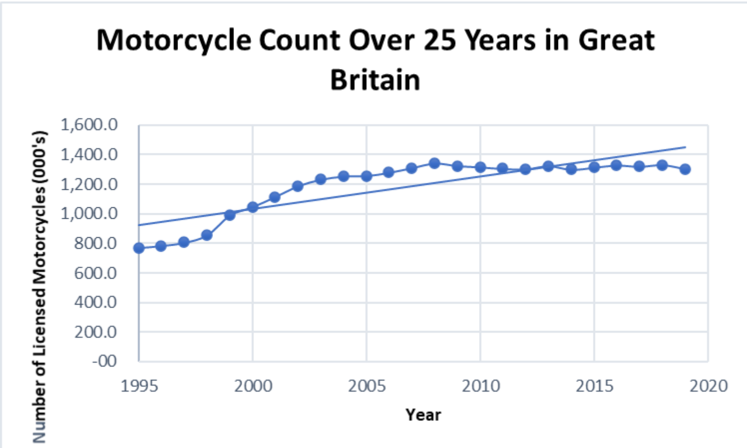

Figure 2 - Number of Licensed Motorcycles (UK)

Virtual models and simulations offer many advantages over traditional operational testing. These advantages range over a wider variety such as "cost, safety and environmental advantages" (National Academic Press, 1998). All these readily available benefits means that multiple industries and organisations such as automotive and Ministry of Defence are rapidly evolving and opting to use virtual models over traditional methods of testing. This reinforces the value of this project as there is a user need (Pugh, 1996) for motorcycle companies looking to perform initial simulations on braking tuning and capabilities without having to invest the capital on manufacturing physical models. These models have been in demand before ABS was even popularised on motorcycles, such as the simulation seen in (Zellner, 1989).

2.0 Literature Review

2.1 Introduction

This section covers all the information gathered in the research of this project. The chapter is divided into the main areas of research investigated. These sections including anti-lock braking system function, Dynamic modelling, Controller modelling. These topics are all key aspects of comprises an ABS. With this in mind, a solid foundation of knowledge on these topics is essential for producing a functioning model.

2.2 Anti-lock Braking System Function

The fundamental purpose of an ABS is to impede the lock-up of a vehicles wheels when excessive braking is applied. This effect is achieved 'by inhibiting further increases or initiating decreases in brake pressure" (Bosch, 1995). This brake pressure is regulated by the release of hydraulic fluid which is controlled by means of solenoids or 'control valves' as the schematic diagram in figure 3 refers to them as. If this release and reapplication of the brake is not carried out the wheel can lock. This can place the wheels into a 'skid condition, during which the deceleration is controlled by the tyre-road friction coefficient and the vehicle is uncontrollable.' (Day, 2014). The point at which the brake is applied and released is determined by the ratio of relative slip between the wheel and the vehicle, this is explain in greater detail in section 2.3.4. In essence the role of an ABS is to keep the wheels of a vehicles at an optimal level traction whilst allowing the vehicle to remain manoeuvrable.

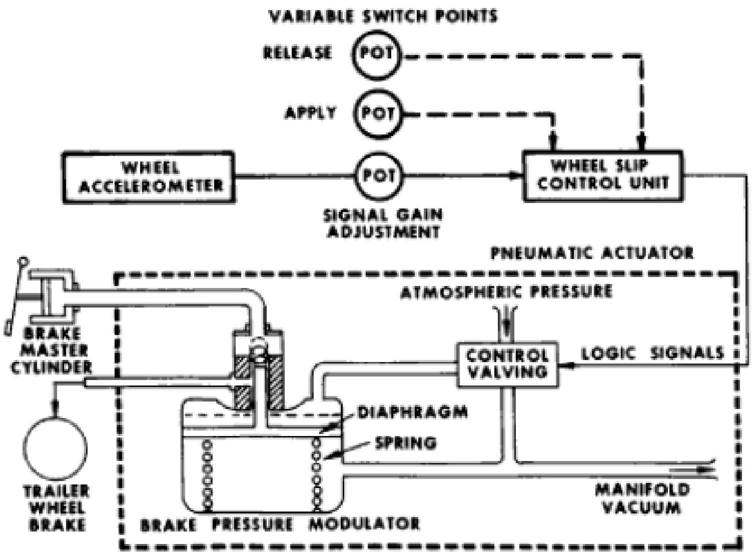

Figure 3 - ABS Schematic Diagram (Harned, 1969, pg.912)

2.3 Dynamic Modelling

2.3.1 Motorcycle Model

Vehicles dynamics play one of the most important roles in creating a braking system model. As without a comprehensive understanding of the forces acting unpon the system, the model will never be correct to yeild accurate results. There are many different model describing scenarios such as this but a common model known as the 'single corner model' (Tanelli *et al*, 2014, p.202). This type of model was seleted for use in this project. This model was selected as it simplifies the system down to only considering the forces acting upon one wheel of a vehicle. A free body diagram (FBD) reppresenting the components affecting the dynamics are shown in figure 4.

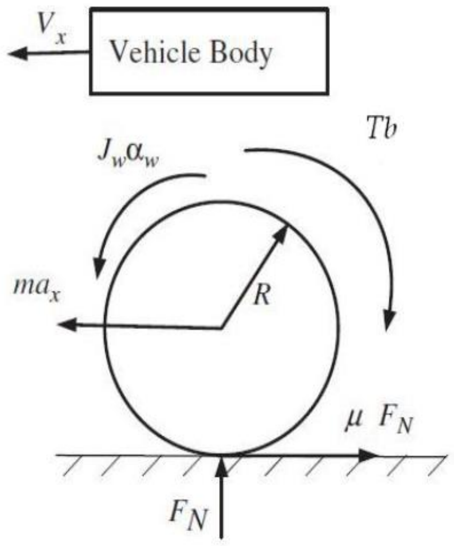

Figure 4 - Single Corner Model (Bhivate, n.d, pg. 9)

Simplfying a complex dynamic system such as a motorcycle down this much leads to shortcomings in the accuracy of results. These shortcomings are further intesified by applying it to a motorcycle rather than a car as it was orginally designed for. These flaws have been explored further in (Corno *et al*, 2009) a book addressing the matter. In the limited scope of this project however the errors associated with this model are not of great significance as the model is designed to be robust, meaning there will inherently be assumptions within the model. This model and the system of equations derived from it describes the plant of the system as seen in figure 5.

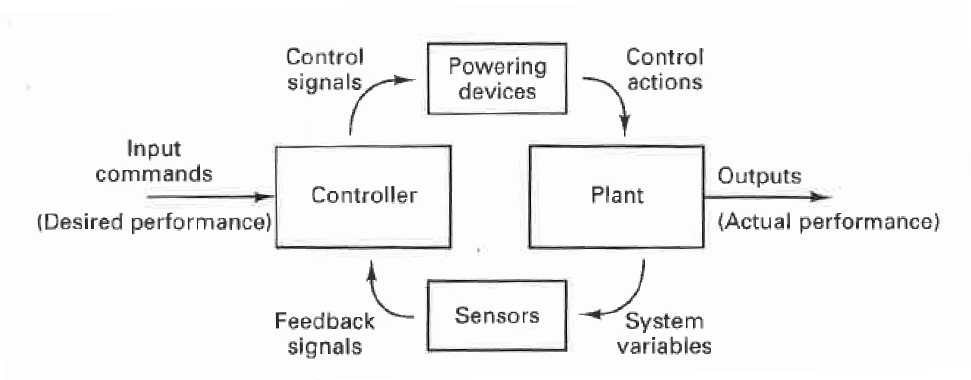

Figure 5 -General Control Block Diagram (Lewis and Yang, 1997)

2.3.2 Longitudinal Forces

The following section discuss the derivation of the equations used to describe the dynamics system of the motorcycle braking. Table 1 lists the definitions of the variables used along with their respective units.

Table 1 - Table of Variables

Variable Name	**Symbol**	**Units**
Acceleration	a	m/s^2
Force	F	N
Half mass of motorcycle	m	kg
Time	t	s
Linear Velocity	V	m/s
Angular Velocity	ω	Radians/s
Coefficient of friction of tyre	μ_t	-
Vertical reaction force	F_r	N
Acceleration due to gravity	g	m/s^2
Displacement	D	m
Angular acceleration	α	$Radian/s^2$
Braking Torque	T_b	Nm
Mass moment of inertia	J	$kg\ m^2$
Slip Ratio	λ	-
Pressure	p	Pa
Rate of pressure change	$\dot{p}$	Pa/s
Coefficient of friction of brake	μ_b	-

Using figure 4 the different forces acting upon the wheel during braking can be seen. First looking at the vehicle body longitudinally, the following equation can be derived.

$$a = \frac{F}{m} \equiv \frac{dV}{dt} = \frac{F}{m} \qquad (1)$$

The mass (m) used in equation represent the half mass of the motorcycle used in the model, this removed the unnecessary need of manipulation later. To find the velocity which is required to determine how close the motorcycle is to stopping both sides must be integrated with respect to time.

$$V = \int \frac{F}{m} dt \qquad (2)$$

The only force acting longitudinally is the frictional force of the tyre acting to slow the motorcycle down, therefore:

$$F = -\mu_t \times F_r = -\mu \times m \times g \qquad (3)$$

The value of gravity (g) used throughout this project will be a standard value of 9.81m/s^2. After substituting and simplifying equations (3) into (2) the final equation for velocity is shown in equation (4). This equation can also be seen other models such as (Genta, 1997, pg. 188).

$$V = \int -\mu_t \times g \, dt \qquad (4)$$

Another desirable output to obtain from data is longitudinal displacement or as it is more appropriately named in this example, stopping distance. To obtain stopping distance the function is simply integrated again.

$$D = \iint -\mu_t \times g \, dt \qquad (5)$$

2.3.3 Rotational Forces

Newtons second law is again applied to equivalate the forces however this time with respect to the rotational direction:

$$\alpha = F_r \times R - T_b \times J \equiv \frac{d\omega}{dt} = F_r \times R - T_b \times J \qquad (6)$$

In contrast to equation (3) it is frictional moment that drives the wheel forward while the brake torque (Tb) is acting against this to slow the wheel down. Using the relationship from equation (3) of frictional force the new formula becomes:

$$\frac{d\omega}{dt} = \mu_t \times m \times g \times R - T_b \times J \qquad (7)$$

Identical to before to find the rotational speed of the wheel the formula must be integrated with respect to time. This equation can be seen in papers by (Bhivate, n.d) and (Saswata, 2015), support its use.

$$\omega = \int \mu_t \times m \times g \times R - T_b \times J \, dt \qquad (8)$$

2.3.4 Tyre Dynamics

Another core aspect to consider when designing the model braking model is tyre dynamics. Specifically, the interactions that occur between the road surface and the tyre of the vehicle during braking that affect properties such as traction. Wheel slip (λ) is one of the properties that affect how much traction is maintained with the ground. Slip, for a braked wheel, is defined as the difference between the driving speed (V) and the circumferential speed (ω) divided by the driving speed (Meywerk, 2015, pg.21). To put this formulaically:

$$\lambda = \frac{V-\omega\times R}{V} \qquad (9)$$

Logically, to achieve the fastest possible brake time, the wheel must have the greatest amount of friction to the road as possible. Friction is a function of slip therefore the greatest amount of friction can only be achieved at a certain percentage of slip as figure 6 shows.

There are two prevalent empirical models that describe this type of interaction; the relatively recent model created by Hans B. Pacejka commonly referred to as the "Magic Formula" (Pacejka, 2012, p.165) the other somewhat dated model being Burckhardt's traction formula (Dousti *et al*, 2014). The model being used throughout this project will be Burckhardt's, this was decided as fewer known variables are required to obtain results, making for a more robust model. The Burckhardt model shown in equation (10) describes the relationship of the tyre longitudinal force coefficient (μ) (Meywerk, 2015, pg. 22) as a function of slip and velocity. Constants C_1-C_4 are dependent on road conditions and are derived from experimental data (Dousti *et al*, 2014) these can be seen in table2.

$$\mu\lambda, V = [C_1(1-e^{-C_2\lambda}) - C_3 \times \lambda]e^{-C_4 V} \qquad (10)$$

Table 2 - Buckhardt Tire Model Parameters for Various Road Conditions (Saswata et al, 2015)

SURFACES TYPES	C_1	C_2	C_3	C_4
Dry asphalt	1.2801	23.99	0.52	0.03
Wet asphalt	0.857	33.822	0.347	0.03
Dry concrete	1.1973	25.168	0.5373	0.03
Snow	0.1946	94.129	0.0646	0.03
Ice	0.05	306.39	0.00	0.03

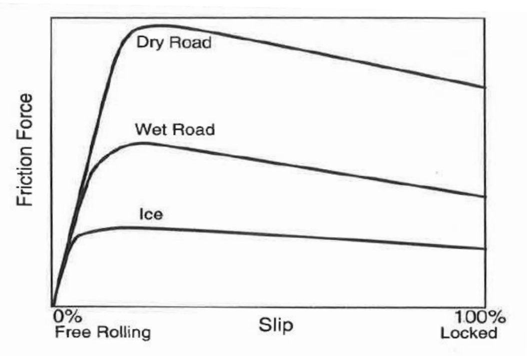

Figure 6 - Burckhardt Friction Model (Gillespie, 1992)

2.3.5 Model Assumptions

Considering all factors that influence a system is often a lengthy and, in some cases, an almost impossible task. It is then imperative during the modelling process to make rational and informed assumptions as these will have a direct impact on the accuracy of the model. Edwards and Hamson (2001) write that “If models are the building blocks, then assumptions are the cement with which put the structure together.” This highlights the importance of making sensible assumptions. The assumptions that allow the use of the equations previously mentioned in section 2.3 are as follows:

- There is no lean angle or steering input from the rider. Hence the motorcycle is only travelling longitudinally.
- Load transfers generate from pitch motion is negligible. Hence All forces acting vertically remain constant.
- There is no change in dynamic wheel radius induced by braking (Tanelli, 2014).
- Road surface conditions do not change during braking, for example, there are no patches of ice or puddles in the road.
- The brakes are modelled as ideal, meaning that friction is not affected by factors such as temperature, wetness or material defects.
- The time delay of brake actuation caused by hydraulic lag is negligible, estimated to be a pure time delay of 7 (ms) (Geromel, 2014, pg. 29)
- Rolling resistance has been neglected as it only contributes about 0.09 m/s^2 of deceleration (Gillespie, 1992, pg. 49) or 2% of the weight force (Cossalter, 1992, pg. 74).
- Aerodynamic drag has been neglected as it is still considered as small relative to the braking torque however could be noticeable at higher velocities (Cossalter, 1997).

Using the information gathered from sections 2.3.1-2.3.4, It is possible to create a list of all factors (Edwards and Hamson, 2001). These have tabulated below and categorised into inputs and outputs as table 3 shows. These are also known as disturbance factors and controlled variables (Bosch, 1995, pg.40).

Table 3 - Input and Outputs of System

Inputs	Outputs
Mass of Motorcycle (m)	Longitudinal Velocity (v)
Radius of Wheel (R)	Rotational Velocity (ω)
Moment of Inetia of Wheel (J)	Displacement (D)
Inintial Velocity (V_o)	Slip (λ)
Road/ Weather Conditions	

2.4 Controller modelling

All ABS system function on the same principle, to keep wheels at an ideal slip ratio to achieve maximum friction (Bosch, 1995). This measurement of slip ratio is completed over discrete time intervals, making this a discrete-event controller. Lewis and Yang (1997) describe that discrete "may occur as the result of detecting that a continuous signal is greater than (or less than) a selected reference level." With the ideal slip ratio representing the reference level which the controller will operate around. This cycle of measuring the state of the system and responding accordingly is depicted in figure 7.

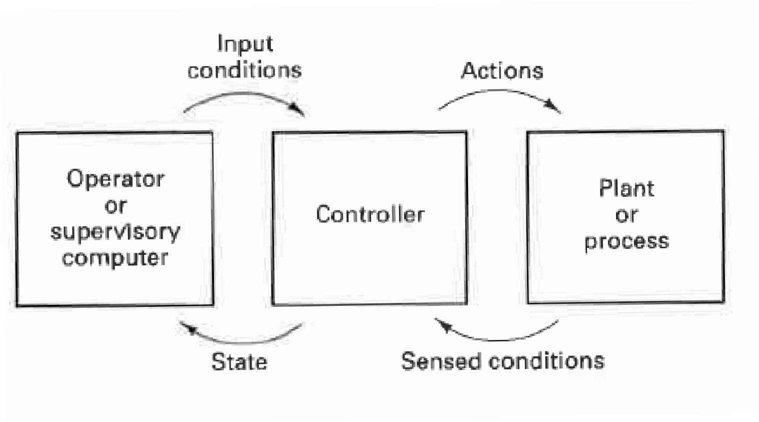

Figure 7 - Block Diagram of Discrete Controller (Lewis and Yang, 1997)

The difference between the actual and desired slip, also known as error (e), is what the controller interprets to decide the proportion of brake pressure must be applied or released. This pressure is what commences the entire braking process as Bosch (1995) states "the control system is defined as starting at the point in the brake system to which the actuation force is directly applied". This brake pressure is then multiplied by the piston area and radius to yield the brake torque as seen in equation (12). This equation is also seen in (Han at al, 2017) thus supporting its use.

$$Brake\ Pressure\ (p) = \dot{p}\ \times step\ size \quad (11)$$

$$Brake\ \ Torque\ (T_b) = p \times \mu_b\ \times piston\ area\ \times piston\ radius\ (12)$$

Where ṗ is the rate of change of brake pressure measured in (Pa/s). The 'step-size' describes the time interval in between each measurement, this can be varied but will be used throughout this project as 0.001 seconds (s). The step size can decrease to improve the accuracy of the results; however this will have prolong the run time of each simulation.

Once the controller has adjusted brake pressure the variables are then run through the series of equations in the plant as described in section 2.3. The plant then yields a new value of slip ratio to be input into the controller and the cycle repeats. This system is what is known as a closed loop feedback system which is visually displayed in figure 8.

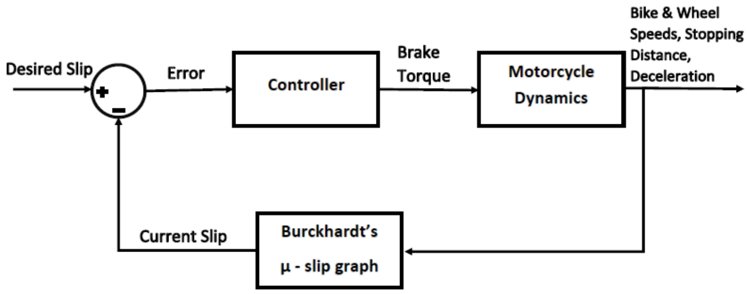

Figure 8 - ABS Block Diagram

2.4.1 Bang-Bang Control

The first controller developed in this project was a very simple 'On/ Off' (Saswata *et al*, 2015) or 'Bang-Bang' controller. This type of controller operates on the simple premise that the controller output (in this case brake pressure) is increased until the output matches or surpasses the set point. Once this is accomplished the output will immediately cease (pressure released). This very simple method of control only considers the error and no other aspects of the plant and hence offers very little for stability or efficiency as will be discussed later in the project.

2.4.2 Fuzzy Control

A more advanced model was then chosen to be based on fuzzy logic. Unlike the digital 'On/ Off' method of control used previously, fuzzy logic is a method of control much better suited for modelling analogue processes (Cox, 1992). It works by dismantling a variable within a process into ranges of values or 'sets' and assigning them subjective linguistic definitions (Darus *et al*, 2009). An example of these sets can be seen in figure 9. These inputs are then entered into a rule base and interpreted by the system which then determines the output. Using figure 9 as an example if temperature is **hot and** room is **empty** then lower temperature. This subjectivity of its definitions is what allows fuzzy logic to be powerfully adaptable depending on what the requirements are.

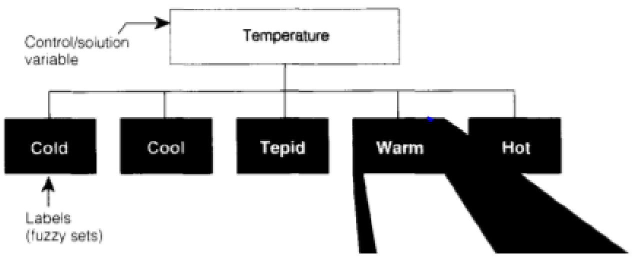

Figure 9 - Fuzzy Network Sets (Cox, 1992)

2.4.3 PID control

Similar to Bang-Bang control, PID control works raising the output based just om the error. But rather than inputting the error directly into the controller, it first undergoes a series of transformations beforehand (Lewis and Yang, 1997). The input error is simultaneously multiplied by a gain, integrated and differentiated (both with gain values of their own) then summed together to give a new input which is then fed into the controller as shown in figure 10. The value of each gain can be adjusted to meet the desired performance criteria, this is known as tuning and will be demonstrated further on into the project. It is not necessary for all three of the transformations to take place to create an improved controller, however, PID control has been used here because Lewis and Yang (1997) state "the differentiator and integrator operating in parallel combine the desired performance characteristics of PI and PD control with surprising effectiveness".

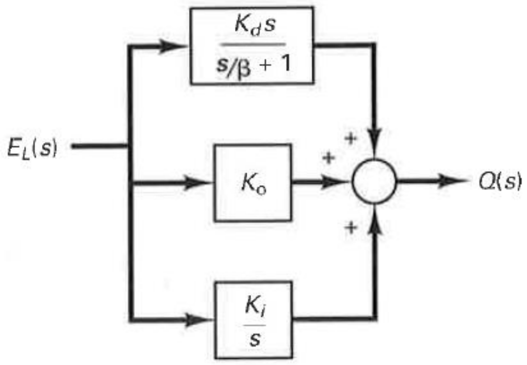

Figure 10 - Example PID Controller (Lewis and Yang, 1997)

2.5 Summary

In summary ABS on motorcycles can shorten stopping distances and provides the rider with steerability and stability of their motorcycle whilst under heavy braking. This can lead to a reduction in dangerous incidents caused by wheel lock up which would occur without it. Using information gained from thorough research into vehicle dynamics a series of equations have been established that describe the dynamic system of the wheels and motorcycle. Assumptions have been made about this model that must be taken into consideration when analysing results. The model was used as the plant in the feedback control system. A list of all factors has been created and divided into the necessary inputs and outputs of the system. The performance of this system is dictated by the method of control used. The different types of controllers that have be evaluated throughout this project have been discussed in brief but will be explain further in section 4.

3.0 Methodology

3.1 – Methodology Literature

To complete this model to within a sensible timeframe and to suitable standard it is very important to understand the fundamentals of design. Design not only entails the features which the model will contain. Design is also defined by Childs (2018) as “the process of conceiving, developing and realising products”. There are many different approaches that can be taken to a project, each with their own advantages and disadvantages. Many people that are unfamiliar with the design process may consider to very linear practice. In contrast to this many design methods take on an iterative process such as the one seen in figure (11). The ‘idea’ and ‘calculation’ stages have already been met in section 1 and 2. Much of the iteration process comes from the ‘synthesis’ and ‘evaluation’ stages. This is because these are stages where the product is constructed, critically reviewed, and then adjusted according to results. Pugh (1996) and Childs (2018) both discuss the use of ‘Total Design’ being used throughout a project, many of these aspects have been incorporated in this project. However not all have been applied as they are specific to physical product design. Given that this project is a virtual simulation there are differences in this approach. Mathematical modelling to determine a plant for a system takes on method of its own as seen in figure 12. Developing a control system can take on a general approach such as the one seen in figure 13. This can vary between different control methods and certain controllers might require certain methods such one seen for fuzzy controllers seen in figure 14.

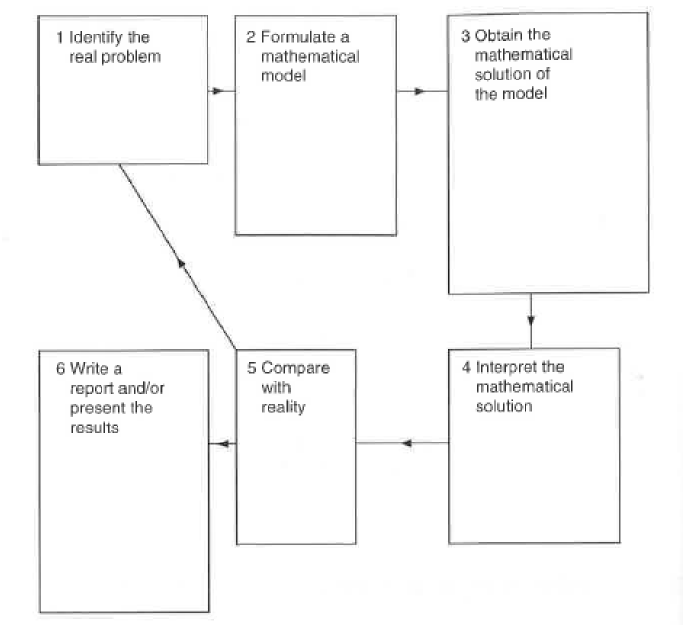

Figure 12 - Modelling Methodology (Edwards and Hamson, 2001)

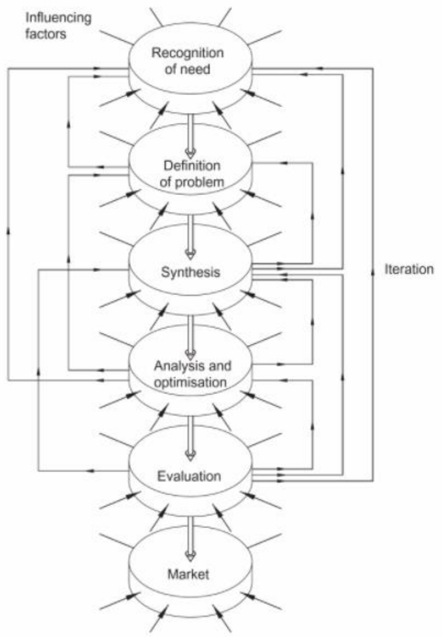

Figure 11 - Total Design Methodology (Childs, 2018)

3.2 Methodology of this project

3.2.1 – Overall Structure

Using information gathered from the literature gathered in section 3.1, these concepts have been applied to the scope of this project. The project began by discovering the need for a product, in this case, a virtual model tailored to a motorcycle scenario as discussed in section 1. Following this a gap in the market can be identified which justifies the creation of this product. Thorough research about ABS was then completed to ensure an extensive understanding on the topic was known. This information was then compiled into a literature review to be used as a reference throughout the duration of the project. Using the knowledge attained in the research a mathematical model to describe tyre, brake and motorcycle behaviour during braking was developed. From this a list of inputs and outputs were be created in establish initial parameters of the model as seen in section 2.3.5.

3.2.2 Creating the Bang-Bang Controller

The next task was to then translate the hand mathematical model over to MATLAB. This was a time-consuming task as all aspect seen within figure 13 had to be considered. Features that had to be included to meet these requirements such as connecting the series of equations to create an iterative dynamic model, creating data arrays, and establishing the close loop control. Data arrays were an essential component of all these controllers as they allow the storage of measurements at discrete time intervals. These allow the study of "time domain behaviour of continuous-time systems" (Lewis and Yang, 1997) which is necessary for performance evaluation. Once the model was finished and functioning was tested multiple times over a variety of conditions to assess its accuracy and limitations. The model was validated against other models created in different studies.

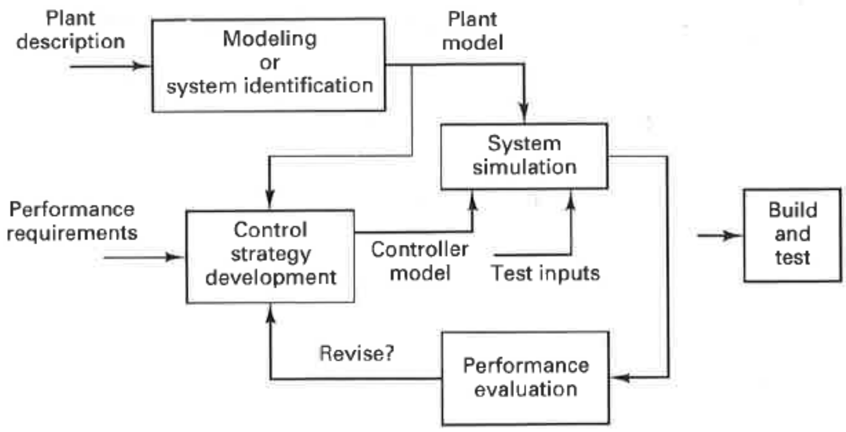

Figure 13 - Control System Design Methodology (Lewis and Yang, 1997)

3.2.3 Creating the PID Controller

The PID controller was developed from the previous bang-bang but rather than using MATLAB, the model was translated to Simulink as seen in figure 36. A PID control block was then added before the controller to create the PID control. The model was then again run and tested over a variety of conditions to ensure its proper function. Once this was confirmed the controller was then tuned and run again to validate results with other models and practical experiments.

3.2.4 – Creating the Fuzzy Logic Controller

Many different methods were considered when deciding how the fuzzy controller should function. Methods such as those seen in (Lu *et al*, 2015) and (Mauer, 1995) were considered but rejected. Unlike the other two controllers there are many variables that can be used to control the output of the controller, each with their respective advantages. Once suitable control variables had been selected the methodology seen in figure 14 was followed. The model was then repeatedly run and adjust made to the membership function as well as rule list to improve performance. Once the model performed to a suitable level, results were then compared to those from models that use the same control variables.

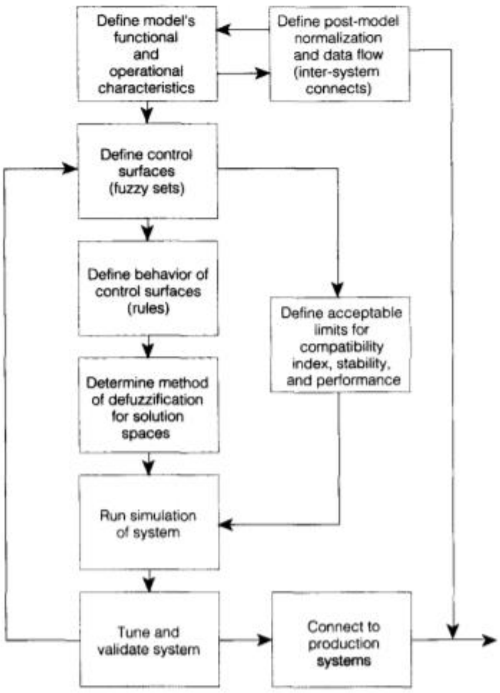

Figure 14 - Fuzzy Controller Methodology (Cox, 1992)

3.3 Model criteria

When entering the modelling stage of this project, it was important to set objectives which the model achieve before it is progressed. As Childs (2018) writes "Specification is usually critical for effective design". Using research gathered in sections 2 and 3 the following criteria was created:

- Must reduce stopping distance more than without ABS.
- Must be able to perform on different road conditions.
- Must be adaptable to different motorcycles. Therefore variables, such as mass and wheel geometries must be adaptable.
- Results must be validated against other models or Practical investigations.
- Performance must reach legal standards.

As with much of the methodology the design specification had to take an iterative approach, as it would be impossible to define all aspects of a project before completion. New criteria were added once it was discovered. This criterion is, in many ways, similar to a product design specification (PDS). Which Pugh *et al* (1996) describes as "A PDS defines, in greater detail, the constraints upon the artefact to be designed". Having these constraints was essential to ensure that the model was made to a suitable standard, whilst also giving the project directions with what needed to be achieved upon completion.

The legal standards that that the system must abide by are those set out in the Federal Motor Vehicle Safety Standards -122 developed by the National Highway Traffic Safety Administration (U.S. Department of transportation, 2013) which are specific to the performance of braking systems of motorcycles. The standards shown in table 4.

Table 4 - FMVSS-122 Legal Braking Standards (U.S. Department of transportation, 2013)

Standard Number	Condition	Performance Requirement
1	Dry road, initial speed of 60 (V) km/h	$\text{Stopping distance (S)} < 0.0087 \times V^2$
2	Dry road, initial speed of 125 km/h	$\text{S} < 0.0067 \times V^2$
3	Wet road, initial speed of 60 km/h	$\text{S} < \dfrac{0.0067 \times V^2}{Max\ friction\ coefficient\ (\mu)}$
4	Wet road, initial speed of 60 km/h	Deceleration (d) over the initial 0.75 > 1.65
5	Wet road, initial speed of 60 km/h	Total average deceleration > 3.3

4.0 Model Production

4.1 Determination of variables

Using the dynamics discussed in section 2.3 there are some variables that are required to be known to make the model function as intended; These variables are all seen in table 5. In all the examples demonstrated in this project will be using a Harley Davidson sportster as this is a very popular model within the UK which could benefit from being retrofitted with a modern braking system. The variables were determined through research using the following sources:

Table 5 - Table of Simulation Variables

Variable	Value	Source
Mass of motorcycle	261kg	Harley Davidson, 2005
Brake Piston Area	9.58cm^2	https://www.motorcycleid.com/performance-machine/brake-caliper-piston-mpn-0052-1400.html?vehicle=179639, n.d
Brake disc effective radius	130mm	https://www.arhcustom.co.uk/product/braking-floating-brake-rotor-front-300mm-l-r-for-harley-davidson-15-20-softail-06-17-dyna-08-17-touring-and-14-20-xl-arm271449, n.d
Brake disc friction coefficient	0.38	Han *et al*, 2017
wheel mass moment of inertia	0.72 kgm^2	Gallego, 2011, pg. 29
Wheel Radius	0.331m	https://www.motorcyclespecs.co.za/model/h-d/harley_davidson_xl_883_sportster%2001.htm, nd
Rate of brake-line pressure	+750bar -500bar	Geromel, 2014, pg. 29

These variables have all been used consistently throughout this project, specifically during the testing and analysis stages so results can be adequately compared. Variables such as wheel radius, motorcycle mass, road condition and initial sped would be required to be adjustable to match the scenario present in other studies. This meant that the program would be required to have variables as user inputs. This was accomplished using 'input' functions in MATLAB and a series if statements as can be seen figure 15. An example of the difference that adjusting these variables makes can be seen in appendix figures 37 and 38.

```
road_con = input('What is the road condition? dry asphalt, wet asphalt, dry concrete, snow or ice ','s');

   if strcmpi('dry asphalt', road_con)
    c1 = 1.2801;
    c2 = 23.99;
    c3 = 0.52;
    sd = 0.2;
```

Figure 15 - User Inputted Variables Code

4.2 Initial Bang-Bang Controller

The First model created was a very basic 'Bang-Bang' controller in which the brakes are applied up until the desired value of slip has been reached. Once the value exceeds the desired value the brakes are immediately disengaged to decreased slip. This causes the slip value to widely teeter around the desired value. This control was implemented into MATLAB using a simple if and else statement determined by the error of slip ratio as shown in figure 16. It was necessary for boundaries to be established as without these the model would not behave as a real system would.

```
e = sd-s; % error calculated
     if e > 0 %on/ off switch equivalent
      p = p + 75000000*step;
      Tb = 0.00004735*p; %Pressure*FricitonCo*Radius*Area

            if Tb>1200 %maxiumum limit on braking torque
             p = 4820000;
             Tb = 1200;
            end
     else %If error < 0
      p = p - 50000000*step; %Release pressure rate
      Tb = 0.00004735*p;
            if p < 0 %Boundary to reject negative pressure
               p = 0;
            end
      end
```

Figure 16 - Bang-Bang Control Method Code

This method of control, though simple and easy to implement, is not a greatly effective as an ABS control system as the tyre is only at an ideal slip ratio very briefly. This creates large variations of wheel slip ratio increases the amount of time to return to the ideal slip ratio. Prolonging the time to return to ideal slip ratio increases the braking distance and stopping time, both of which can be safety critical in emergency situations. The model also possesses other limitations such as requiring a minimum step size of at least 0.001 seconds, a step size larger than this will cause discontinuities in the code and create an infinite cycle of iterations due to inaccuracy issues. The code used to create this model can be found in appendix A.

4.3 PID Controller

A very standard way of improving a simple control system is to implement the use of a PID controls which provide suitable gains for optimising the performance of a system. This was accomplished by transferring the system made in 4.2 into Simulink and introducing a PID controller block before the controller which can be seen in figure 17. The rest of the SIMULINK model can be seen in Appendix A.

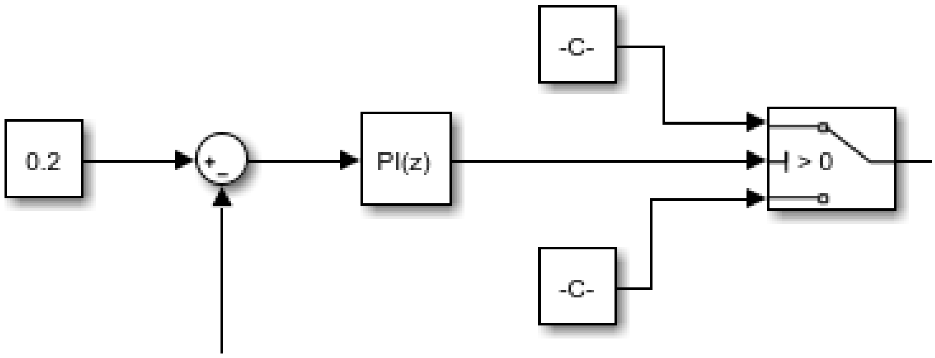

Figure 17 - PID Controller in SIMULINK

Once implemented each of the controller gains can be altered to provide increased performance, this is known as tuning. There are many different methods used to tuned control systems such as Zielger-Nichols and Tyreus Luyben. However due to issues with the linearisation of the plant system in SIMULINK these were unable to be accomplished. Instead, very simple trial and error manual tuning has been carried out on the controller. A method in which a gain is adjusted until the further adjustment of that gain no longer increases performance, while this does increase performance there are still further improvements that can be made to make the system optimal for its use. The final gains obtained for the controller can be seen in figure 18.

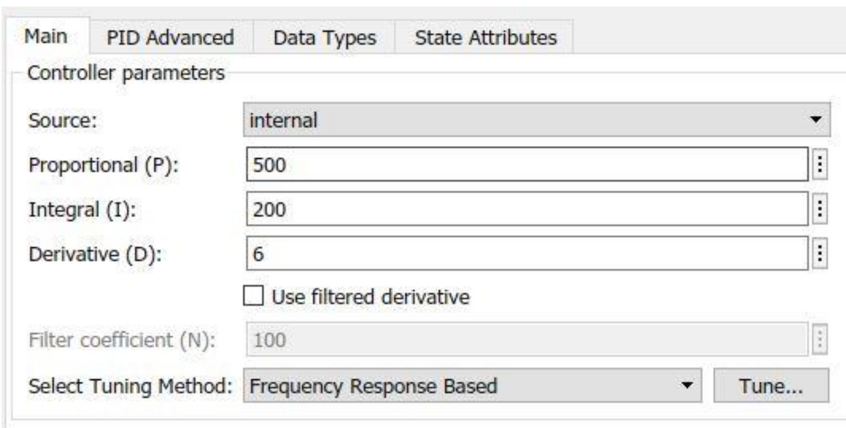

Figure 18 - PID Control Block Variables

4.4 Fuzzy controller

The fuzzy controller model functions by the technique of using the error (e) of the system and the differential of the error (de) to predict the current circumstances of the brakes. This is a common method and is effective at providing suitable outputs to the system. Other examples of this method being used can be found in (Rosinová and Kozáková, 2020) and (Xu and Wu, 2012). The controller was developed using MATLAB built in Fuzzy Logic toolbox, making use of its fuzzy controller user interface shown in figure 19.

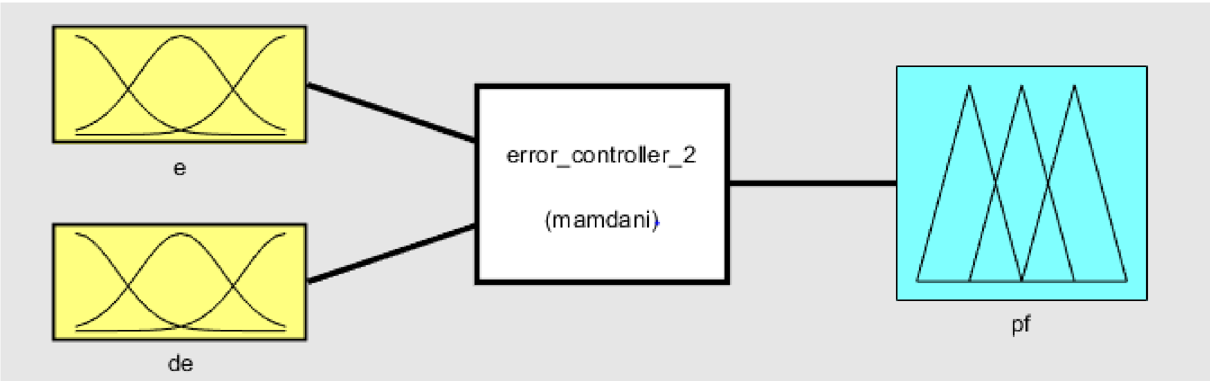

Figure 19 - MATLAB Fuzzy Logic User Interface

4.4.1 Fuzzy Inputs

The inputs have been created as seen in figures 4.4.1 and 4.4.2 are split into 5 sets each with their own respective membership functions: nl (negative large), ns (negative small), zr (zero), ps (positive small) and pl (positive large). Triangular membership functions that have been used in figure 21 are the most widely used as its fuzzy sets as it shows linear distribution (Lu *et al*, 2015) of the input. An import distinction to make between these inputs is the ranges of their sets. The range of the error is between the upper and lower bounds of the achievable error with the desired slip, which in the case of dry asphalt is 0.2 to -0.8 As figure 20 shows. The sets are heavily skewed to the positive side as the 'zr' point is the ideal slip ratio and distributing the sets further out would allow for greater fluctuation in slip, hence increasing stopping times.

The distribution of sets for de differs to that of e as figure 21 shows. This is due to the behaviour of de over the course of the simulation. At the start of the simulation the de is very negatively large as there is a sudden large increase in slip ratio as the brakes are initially applied. Towards the end of the simulation de rapidly fluctuates as wheel velocity is low and small adjustments to braking make a larger impact on slip. This behaviour means that the upper and lower bounds of the range is significantly larger even though de it is rarely at these values. The nominal value of de for the duration of the simulation is relatively low (typically between -5 to 5) and it is this range that that the sets have been designed for.

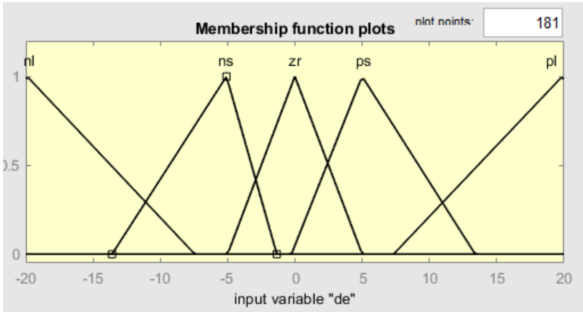

Figure 21 - Fuzzy Input de

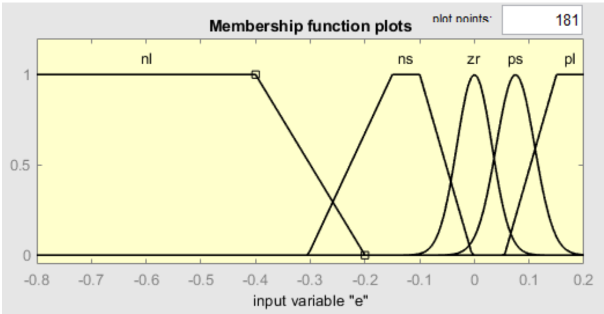

Figure 20 - Fuzzy Input e

4.4.2 Fuzzy Rule List

The rule of a fuzzy controller is arguably the most important part of the process as it determines how the inputs are interpreted and so directly impacts the controller's performance. To sensibly design a rule list a comprehensive knowledge of the inputs and their interaction with each other and the system must be understood. Firstly, beginning with the error. Table 6 describes the three possible states the error can be with and what connotation that represents.

Table 6 - Error Value Definitions

Error Value	Connotation
Positive	The slip ratio is below the desired value and must be raised by decreasing wheel speed hence increasing brake torque.
Zero	The wheel is at the desired slip ratio and maximum traction is occurring.
Negative	The slip ratio is above the desired value and must be lowered by increasing the wheel speed hence decreasing brake pressure.

The derivative of the error as implies simples describes the rate of change of the error. Figures 22 and 23 show the two variables plotted together. This plot aids in understanding the relationship between the error (in blue) and its derivative (in red). The plot has been segmented into 4 regions of its first oscillation, a brief description on each region has been made to quantify what is occurring.

1. Error is positive so the brakes are applied, lowering the error, making de negative.
2. Error is negative and de negative. This means the ideal slip has been 'overshot' and brake pressure must be decreased to return to it. However, lowering the brake pressure sufficiently to see a positive increase in slip take time, leaving the system in this sub optimal state.
3. Error is negative and de is positive. Brake pressure has decreased sufficiently to increase slip, making de positive.
4. Error is positive and de is positive. Once again slip ratio has overshot the ideal value, brake pressure must again be applied to lower it.

This 4 stage cycle is then repeatedly oscillated until the motorcycle has come to a stop.

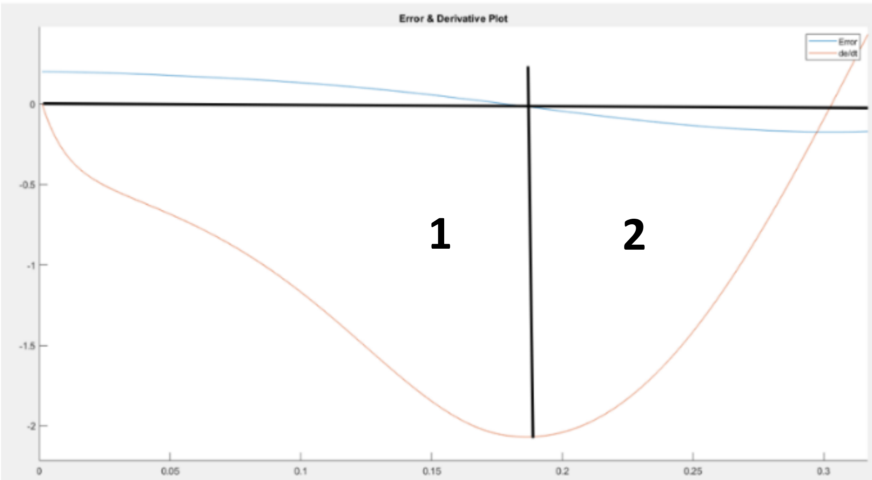

Figure 22 - Error vs de Plot 1

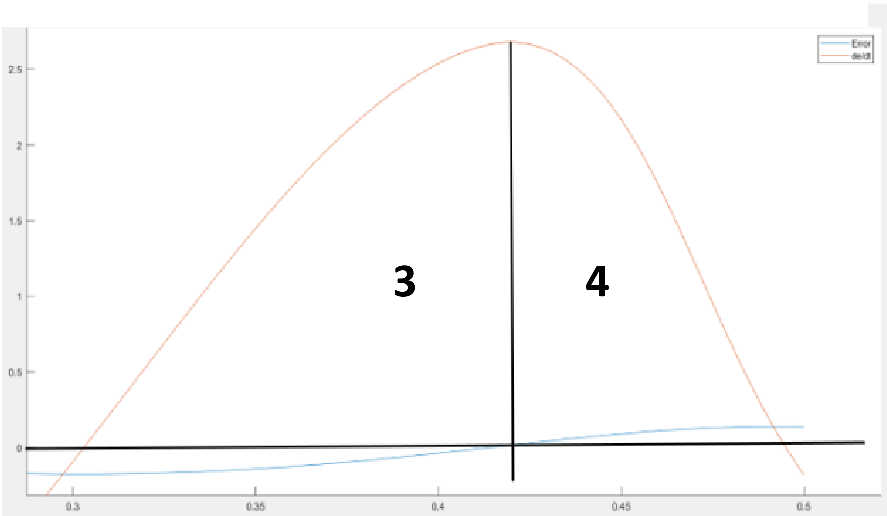

Figure 23 - Error vs de Plot 2

Using the descriptions above a full understanding of how the inputs dictate the state of the system an effective rule list can be made. Table 7 depicts a tabulated form of the rule which provides easier interpretation. The columns describing the which set the de value lies withing and the rows describing the error. The cells which the row and column intersect depict the interpreted outcome for the system. The rule table is visibly symmetrical diagonally, this is due to two different brake pressure rates being used for application and release as discussed in section 4.1.

Table 7 - Fuzzy Controller Rule List

	de				
e	NL	NS	ZR	PS	PL
NL	VL	VL	VL	VL	VL
NS	L	L	M	S	S
ZR	M	S	VS	S	S
PS	S	S	M	L	L
PL	VL	VL	VL	VL	VL

4.4.3 Fuzzy Outputs

The function of the rule list is to interpret the values of the inputs and provide a corresponding output. These outputs, similarly to inputs, are divided into linguistic sets. The sets in the case are very small (vs), small (s), medium (m), large (l) and very large (vl) as figure 25 shows. The membership functions of the sets have varied, most notably the large gaussian membership function used for the large output. These functions have been selected as the provide a much smoother transition of the output. the 'large' output has been widely distributed as this is the range the controller will mostly use, while the very small and very large outputs are relatively small in comparison as these values are only required at the start and end of the braking. A method of displaying all aspect the fuzzy controller in one graphic is by plotting a 3D surface representing the relationship between inputs and outputs. The surface describing this controller can be seen in figure 24.

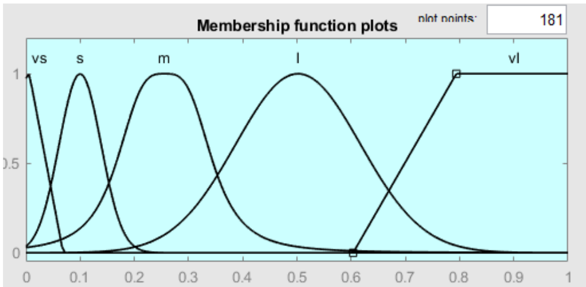

Figure 25 - Fuzzy Controller Output

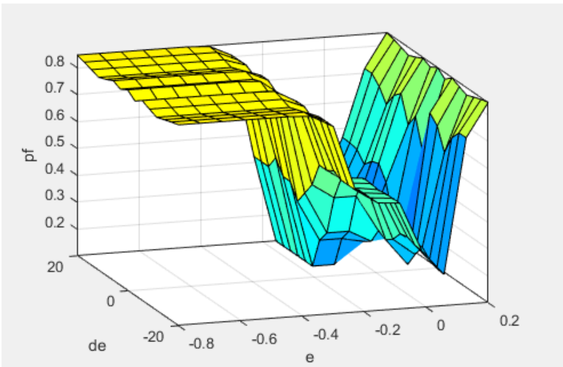

Figure 24 - Fuzzy Controller Surface Graph

5.0 Analysis of Results

This section will include the performance of all the different control methods use to see which is the most effective. This section will also include validation for the use of the system by emulating conditions of other simulations along with physical investigations and comparing the results.

5.1 Results

The following table shows a comparison between the braking distance, stopping time and average deceleration of all the controllers made to compare their performances. These simulations were all run using the same variables seen in table 8, the conditions of the simulation are on dry asphalt road at an initial speed of 50 miles per hour.

Table 8 - Simulation Results Table

Control Method Used	Stopping Time (s)	Braking Distance (m)	Average Deceleration (m/s)
Bang-Bang	2.973	36.38	7.518
PID	2.809	34.9822	7.957
Fuzzy Logic	2.847	35.3103	7.8511
No ABS	4.259	52.748	5.248

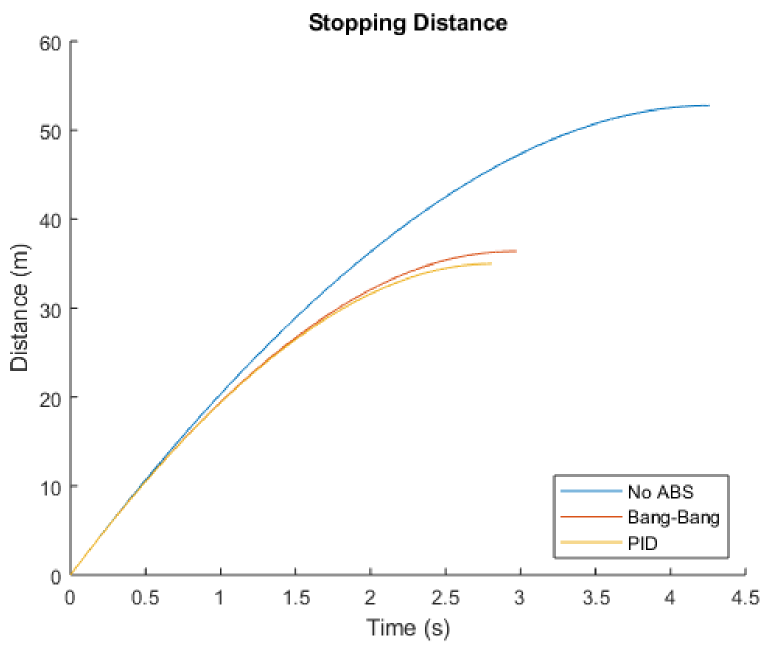

Figure 26 - Simulation Results Graph

As table 8 and figure 26 shows, the highest performing controller was the PID, reducing stopping distance by 34% and increase the average deceleration by 52% compared to the theoretical no ABS model. These results contradict those from the investigation performed by Rosinová. and Kozáková (2020). However, that paper does not provide details on how or if the PID controller used has been tuned. Along with this the fuzzy controller for that investigation may be more optimised for its function compared to the controller made in this project.

Figure 27 and 28 show the results of the simulation for both the PID and Bang-Bang controllers. There are clear differences between the results, the most noticeable being the variation in slip ratio seen in figure 27. The fluctuation of slip ratio of the PID controller decays, this reduction in variation suggests that the system is more stable (Lewis and Yang, 1997). This reduced variation in slip ratios effect on braking is clear as figure 28 shows the wheel speed for the PID controller is almost a smooth. This means that the PID controller keeps the wheel at, on average, a higher value of friction leading to reduced braking distance and stopping time.

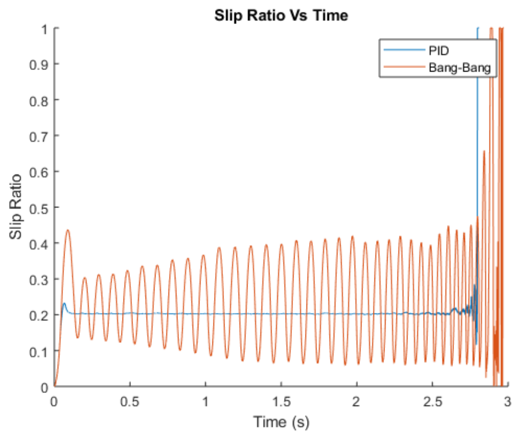

Figure 27 - Slip Ratio of Bang-Bang and PID Control

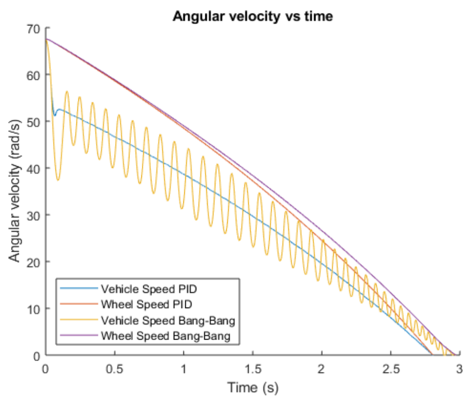

Figure 28 - Simulation Speeds of Bang-Band and PID Control

Referring to the model criteria in section 3.3, a requirement of the model was that it must comply with the standards set out in FMVSS – 122 (Department of Transportation, 2013). Table 9 shows the comparison of the performance required by the standards and the performance simulated to by the PID control system run under the required conditions. The model successfully passed all the legal requirements that an ABS system must abide by.

Table 9 - Simulations Results for FMVSS-122 Standards

Standard number	Criteria	Performance Required	Simulated Performance
1	Stopping Distance	31.32	17.51
2	Stopping Distance	117.19	109.83
3	Stopping Distance	241.2	25.36
4	Deceleration	1.65	4.89
5	Deceleration	3.3	5.68

5.2 Validation of Results

For these results to be credible they must be validated against secondary sources. In this case of this project, it would be preferable to compare these models to other simulation models in addition to practical experiments that have been carried out. Simulations designed under similar conditions are common and can readily be compared. There was difficulty finding experimental data for ABS performance, specifically incorporating motorcycles, as this does not appear to be such an openly investigated area.

5.2.1 Simulation Comparison

Many of the modern models investigating ABS function and performance are designed around cars rather than motorcycles. However, given the robust design of this model the inputs can be varied to match those used in car models for comparisons. Simulation conditions have me emulated wherever possible to obtain the most accurate comparison.

Table 10 - Results Comparison of Simulation Models

Bang- Bang Controller							
	Study Simulation		Project Simulation Data		Error		Source
Number	Braking Distance (m)	Stopping Time (s)	Braking Distance (m)	Stopping Time (s)			
1	16.5	4.5	17.33	1.944	-4.8	131.5	Saswata *et al*, 2015
2	70	2.7	17.44	1.985	301.4	41.1	Arzumanyan *et al*, 2015
PID Controller							
3	31	2.3	61.255	3.845	-49.4	-40.2	Bhivate, n.d
4	70	4	60.81	3.863	15.1	3.5	More *et al*, 2017
5	NA	2.2	46.84	3.34	NA	-34.2	Chen *et al*, 2019
Fuzzy Controller							
6	10.15	1.76	15.99	1.84	-36.5	-4.3	Rosinová. D. and Kozáková. A, 2020
7	20.07	2.8	22.14	3.11	-9.3	-10	Xu and Wu, 2012
8	16.29	1.57	52.47	7.31	-69	-78.5	Zhang *et al*, 2008

Bang-Bang Controller results

The results of the bang-bang controllers are highly varied, this could be due to the difference in assumptions used during the modelling process. The difference in assumption would be more noticeable in a simple controller such as this. This can be seen in results as even though both simulations start under very similar conditions. The braking distance and stopping time of each are drastically different. This shows large amounts of error between on model and another to begin with

PID Controller Results

The results of the PID controllers have a distinct pattern in the results of the (bhivate, n.d) and (Chen *et al*, 2019) yield intermediate error values and the results of (More *et al*, 2017) are suitably low. Corresponding to this the two models that yield higher errors are both car models; whilst the more aggregable model is a motorcycle model, very similar to the model designed in this project. This could indicate a that the model is less functional as a quarter car model and more proficient as a motorcycle however further research would have to be conducted to confirm this. The PID Controller on average had results most similar to those found in other studies, approximately -20% overall. Because of the PID controller's high performance and reliability it was selected to be used in the comparison practical investigations discussed in section 5.2.2.

Fuzzy Logic Controller Results

Finally, the results of the fuzzy controller are apparent to see. In all cases the sourced models outperformed the fuzzy controller designed in this project. This clearly demonstrates that the fuzzy controller is far from optimised. In addition to this some of the sourced models also include a PI controller in addition to the fuzzy controller. This an improvement that could be taken into consideration for the designed controller.

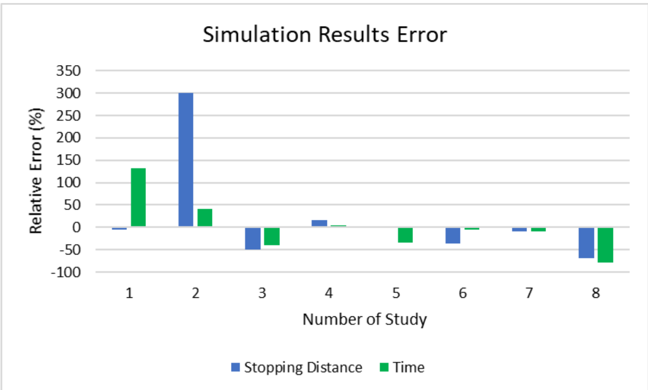

Figure 29 - Graph of Simulations Relative Error

5.2.2 Experimental Comparison

This section will investigate the practicality of using simulations in real life scenarios to predict results. Two published papers will be used to compare results, one paper published by the United States Department of Transportation (2006) and another paper published by Vavryn and Winkelbauer (2004). In each case the simulation will emulate the conditions as described in each paper. In particular the specifications of the motorcycle used, as shown in table 11, these specifications were found using (MotorcycleSpecs, n.d a-f).

Table 11 - Experimental Motorcycle Variables (MotorcycleSpecs, n.d a-f)

Motorcycle	Mass	Wheel Radius
Honda VFR800	242	0.3
BMW F650	173	0.331
BMW R1150R	238	0.3
Yamaha FJR 1300	264	0.3
Peugeot Elystar 125	155	0.245
BMW 650 Scarver	170	0.293

Some important factors to consider while comparing these experiments to simulation results are:

- Given that both these experiments are held under in a test environment it has been assumed that 'thinking distance' is negligible and the time travelled is spent braking.

- Both studies did include data regarding the braking performance of motorcycles without ABS, however, the simulation modelling a motorcycle without ABS has not been compared to this. This is because both studies investigated the use of participants utilising their own braking skills and not applying the brake constantly and therefore the two would not be accurate to compare.

- Practical ABS take into consideration a much broader range of assumptions that are far from the scope of this project. Experimental will nonetheless be taken into consideration as it provides an idea of the suitable range that this model should perform at, conversely, investigation into practical data provides an indication of what assumptions create larger error that cannot be ignored.

The United States Department of Transportation (2006) experiment investigates the use of 4 different motorcycles, both heavily and lightly loaded, travelling at travelling at two different speeds each, under both wet and dry conditions.

Table 12 - U.S Department of Transportation (2006) Results Comparisons

Motorcycle		Speed (km/h)	Experimental Braking Distance (m)	Simulation Data Braking Distance (m)	Error (%)
Dry Surface Braking					
Honda VFR800	Lightly loaded	48.3	11.72	11.63	1.64
		128.8	77.66	121.61	-36.14
	Heavily loaded	48.3	14.12	10.789	30.87
		128.8	99.38	119.89	-17.11
BMW F650	Lightly loaded	48.3	13.74	11.32	21.38
		117	65.98	93.44	-29.39
	Heavily loaded	48.3	14.67	10.68	37.36
		117	70.98	93.46	-24.05
BMW R1150R	Lightly loaded	48.3	11.89	11.5	3.38
		117.8	68.56	121.6	-43.62
	Heavily loaded	48.3	12.85	10.8	18.98
		128.8	78.01	119.87	-34.92
Yamaha FJR 1300	Lightly loaded	48.3	14.9	11.55	29.05
		128.8	84.14	121.73	-30.88
	Heavily loaded	48.3	14.39	10.81	33.12
		128.8	84.3	119.88	-29.68
Wet Surface Braking					
Honda VFR800	Lightly loaded	48.3	15.24	16.15	-5.63
	Heavily Loaded		16.36	15.52	5.41
BMW F650	Lightly loaded	48.3	18.23	15.99	14.01
	Heavily Loaded		22.05	15.4	43.18
BMW R1150R	Lightly loaded	48.3	14.76	16.16	-8.66
	Heavily Loaded		15.34	15.52	-1.16
Yamaha FJR 1300	Lightly loaded	48.3	22.96	16.1	42.61
	Heavily Loaded		18.54	15.51	19.54

This paper is an excellent source of information as the test procedure as well as test conditions are very well documented. The road conditions are specified as wet and dry asphalt. new tires were used, this is important as tyre wear can notably increase stopping distance (Bosch, 1995, pg. 16). New brakes were also installed on all the motorcycles used and lightly conditioned to ensure they abide by standards of FMVSS-122 also removing any factors associated with new equipment that could create inconsistencies. The experiment was completed multiple times reduce anomalous results. Two tests of the bikes being lightly and heavily loaded were run, lightly loaded entailing just the rider and test equipment, while heavily loaded refers to 90% of the maximum design weight of the motorcycle.

The procedure does state that both the front and rear brakes are used while test which could be contributing factor to the significantly shorter braking distances in some cases. The procedure also states that there was an allowance of ± 5km/h upon the entry speed but these are not tracked, and an average used which creates a deviation in answers. These results have been plotting in figure 30 and 31 to make trends easier to distinguish.

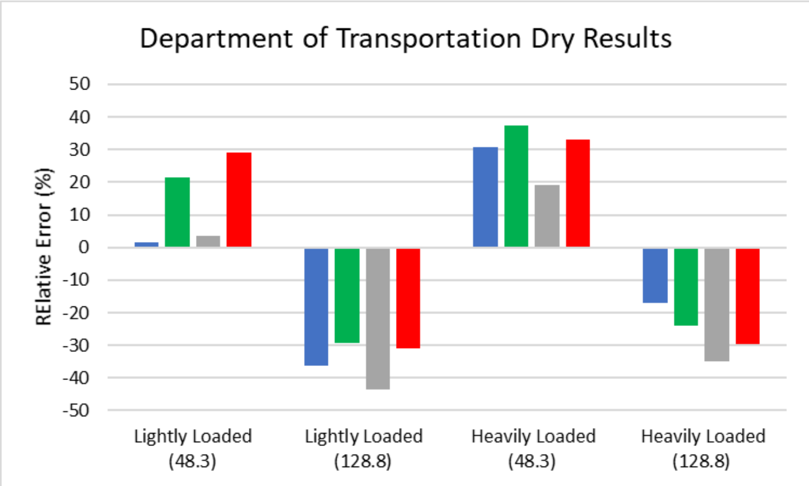

Figure 30 - Dry Braking Error Results Graph

Inspecting figure 30 it is clearly to see the results are most reliable when the bikes are lightly loaded and travelling at the slower speed. Another clear observation is that the simulation consistently gives overestimations at higher initial speeds.

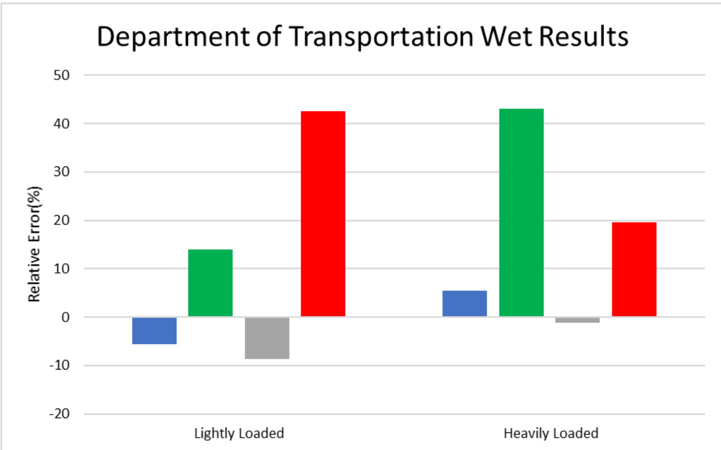

Figure 31 - Wet Braking Error Results Comparison

Under wet conditions the model performed moderately reliably on average. Undesirably however there is no discernible pattern between over and under estimation, nor between the effect of mass. this is likely due to the complex interactions taking place on wet surfaces such as friction variation due to wetness and aquaplaning.

The experiment carried out by Vavryn and Winkelbauer (2004) was designed to assess the impact that an ABS would have in the braking ability of both skilled and novice riders. Its procedure was to simply measure deceleration at two different points during a braking manoeuvre. This experiment was carried out using a large sample size of almost 150 riders which is beneficial for reliability.

Table 13 - Vavryn and Winkelbauer (2004) Results Comparison

Motorcycle	Speed	Experimental Data Deceleration	Simulation Data Deceleration	Error (%)
Peugeot 125 Elystar	50	7.8	6.88	11.85959
	60		5.88	30.90548
BMW 650 Scarver	50	7.72	7.21	7.114943
	60		6.41	20.5246

Though this paper is a useful insight into the real braking behaviour of an ABS, the procedure and data acquisition employed throughout is unreliable. Frequently making vague statements within the procedure such as the light gates spaced by "about 5 metres" (Vavryn and Winkelbauer, 2004, pg. 3). In addition to also not stating what the distance between the sender and receiver of the light gates are. This experiment also only describes the decelerations between those 5 metres; but as the simulations and experimental data shows deceleration is not constant or even linear throughout a braking manoeuvre as figure 32 shows. It is worth noting that if the average deceleration taken over the entire braking distance of the simulation is 8.22 and 8.25m/s^2 which lowers the percentage error to about -5% in each case. This study is also largely focusing on the skill aspect of novice and skilled riders and as such there is standard deviation of 1-1.4% in each experiment. A final factor that would lead to lower decelerations in the simulation is that both the front and rear brake is used in the experiment whereas the simulation model accounts for 100% of the braking coming from the front wheel alone. Skilled riders in particularly would have much greater chance of being able to stop faster with knowledge how to distribute the brake force of both wheels.

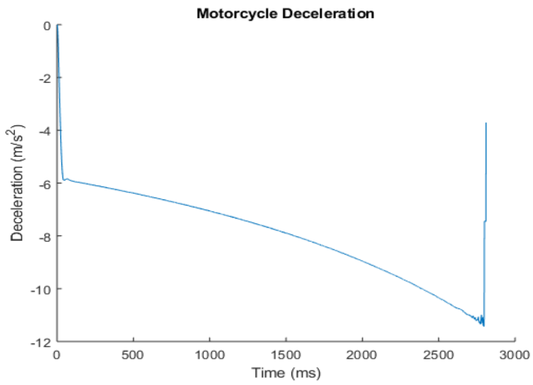

Figure 32 - Graph of Simulated Motorcycle Deceleration

Both these studies have yielded some very interesting findings such as that in both cases the model performed more reliably to the experiments at lower speeds, with approximately 5-15% less relative error. At faster speeds, the model consistently overestimated the experimental results by about 20-35%. This could be because at lower speeds, running resistances such as this seen in figure 33 become less impactful as they are both functions of speed (Cossalter, 2006) (Genta, 1997).

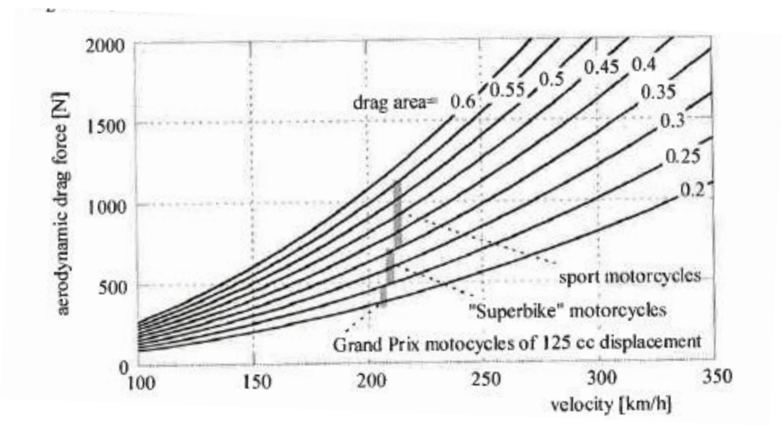

Figure 33 - Aerodynamic Drag With Speed (Cossalter, 2006, pg.76)

These results also highlight a potentially large flaw with the current model. In some cases simulations that under the same conditions with a heavier loaded motorcycle will simulate a shorter braking distance than a lighter loaded one. Knowledge gained from the research carried out during this project and the experimental data suggests that opposite should be true. So an investigation was completed in which a simulation would run under the same conditions with increasing mass. The results are shown in figure 35 show a reasonable result of increase stopping distance with some acceptable variation which could be the cause of the error. Figure 36 on the other hand is same simulation performed at an initial speed of 100mph instead of 50. This results clearly depict a regular step change in stopping distance which is not correct. Therefore this model should be taken under careful consideration when using at higher speeds.

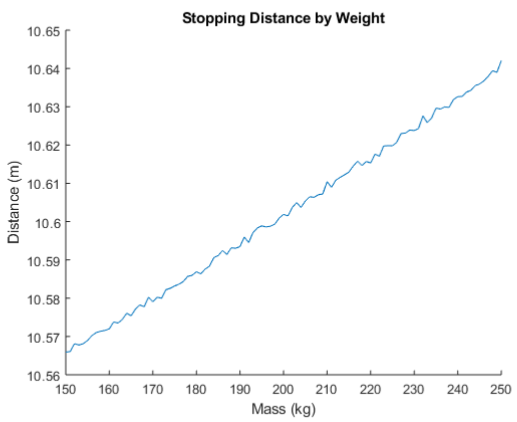

Figure 35 - Stopping Distance by Weight (50mph)

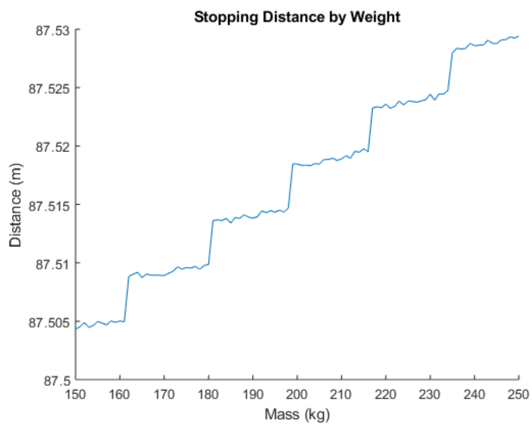

Figure 34 - Stopping Distance by Weight (100mph)

5.2.3 Errors and Accuracy

As section 5.2.1 and 5.2.2 show, there are errors in the results found in the designed ABS models to those found secondary sources. Absolute error, in mathematical terms, is the difference between actual result and the expected result. For any of the simulated results to have no error would be to create 'perfect' model, one that encompasses all aspect of a given system. As mentioned in section 2.3.5 such a model would be far too time consuming to produce so, in the words of Edwards and Hamson (2001) "we cannot hope to avoid errors." They continue to present the four primary sources of errors:

- Errors due to modelling assumptions.
- Errors due to using an approximate method of solution.
- Errors due to rounding.
- Errors in data.

All these errors are present within the ABS model created during this project along with all the other models sourced as comparisons.

Absolute error is useful for representing a direct relationship between two different values however can become misconstrued as the accuracy of this result is related to the magnitude. To avoid this confusion relative error has been used as a gauge of accuracy instead. This inherently considers the absolute error as a ratio of the magnitude as shown in equation (13).

$$Relative\ error = \frac{True\ value - Estimated\ Value}{Estimated\ Value} \times 100 \tag{13}$$

So as error is unavoidable results may never be entirely reliable. it is then standard practice to make an estimation of what the maximum error is likely to be so users of the model can decide if it suitable for a given function. Therefore, using this model for its ideal use of a lightly loaded motorcycle travelling at 50km/h or less. The maximum expected error would be approximately 29.05% or an average of 10.89%.

6.0 Conclusion (4000)

To summarise the points made throughout this project. The original goal of the project ‘to create a virtual model of an ABS undergoing an emergency stop manoeuvre, capable of analysis’ has been thoroughly met. During this project, a suitable model was created using research into dynamic and control systems the foundation to build upon. This model was successfully translated into MATLAB and multiple control methods have been implemented to compare their performances.

The PID Controller was the highest performing controller, drastically reducing stop distances compared to the theoretical no ABS model. The PID controller was also found to comply with all other standards discussed in the design criteria, including legal standards. Each control method was then compared to other virtual models of same controller type to justify the range of the results found.

Lewis and Yang (1997) state that “If a system model is accurate, the observation of the system variables will accurately reveal the behaviour of the physical system”, this project has explored accuracy of the model using experimental data. Considering all the information discussed above if this model was to be implemented in a real-life scenario it should only be used as a general guide, rather than an exact method. If accuracy is the ultimate goal, then lighter masses at slower speeds should be applied; if conservative results are acceptable then higher speeds and heavy masses can be applied.

6.1 Further Work

This project has addressed work within the limited scope decided upon starting, however, there is still much further work that would greatly benefit the world of motorcycle safety and simulation. Such further work would include developing more detailed model to include:

- The whole motorcycle body, so factors such as roll, pitch and yaw can be accounted for. Such models as those found in (Tanelli, 2014), (Pacejka, 2012) and (Karnopp, 2013)
- The thermo and fluid dynamics that affect brake friction under certain conditions that could lead to less optimal grip such as in rain or with overheating brakes.
- The weight transfer over the motorcycle as excessive use of a single brake.
- A change in the riding surface or weather conditions as terrain changes multiple times normal in day-to-day riding.
- Create fuzzy controller with PID incorporated such as those seen in (Xu and Wu, 2012)
- Advance the model using an advanced friction model such as Pacejka's 'Magic Formula' (Pacejka, 2012, pg.165).
- Total running resistance, Rolling resistance, aerodynamic drag and climbing resistance (Bosch, 1995, pg.20).
- Effects of suspension on vibrations of the brakes (Cossalter, 2006)

7 References

ARH Custom (n.d) *Harley Davidson Sportster front disc brake*. Available at: https://www.arhcustom.co.uk/product/braking-floating-brake-rotor-front-300mm-l-r-for-harley-davidson-15-20-softail-06-17-dyna-08-17-touring-and-14-20-xl-arm271449 (Accessed 10th December 2020)

Arzumanyan N. K., Smirnova M. A. and Smirno M. N. (2015). *Synthesis and modeling of anti-lock braking system*. International Conference "Stability and Control Processes" in Memory of V.I. Zubov (SCP), St. Petersburg, Russia, 2015, pp. 552-554, doi: 10.1109/SCP.2015.7342222. [online] Available at: https://ieeexplore.ieee.org/document/7342222 (Accessed 15th October 2020)

Bhivate, P (d.n). *"Modelling and Development of Antilock Braking System"* National Institution of Technology. Rourkela, India. [online] Available at: https://core.ac.uk/download/pdf/53187976.pdf (Accessed 2nd October 2020)

Bosch R. GmbH (1995) *Automotive brake systems*. 1st edn. Stuttgart: Robert Bosch.

Chen X., Hu M. and Guan Q. (2019). *Modeling and Simulation of Vehicle Braking System Based on PID Control.* 2019 IEEE 10th International Conference on Software Engineering and Service Science (ICSESS), Beijing, China, 2019, pp. 654-657, doi: 10.1109/ICSESS47205.2019.9040743. [online] Available at: https://ieeexplore-ieee-org.oxfordbrookes.idm.oclc.org/document/9040743 (Accessed 11th January 2021)

Childs, PRN 2018, Mechanical Design Engineering Handbook, Elsevier Science and Technology, San Diego. Available from: ProQuest Ebook Central. [online] (Accessed 20th December 2020).

Corno, M., Savaresi, S.M. and Balas, G.J. (2009), *On linear-parameter-varying (LPV) slip-controller design for two-wheeled vehicles*. Int. J. Robust Nonlinear Control, 19: 1313-1336. doi:10.1002/rnc.1381 [online] (Accessed 11th October 2020)

Cossalter, V. (2006) *Motorcycle dynamics*. 2Nd English edn. Place of publication not identified: Lulu Com.

Cox, E. (1992). *Fuzzy fundamentals.* in IEEE Spectrum, vol. 29, no. 10, pp. 58-61, Oct. 1992, [online] Available at: https://ieeexplore-ieee-org.oxfordbrookes.idm.oclc.org/stamp/stamp.jsp?tp=andarnumber=158640andtag=1 (Accessed 9th January 2021)

Darus, Rosheila and Md Sam, Yahaya. (2009). *Modeling and control active suspension system for a full car model*. Proceedings of 2009 5th International Colloquium on Signal Processing and Its Applications, CSPA 2009. 13 - 18. 10.1109/CSPA.2009.5069178. [online] Available at: https://www.researchgate.net/publication/224503085_Modeling_and_control_active_suspension_system_for_a_full_car_model (Accessed 18th January 2021)

Day, AJ (2014). *Braking of Road Vehicles*. Elsevier Science and Technology, Oxford. Available from: ProQuest Ebook Central. (Accessed 10th October 2020)

Department of transportation. (2016a) *National Travel survey, Motorcycle use in England* [online] United Kingdom. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/694965/motorcycle-use-in-england.pdf (Accessed 9th October 2020)

Department of transportation. (2016b) *Reported road casualties in Great Britain: main results 2015* [online] United Kingdom. [online] Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/533293/rrcgb-main-results-2015.pdf (Accessed 9th October 2020)

Department of vehicle statistics (2020) *Licensed motorcycles, scooters and mopeds at the end of the quarter, Great Britain from 1994 Q4; also United Kingdom from 2014 Q3* United Kingdom. [Online] Available at: https://www.gov.uk/government/statistical-data-sets/veh03 (Accessed 9th October 2020)

Dousti, Morteza and Baslamisli, Selahattin and Onder, E. and Solmaz, S.. (2014). *Design of a multiple-model switching controller for ABS braking dynamics*. Transactions of the Institute of Measurement and Control. 37. 10.1177/0142331214546522. [online] Available at: https://www.researchgate.net/publication/270684635_Design_of_a_multiple-model_switching_controller_for_ABS_braking_dynamics (Accessed 12th October 2020)

Edwards, D. and Hamson, M. (2001) *Guide to mathematical modelling*. 2nd edn. Basingstoke: Palgrave (Palgrave mathematical guides).

Gallego M. S. (2011). *Analysis of dynamic handling of one motorcycle using simulations tools. AGH University of Science and Technology, Poland. [online] Available at:* https://core.ac.uk/download/pdf/30045248.pdf (Accessed 10th December 2020)

Genta, G. (1997) *Motor vehicle dynamics : modeling and simulation*. River Edge, NJ: World Scientific (Series on advances in mathematics for applied sciences, v. 43).

Geromel, N. (2014). *Modelling and control of the braking system of the electric Polaris Ranger all-terrain-vehicle*. University of Padua, Italy. [online] Available at: https://core.ac.uk/download/pdf/41982275.pdf (Accessed 18th December 2020)

Green, D. (2006). *A Comparison of Stopping Distance Performance for Motorcycles Equipped with ABS , CBS and Conventional Hydraulic Brake Systems*. United States Department of Transportation, National Highway Safety Administration. [online] Available at: https://msf-usa.org/downloads/imsc2006/Green-Comparison_of_Stopping_Distance-Paper.pdf (Accessed 28th January 2021)

Han, Kyoungseok and Choi, Seibum and Lee, Jonghyup and Hyun, Dongyoon and Lee, Jounghee (2017). *Accurate Brake Torque Estimation with Adaptive Uncertainty Compensation Using a Brake Force Distribution Characteristic.* IEEE Transactions on Vehicular Technology. PP. 1-1. 10.1109/TVT.2017.2720846. [online] (Accessed 20th December)

Harned, J. L., *et al*. *Measurement of Tire Brake Force Characteristics as Related to Wheel Slip (Antilock) Control System Design. SAE Transactions*, vol. 78, 1969, pp. 909–925. *JSTOR*, Available at: www.jstor.org/stable/44564290. [online] (Accessed 15th November)

Johnson, A. (2001) “Unpacking Reliability: The Success of Robert Bosch, Gmbh in Constructing Antilock Braking Systems As Reliable Products,” *History and Technology*, 17(3), pp. 249–270. doi: 10.1080/07341510108581994. [online] (Accessed 19th October 2020)

Karnopp, D. (2013) *Vehicle dynamics, stability, and control*. 2nd edn. Boca Raton, FL: CRC Press (Mechanical Engineering). [online] Available at: https://learning.oreilly.com/library/view/vehicle-dynamics-stability/9781466560857/?ar (Accessed: 10th January 2021)

Lewis, P. H. and Yang, C. (1997) *Basic control systems engineering*. Upper Saddle River, NJ: Prentice Hall.

Lu. X., Zhou Z. and Wang Y. (2015) "Design and comparative study of ABS control strategies based on co-simulation," *2015 IEEE International Conference on Cyber Technology in Automation, Control, and Intelligent Systems (CYBER)*, Shenyang, China, pp. 1665-1670. [online] Available at: https://ieeexplore.ieee.org/document/7288196 (Accessed 7th January 2021)

Mauer G.F. (1995). *A fuzzy logic controller for an ABS braking system.* in *IEEE Transactions on Fuzzy Systems*, vol. 3, no. 4, pp. 381-388. [online] Available at: https://ieeexplore.ieee.org/document/481947 (Accessed 19th December 2020)

Meywerk, Martin. (2015) *Vehicle Dynamics*, John Wiley and Sons, Incorporated, 2015. *ProQuest Ebook Central*. [online] Available at: https://ebookcentral-proquest-com.oxfordbrookes.idm.oclc.org/lib/brookes/detail.action?docID=1895837 (Accessed 5th November 2020)

More H. R., Digrase A. A. and Wayse A. V. (2017). *Linear PID control technique for single wheel ABS (anti-lock braking system) of motorcycle*. *2nd International Conference for Convergence in*

Technology (I2CT), Mumbai, India, 2017, pp. 277-281, doi: 10.1109/I2CT.2017.8226135 [online] (Accessed 17th January 2021)

Motorcycle ID (n.d) *Performance Machine 0052-1400 – Brake Caliper Piston.* Available at: https://www.motorcycleid.com/performance-machine/brake-caliper-piston-mpn-0052-1400.html?vehicle=179639 (Accessed 5th November 2020)

MotorcycleSpecs (n.da) *BMW F650 Funduro.* Available at: https://www.motorcyclespecs.co.za/model/bmw/bmw_f650%2097.htm (Accessed 5th January 2021)

MotorcycleSpecs (n.db) *BMW F650CS Scarver.* Available at: https://www.motorcyclespecs.co.za/model/bmw/bmw_f650_cs.htm (Accessed 5th January 2021)

MotorcycleSpecs (n.dc) *BMW R 1150R.* Available at: https://www.motorcyclespecs.co.za/model/bmw/bmw_r1150r.htm(Accessed 5th January 2021)

MotorcycleSpecs (n.dc) *Harley Davidson XL 883 Sportster.* Availably at: https://www.motorcyclespecs.co.za/model/h-d/harley_davidson_xl_883_sportster%2001.htm (Accessed 5th January 2021)

MotorcycleSpecs (n.dd) *Honda VFR 800F V-TEC*. Available at: https://www.motorcyclespecs.co.za/model/Honda/honda_vfr800_abs_04.html (Accessed 5th January 2021)

MotorcycleSpecs (n.de). *Peugeot Citystar 125.* Available at: https://www.motorcyclespecs.co.za/model/Peugeot/Peugeot_Citystar_125_12.html (Accessed 5th January 2021)

MotorcycleSpecs (n.df) *Yamaha FJR 1300.* Available at: https://www.motorcyclespecs.co.za/model/yamaha/yamaha_fjr1300%2013.html (Accessed 5th January 2021)

National Academic Press (1998) *Statistics, Testing, and Defense Acquisition: New Approaches and Methodological Improvements* [online] Washington D.C, United States. [online] Available at: https://www.nap.edu/read/6037/chapter/11 (Accessed 18th October 202)

Pacejka, H. (2012) *Tire and Vehicle Dynamics, Elsevier Science* and *Technology*. Oxford. Available from: ProQuest Ebook Central. [online] Available at: https://oxfordbrookes.on.worldcat.org/oclc/794489044 (Accessed 10th October 2020)

Pugh, S., Clausing, D. and Andrade, R. (1996) *Creating innovative products using total design : the living legacy of stuart pugh*. Reading, Mass.: Addison-Wesley Pub.

Rizzi, M., Strandroth, J., Holst, J. and Tingvall, C., 2016. *Does the improved stability offered by motorcycle antilock brakes (ABS) make sliding crashes less common? In-depth analysis of fatal crashes involving motorcycles fitted with ABS*. *Traffic injury prevention*, *17*(6), pp.625-632. [online] Available at: https://www.tandfonline.com/doi/abs/10.1080/15389588.2015.1134794 (Accessed 18th October2020)

Rosinová. D. and Kozáková. A. (2020). *Laboratory ABS Control: Fuzzy or PID Controller?.* Cybernetics and Informatics (KandI), Velke Karlovice, Czech Republic, 2020, pp. 1-5. [online] Available at: https://ieeexplore-ieee-org.oxfordbrookes.idm.oclc.org/stamp/stamp.jsp?tp=andarnumber=9039796 (Accessed 4th January 2021)

Saswata, Senapati and Rajendra, Ullash and Saswata, Champatiray and Rajendra, Senapati. (2015). *Novelty of Anti-Lock Braking System in Proposed Sliding Mode Controller.* [Online]. Available at: https://www.researchgate.net/publication/305676919_Novelty_of_Anti-Lock_Braking_System_in_Proposed_Sliding_Mode_Controller (Accessed 8th October2020)

The Royal Society for the Prevention of Accidents. (2017) *RoSPA Road Safety Research: Common Motorcycle Crash Causes* [Online] United Kngdom. [online] Available at: https://www.rospa.com/rospaweb/docs/advice-services/road-safety/motorcyclists/common-motorcycle-crash-causes.pdf (Accessed 11th October2020)

Tanelli, M, Corno, M, and Saveresi, S. (2014). *Modelling, Simulation and Control of Two-Wheeled Vehicles.* John Wiley and Sons, Incorporated, New York. Available from: ProQuest Ebook Central. [online]. Available at: https://ebookcentral-proquest-com.oxfordbrookes.idm.oclc.org/lib/brookes/reader.action?docID=1629338andppg=225 (Accessed 11th October2020)

U.S. Department of transportation (2013). *LABORATORY TEST PROCEDURE FOR FMVSS 122 Motorcycle Brake Systems.* Washington D.C, united states. [online] Available at: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/tp-122-03_tag.pdf (Accessed 15th November 2020)

Vavryn, K. and Winkelbauer, Martin. (2004). *Braking Performance of Experienced and Novice Motorcycle Riders - Results of a Field Study*. [online]. Available at: https://www.researchgate.net/publication/242453707_Braking_Performance_of_Experienced_and_Novice_Motorcycle_Riders_-_Results_of_a_Field_Study (Accessed 2nd January 2021)

Xu. S. and Wu. H. (2012). *The research and analysis of the efficiency of automobile ABS brake based on fuzzy control* 2nd International Conference on Consumer Electronics, Communications and Networks (CECNet), Yichang, China, 2012, pp. 697-700. [online] Available at: https://ieeexplore-ieee-org.oxfordbrookes.idm.oclc.org/stamp/stamp.jsp?tp=andarnumber=6201614andtag=1 (Accessed 20th December 2020)

Zellner, J. W., Kebschull, B. K. and Tsuchida, T. (1989) "Influence of Antilock Brakes on Motorcycle Braking in a Turn," *SAE Transactions*, 98, pp. 1331–1346. [online] (Accessed 23rd October2020)

Zhang J. M ,Song B.Y. and Sun G (2008) . *An Advanced Control Method for ABS Fuzzy Control System.* International Conference on Intelligent Computation Technology and Automation *(ICICTA)*, Changsha, China, 2008, pp. 845-849, doi: 10.1109/ICICTA.2008.300. [online] Available at: https://ieeexplore.ieee.org/document/4659606 (Accessed 14th November 2020)

8 Appendices

Appendix A – MATLAB Code and Simulink models

Bang-Bang Controller Code:

```
clear;
clc;
j = 0.72; %mass moment of wheel
R = 0.331; %wheel radius
g = 9.81; %gravity
v = 22.352; %inital vehicl linear velocity in m/s
v0 = v;
w = v/R; %Angular velocity of wheel
sd = 0.2; %Desired relative slip value
m = 130.5; %half mass of motorcycle
t = 0; %initial time
s=0; %initial slip
k=0; %inital counter
Tb=0; %initial braking torque
d=0; %initial stopping distance
p = 0;
step = 0.001;
e=0;

while v > 0 %loop occurs until vehicle body is sufficiently
slow
    k = k+1; %counter for array stoage
    t = t+step; %time-step
    s = (v - w*R)/v; %Relative slip calculation
    if s <0
        s = 0;
    end
    e = sd-s; % error calculated
         if e > 0 %on/ off switch equivalent
          p = p + 75000000*step;
          Tb = 0.00004735*p; %Pressure*FricitonCo*Radius*Area

                if Tb>1200 %maxiumum limit on braking torque
                 p = 4820000;
                 Tb = 1200;
                end
         else %If error < 0
          p = p - 50000000*step; %Release pressure rate
          Tb = 0.00004735*p;
                if p < 0 %Boundary to reject negative pressure
                   p = 0;
                end
           end
    mu = (1.2801*(1-exp(-23.99*s))- 0.52*s)*exp(-0.03*v);
%Buckhardt formula for friction coefficient calculation
```

```
    brake(k)= Tb; % braking torque array storage
    fri(k) = mu; % friction coefficient array storage
    slip(k) = s; % relative slip array storage
    wspeed(k) = w; % wheel angular velocity array storage
    linspeed(k) = v/R; % vehicle body array storage
    dist(k)=d; % stopping distance array storage
    time(k) = t; % time array storage
    v =v +(-1*abs(mu)*g)*step; % vehicle body linear velocity
calculation
    w = w+ ((mu*R*m*g-Tb)/j)*step ; % wheel angular velocity
calculation
    if w<0
        w=0;
    end
    d = (d+ v*step); %stopping distance calculation
end
dfinal = max(d);
tfinal = max(t);
decel = (v0/tfinal);
figure (1)
hold on
plot (time, wspeed);
plot (time, linspeed);
title ('Angular velocity vs time');
xlabel ('Time (s)');
ylabel('Angular velocity (rad/s)');

figure (2)
hold on
plot (time, slip);
plot (time, fri);
title ('Slip vs Tim');
xlabel ('Time (s)');
ylabel ('Slip');
legend ('slip', 'mu');

figure (3)
hold on
plot (time, dist);
title ('Displacement vs time');
xlabel ('Time (s)');
ylabel('stopping distance');

disp ('The braking distance is');
disp(dfinal);
disp ('The time taken is');
disp(tfinal);
disp ('The average deceletarion is');
disp(decel);
```

SIMULINK PID Controller Script:

```
clear;
clc;
j = 0.72;
g = 9.81;
m = input('What is the mass of the motorcycle? (kg) ');
R = input('What is the radius of the wheel? (m) ');
i_speed = input('What is the initial speed? (mph) ');
v0 = (i_speed*0.44704);
w0 = (v0/R);

road_con = input('What is the road condition? dry asphalt, wet
asphalt, dry concrete, snow or ice ','s');

   if strcmpi('dry asphalt', road_con)
    c1 = 1.2801;
    c2 = 23.99;
    c3 = 0.52;
    sd = 0.2;


   elseif strcmpi ('wet asphalt', road_con)
    c1 = 0.857;
    c2 = 33.822;
    c3 = 0.347;
    sd = 0.1;

   elseif strcmpi ('dry concrete', road_con)
    c1 = 1.1973;
    c2 = 25.168;
    c3 = 0.5373;
    sd = 0.15;

   elseif strcmpi ('snow', road_con)
    c1 = 0.1946;
    c2 = 94.129;
    c3 = 0.0646;
    sd = 0.025;

   elseif strcmpi ('ice', road_con)
    c1 = 0.05;
    c2 = 306.39;
    c3 = 0;
    sd = 0.01;
end
sim('enter_values_pid_controller');

figure (1)
hold on
title('Vehicle Speeds')
plot (vrot);
```

```
plot (wrot);
xlabel ('Time (s)')
ylabel ('Speed (Rad/s)')
legend ('Vehicle Speed', 'Wheel Speed');

figure (2)
hold on
plot (distance);
title ('Stopping Distance')
xlabel ('Time (s)')
ylabel ('Distance (m)')

figure (3)
hold on
plot (slip);
title ('Slip Ratio')
xlabel ('Time (s)')
ylabel ('Slip')
```

Fuzzy Logic Controller Script:

```
clear;
clc;
j = 0.72; %mass moment of wheel
R = 0.331; %wheel radius
g = 9.81; %gravity
v = 22.352; %inital vehicl linear velocity in m/s
v0 = v;
w = v/R; %Angular velocity of wheel
sd = 0.2; %Desired relative slip value
m = 165.5; %half mass of motorcycle
t = 0; %initial time
s=0; %initial slip
k=0; %inital counter
Tb=0; %initial braking torque
d=0; %initial stopping distance
p = 0;
step = 0.001;
e=0;
eprev=0;
de=0;

while v > 0 %loop occurs until vehicle body is sufficiently
slow
    k = k+1; %counter for array stoage
    t = t+step; %time-step
    s = (v - w*R)/v; %Relative slip calculation
    if s <0
        s = 0;
    end
    eprev=e;
    e = sd-s; % error calculated
```

```
    if k>1
    de=(e-eprev)/step;
    end
      fis=readfis('error_controller_2');
    pf = evalfis([e de],fis);
         if e > 0 %on/ off switch equivalent
          p = p + 75000000*step*pf;
          Tb = 0.000249*p;

         if Tb>1200 %maxiumum limit on braking torque
            p = 48200;
            Tb = 1200;
         end
         else
          p = p - 50000000*step*pf;
          if p < 0
              p = 0;
          end
          Tb = 0.000249*p;
         end
    mu = (1.2801*(1-exp(-23.99*s))- 0.52*s)*exp(-0.03*v);
%Buckhardt formula for friction coefficient calculation
    pressure(k) = pf;
    error(k) = e;
    brake(k)= Tb; % braking torque array storage
    fri(k) = mu; % friction coefficient array storage
    slip(k) = s; % relative slip array storage
    wspeed(k) = w; % wheel angular velocity array storage
    linspeed(k) = v/R; % vehicle body array storage
    dist(k)=d; % stopping distance array storage
    time(k) = t; % time array storage
    echange(k) = de;
    v =v +(-1*mu*g)*step; % vehicle body linear velocity
calculation
    w = w+ ((mu*R*m*g-Tb)/j)*step ; % wheel angular velocity
calculation
    if w<0
        w=0;
    end
    d = (d+ v*step); %stopping distance calculation

end

figure (1)
hold on
plot (time, wspeed);
plot (time, linspeed);
title ('Angular velocity vs time');
xlabel ('Time (s)');
ylabel('Angular velocity (rad/s)');
```

```
figure (2)
hold on
plot (time, slip);
title ('Slip vs time');
xlabel ('Time (s)');
ylabel('Slip (%)');

figure (3)
hold on
plot (time, dist);
title ('Displacement vs time');
xlabel ('Time (s)');
ylabel('stopping distance (m)');
```

No ABS Script :

```
clear;
clc;
j = 0.72; %mass moment of wheel
R = 0.331; %wheel radius
g = 9.81; %gravity
v = 22.352; %inital vehicl linear velocity in m/s
v0= v;
w = v/R; %Angular velocity of wheel
sd = 0.2; %Desired relative slip value
m = 165.5; %half mass of motorcycle
t = 0; %initial time
s=0; %initial slip
k=0; %inital counter
Tb=0; %initial braking torque
d=0; %initial stopping distance
p = 0;
step = 0.001;

while v > 0 %loop occurs until vehicle body is sufficiently
slow
    k = k+1; %counter for array stoage
    t = t+step; %time-step
    s = (v - w*R)/v; %Relative slip calculation
    if s > 1
        s=1;
    end

          p = p + 75000000*step;
          Tb = 0.000249*p;

         if Tb>1200 %maxiumum limit on braking torque
            p = 4820000;
            Tb = 1200;
          end
    mu = (1.2801*(1-exp(-23.99*s))- 0.52*s)*exp(-0.03*v);
%Buckhardt formula for friction coefficient calculation
```

```
    brake(k)= Tb; % braking torque array storage
    fri(k) = mu; % friction coefficient array storage
    slip(k) = s; % relative slip array storage
    wspeed(k) = w; % wheel angular velocity array storage
    linspeed(k) = v/R; % vehicle body array storage
    dist(k)=d; % stopping distance array storage
    time(k) = t; % time array storage
    v =v +(-1*mu*g)*step; % vehicle body linear velocity
calculation
    w = w+ ((mu*R*m*g-Tb)/j)*step ; % wheel angular velocity
calculation
    if w<0
        w=0;
    end
    d = (d+ v*step); %stopping distance calculation
end
dfinal = max(d);
tfinal = max(t);
decel = (v0/tfinal);

figure (1)
hold on
plot (time, wspeed);
plot (time, linspeed);
title ('Angular velocity vs time');
xlabel ('Time (s)');
ylabel('Angular velocity (rad/s)');

figure (2)
hold on
plot (time, slip);
title ('Slip vs Time');
xlabel ('Time (s)');
ylabel ('Slip');

figure (3)
hold on
plot (time, dist);
title ('Displacement vs time');
xlabel ('Time (s)');
ylabel('stopping distance');

figure (4)
hold on
plot (time, fri);
title ('friction vs time');
xlabel ('Time (s)');
ylabel('friction');

disp ('The braking distance is');
disp(dfinal);
```

```
disp ('The time taken is');
disp(tfinal);
disp ('The average deceletarion is');
disp(decel);
```

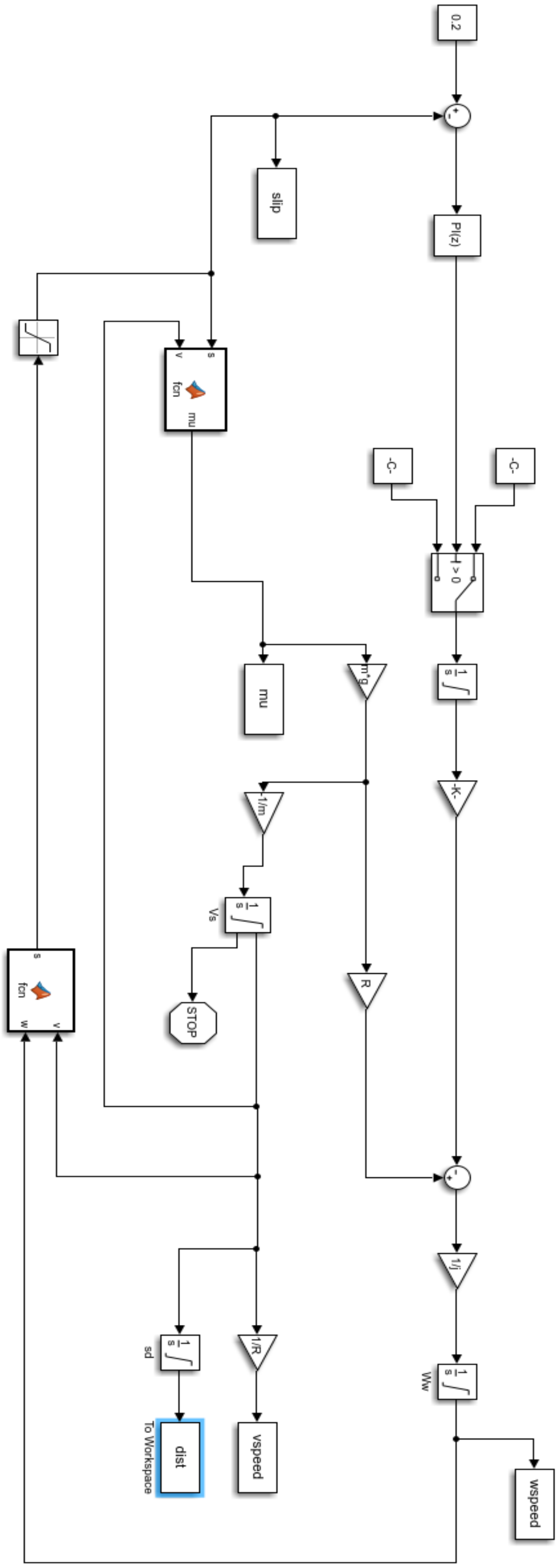

Figure 36 - PID Control SIMULINK Model

Appendix B Simulation results

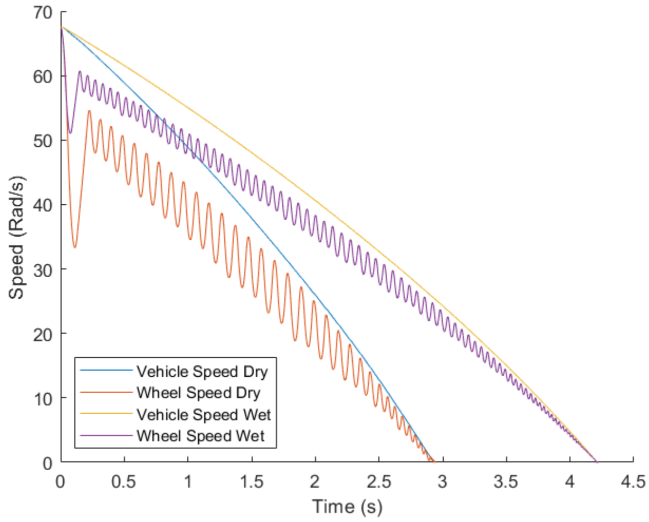

Figure 37 -Speeds During Wet and Dry Braking

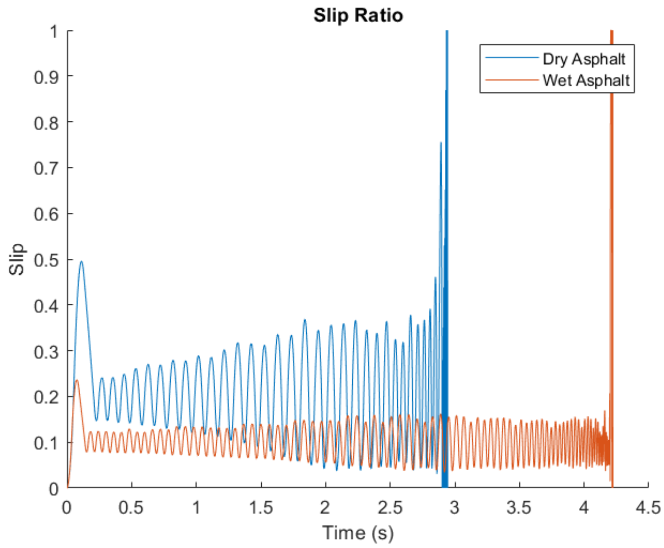

Figure 38 - Slip Ratio During Wet and Dry Braking

No ABS Results:

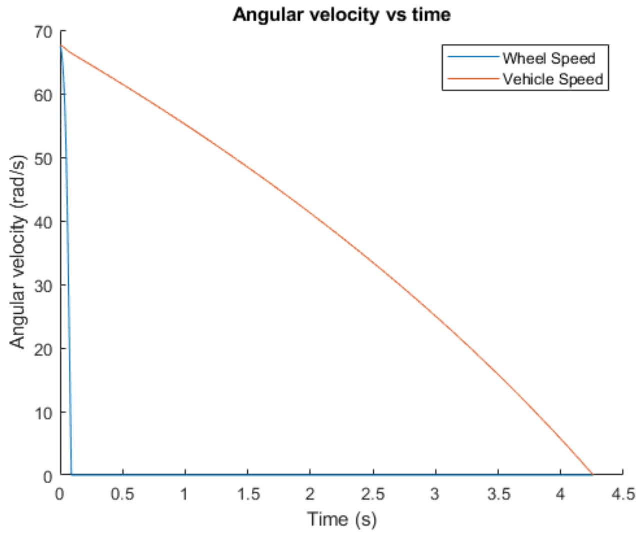

Figure 39 - Speeds With No ABS

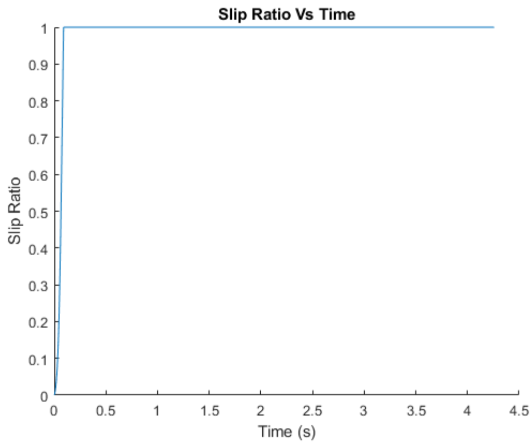

Figure 40 - Slip Ratio With No ABS

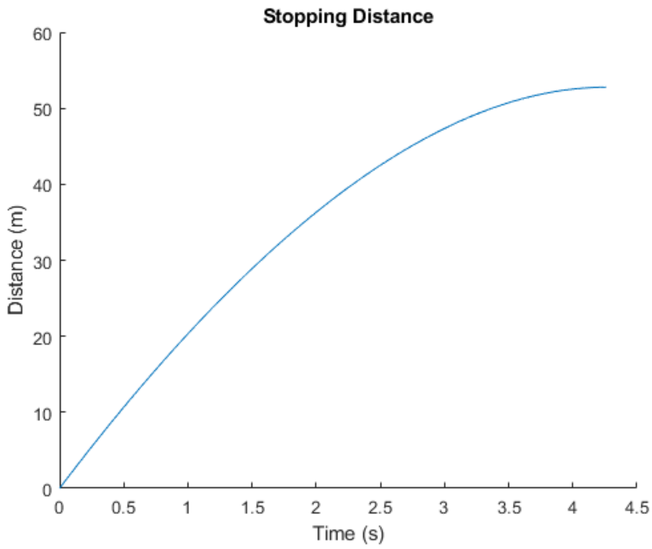

Figure 41 - Stopping Distance With No ABS

Bang-Bang Controller Results:

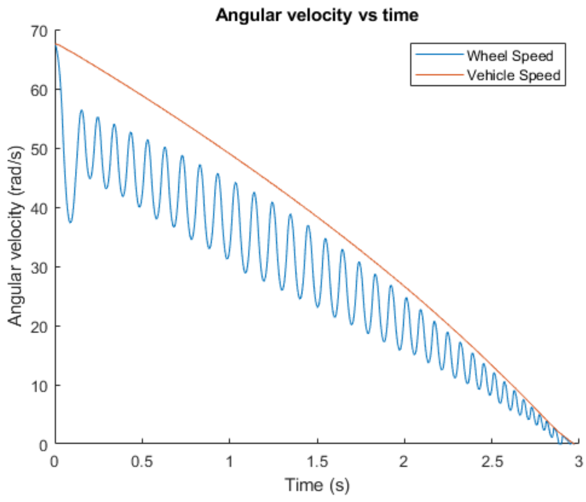

Figure 42 - Speeds With Bang-Bang Control

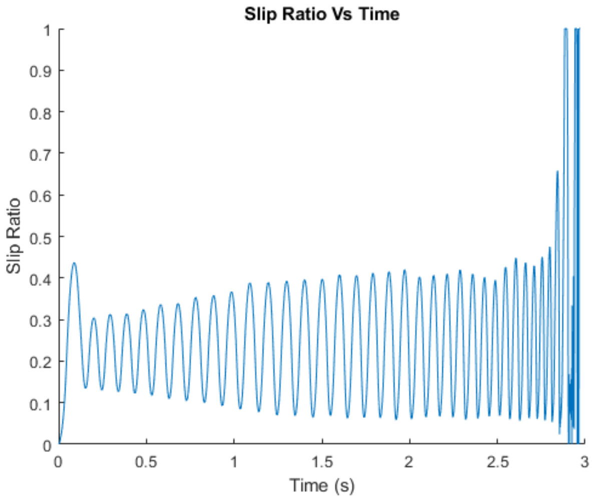

Figure 43 - Slip Ratio With Bang-Bang Control

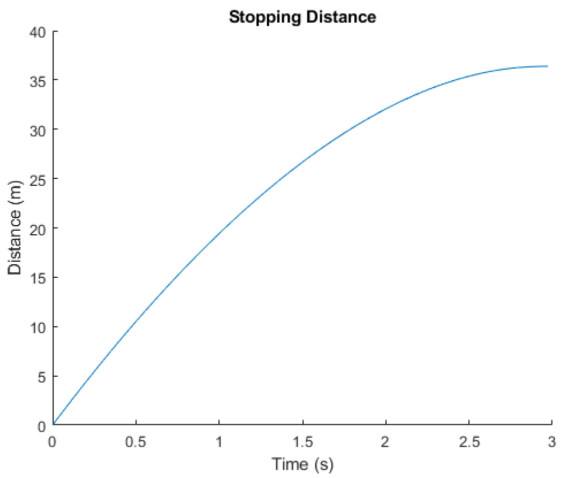

Figure 44 - Stopping Distance With Bang-Bang Control

PID Controller Results:

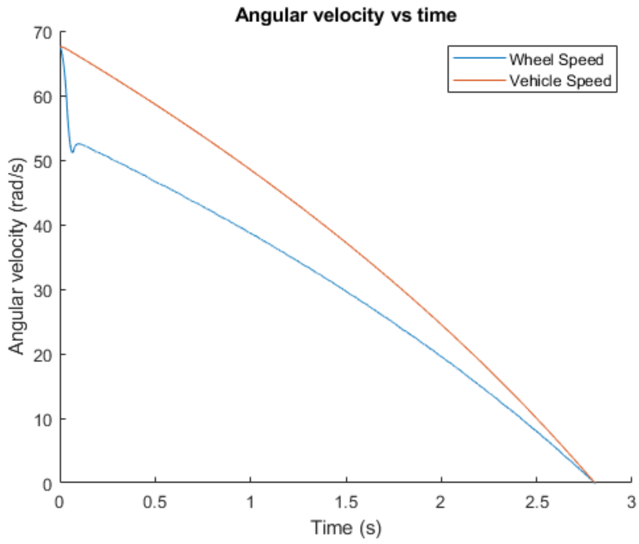

Figure 45 - Speeds With PID Control

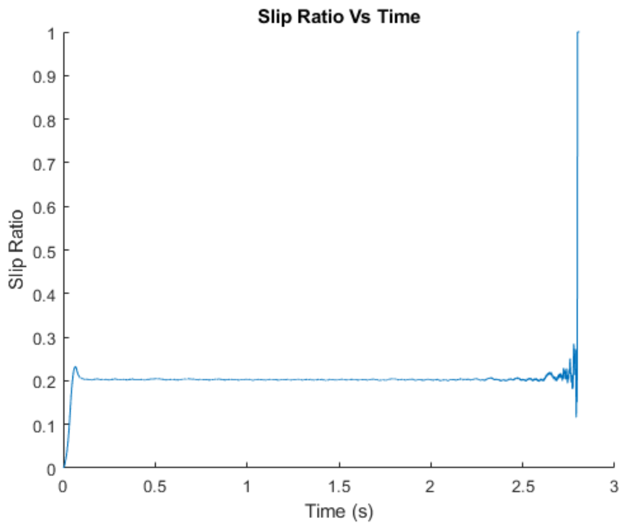

Figure 46 - Slip Ratio With PID Control

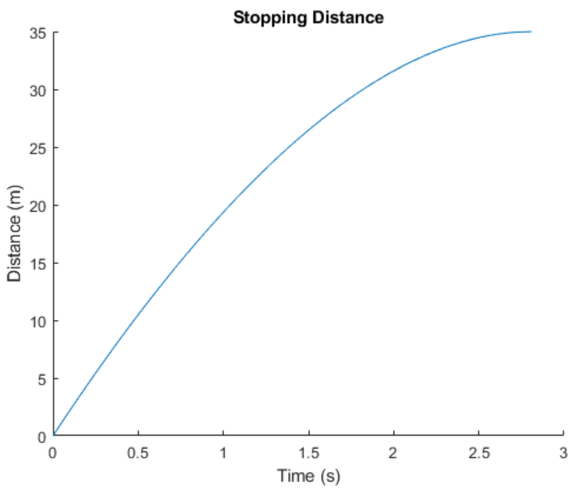

Figure 47 - Stopping Distance With PID Control

Fuzzy Controller Results:

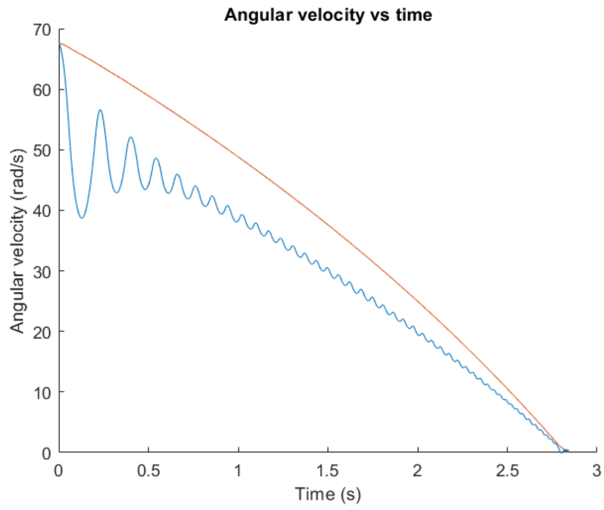

Figure 48 - Speeds With Fuzzy Control

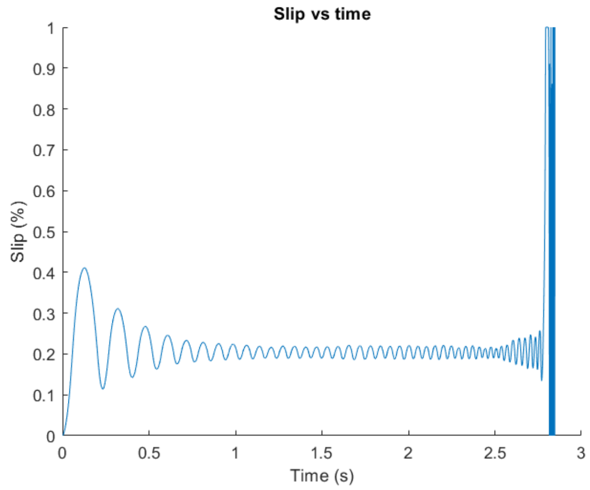

Figure 49 - Slip Ratio With Fuzzy Control

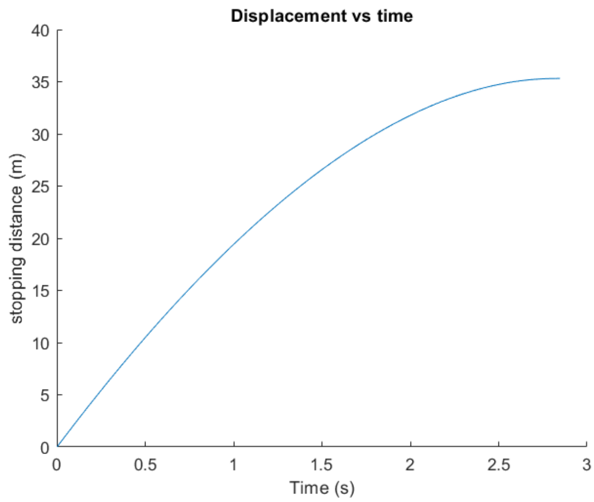

Figure 50 - Stopping Distance With Fuzzy Control