**SIMULINK MODEL OF ANTI-LOCK BRAKING SYSTEM**



Prepared for



The Society of Automotive Engineers

Collegiate Club Number - SAEICCBIS022  
National Institute of Technology Karnataka

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May 15, 2021

ABSTRACT

An Anti-Lock Braking System (ABS) is an active safety feature in aircraft and land vehicles used to prevent wheel lock-up and skid during braking allowing the driver to maintain more control over the vehicle whenever the wheels get locked. ABS requires improvement in the areas of stability, steerability and stopping distance. In this project, we present a mathematical model of quarter vehicle, including aerodynamic parameters and the implementation of ABS modelling using MATLAB Simulink. The non-linearity associated with the road friction coefficient and various input arguments like mass, velocity, aerodynamics parameters make it necessary for a robust tuning algorithm. Here, the framework is limited to demonstrating uniquely for straight-line slowing down with PID Tuning algorithm and slip control system. We have compared the performance of the open-loop system and the PID Controller.

Table of Contents

[SECTION – I INTRODUCTION 3](#_Toc71970471)

[Timeline 3](#_Toc71970472)

[Tools and Technologies 3](#_Toc71970473)

[Brief Introduction 4](#_Toc71970474)

[Literature Review 4](#_Toc71970475)

[SECTION – II CONCEPT DEVELOPMENT AND EVALUATION 5](#_Toc71970476)

[Introduction 5](#_Toc71970477)

[Methodology 6](#_Toc71970478)

[Results and Discussion 14](#_Toc71970479)

[Conclusion 18](#_Toc71970480)

[Future Scope 18](#_Toc71970481)

[References: 18](#_Toc71970482)

# SECTION – I INTRODUCTION

## Timeline

|  |  |  |
| --- | --- | --- |
| Month | Week | Task Accomplished |
| Dec-20 | One | Introductory Meet – Project Start |
| Dec-20 | Two | Completed MATLAB Fundamentals Course from MathWorks |
| Dec-20 | Three | Learnt Simulink from SAE KEP |
| Jan-21 | Three | Started Learning Basic Vehicle Dynamics – (Brake Bias) |
| Feb-21 | One | Learnt Load Transfer Calculations for a Half Car Model – (NPTEL) |
| Feb-21 | Four | Project Review – 01 |
| Mar-21 | Two | Literature Review for ABS Simulink Model |
| Apr-21 | Four | Started Making Simulink Model of Braking System (Open Loop) |
| May-21 | One | Added PID Controller to the Open Loop Model and Tuned |
| May-21 | Two | Added Drag and Downforce to the Simulink Model |
| May-21 | Two | Project Review – 02 (Final Review) |
| May-21 | Two | PID Auto-Tuning with genetic Algorithm on Simulink |
| May-21 | Three | Documentation and Submission of Final Report |

## Tools and Technologies

|  |  |  |
| --- | --- | --- |
| S. No | Tool / Technologies used | Remark |
| 1 | MATLAB  Modules Used: Simulink, Control Engineering Toolbox | Coding and Optimization |
| 2 | Microsoft Excel | Plotting graphs |

## Brief Introduction

An Anti-Lock Braking System is an active safety feature in aircraft and land vehicles used to prevent wheel lock-up and skid during braking allowing the driver to control the vehicle. It can decrease the braking distance on dry and regular roads. ABS requires improvement in the areas of stability, steerability and stopping distance.

In this project, a quarter vehicle model is developed and used to study the braking performance of a straight-line braking test vehicle on a flat dry asphalt road in the MATLAB-Simulink software environment. The vehicle model includes the aerodynamic model and a model of the antilock braking system. As this is a simulation model, there is no chance of using a real-time sensor for getting the wheel speed and vehicle speed. We have used Newton's kinematic equations to get the values of the same. We have avoided the hydraulic modulator, and we are directly adjusting the brake torque from the feedback loop. Also, The framework here is demonstrated uniquely for straight-line slowing down. If there were an occurrence of cornering, the side slip ratio should be controlled so that wheels do not lock and subsequently guaranteeing steerability.

## Literature Review

Sharkawy [7] has studied the changes in the coefficient of friction at various road conditions. We have extracted the friction formula from this literature and have plotted the same at various velocities. He has also tuned the ABS with the Genetic algorithm and fuzzy. However, we have attempted to tune the ABS PID model with Genetic algorithm.

Bhivate [8] has made the Simulink model of the Antilock brake system without the aerodynamic components. He has used state-space equations of motion to model the Simulink model. In this project, we did the Simulink model with direct calculation, and the results were reasonable matching. The direct calculation is a much simpler method.

Rangelov [9] has modelled an antilock braking system for a quarter car model on a flat and uneven road. He has made the ABS based on various methodologies like slip control, acceleration control, tire moment control braking. He has also included a suspension model for the quarter car vehicle.

Harifi [10] made a primary controller design and improved using an integral switching surface to reduce chattering effects. He also compared the performance of the designed controller with three of the results of the overall paper to determine the performance of sliding mode control integrated with integral switching surface.

# SECTION – II CONCEPT DEVELOPMENT AND EVALUATION

Introduction

The ABS consists of a wheel speed sensor, hydraulic modulator and an Electronic Control Unit (ECU). It has a feedback system that finds the error between the actual and desired slip ratio and adjusts the Brake Pressure accordingly to get the optimum slip ratio and maximum traction. The system shuts down if the vehicle speed is under the pre-set threshold.

Before getting into more details, it is essential to understand the motivation and need to prevent wheel skidding. Wheel locking is when the tyre stops rotating under braking and slides along the top of the surface. It is terrible because it is less efficient (coefficient of kinetic friction is lower than the coefficient of static friction) (explained in Figure 2). Hence, it will take longer to slow the vehicle down and wear a flat spot on the tyre if it locks for a long time. Flat spotted tyres tend to lock more quickly in the future at the flat spot point and cause vibrations that can damage the car.

During braking, we generally use brake pad friction on the wheels to slow the vehicle down. When brake hard, sometimes, the brake pads stop the wheel from spinning. In other words, when the brake pads are so tightly pressed against the drum/disc, the wheel locks up. Now, although the wheel is not moving because of the car's momentum, it will still keep moving forward for a short distance; this is skidding, where the tyres/tires do not roll over the tarmac but are dragged.

In Ancient time, a balance bar was used to adjust the brake bias instead of an ABS. The function of a balance bar is to allow the adjustment of brake line pressure distribution between two master cylinders. The torque on one side of the bar must balance the torque on the other side. Balancing bars take the force from one side and give it to the other. The Brake bias/Brake balance, front to rear, is critical to the stability of a racing car during the braking and turn-in phase; too much rear braking will tend to cause the car to spin; too much front and car will not turn in. Brake biasing is only seen in racing cars.

Brake biasing is the condition where we give different brake forces to the rear and front wheels. Generally, we give more braking force to the front than to the rear as the centre of gravity tends to move forward when we apply brakes. For the stability of the vehicle, both wheels should skid at the same time.

When the front wheels lock, there is a loss of steerability, i.e., it caused understeer due to the absence of lateral friction. If the front wheels get locked, the driver loses the steering control. However, this can be detected more readily by an experienced driver, and the driver can regain control by releasing the brakes. However, when the rear wheels lock, it is more critical as directional stability is lost, and there are chances that the car spins out. In this case, the vehicle over-steers. The rear part of the vehicle rotates about its axis if any lateral perturbation is applied to the vehicle. Although the ABS cannot adjust the wheel's locking up, ABS needs to get the correct sequence of locking up.

## Methodology

We are assuming that the mass is equally distributed on all four wheels of the vehicle. We consider the mass of a quarter car model at 0.25\*m. The Kinematic equations of motion of the quarter car model are as follows:

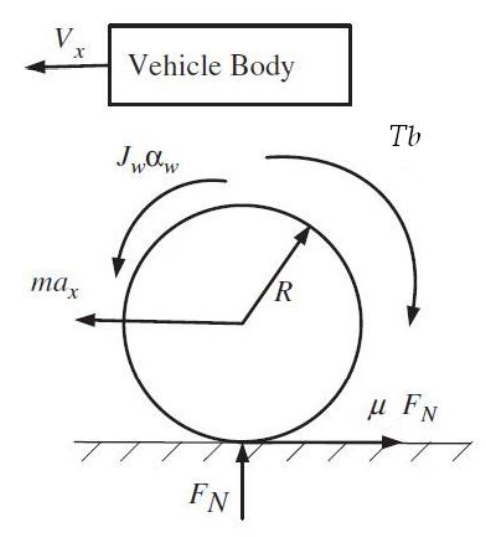
The Down Force on the vehicle is: (1)

Figure Quarter Car Vehicle Model

The Normal Force of the Vehicle: (2)

The Drag Force of the Vehicle

(3)

For a Quarter Car Model: (4)

The equation for braking force balance in the longitudinal direction (vehicle)

(5)

(6)

(7)

Balancing the Torque at the Wheel Centre

(8)

(9)

(Assuming the Downforce and Drag forces are passing through the wheel centre, we have not included them in the torque equations)

Now, Wheel Slip Ratio can be defined as (10)

In the case of pure rolling, we have , and the value of . On Contrast, in the case of skidding, we have which make the value of .

In this paper, the tire friction model adopted in Harifi et al. (2008) [10] has been used. It provides the tire-road coefficient of friction as a function of the wheel slip and the vehicle velocity Vx. Researches show that the road coefficient of adhesion is a nonlinear function of wheel slip () and the vehicle velocity (Vx) in a specified road condition. The road friction coefficient function is as follows:

(11)

Where,

c1 is the maximum value of the friction curve

c2 is the friction curve shapes/slope

c3 is the friction curve difference between the maximum value and the value at = 1

c4 is the wetness characteristic value, which varies from 0.02-0.04 s/m

The above graph shows that the maximum slip is attained at a slip ratio of 0.2. However, in Snowy and the icy road, there is no significant change in the road friction coefficient at different values of slip. The Plots Below are plots of different types of the road at varying vehicle speeds.

Figure Road friction coefficient v/s Wheel Slip ratio at vehicle speed 30 m/s

|  |  |  |  |
| --- | --- | --- | --- |
| **Surface** | **C1** | **C2** | **C3** |
| Dry asphalt | 1.2801 | 23.99 | 0.52 |
| Wet asphalt | 0.857 | 33.822 | 0.347 |
| Dry Concrete | 1.1973 | 25.168 | 0.5373 |
| Snow | 0.1946 | 94.129 | 0.0646 |
| Ice | 0.05 | 306.39 | 0 |
| Current Study | 1.28 | 12 | 0.28 |

Table 1 Road friction coefficient parameters set for different road surfaces.

The value of c4 varies from 0.02 s/m to 0.04 s/m, depending on the wetness of the road.

Figure Road friction coefficient of Dry Asphalt road at different velocities

Figure Road friction coefficient of Wet Asphalt road at different velocities

Figure Road friction coefficient of road of current study at different velocities

Figure Road friction coefficient of Snowy road at different velocities

Figure Road friction coefficient of Dry Concrete road at different velocities

Figure Road friction coefficient of Icy road at different velocities

There is no significant change in the wheel slip point at which friction attains its peak value for almost all kinds of roads. So, a slip ratio of 0.2 can be made as a universal optimum slip value.

A feedback control system is a closed-loop control system in which a sensor monitors the output (slip ratio) and feeds data to the controller, which adjusts the control (brake Torque) as necessary to maintain the desired system output (match the wheel slip ratio to the reference value of slip ratio). The PID Controller flow diagram is as shown below.

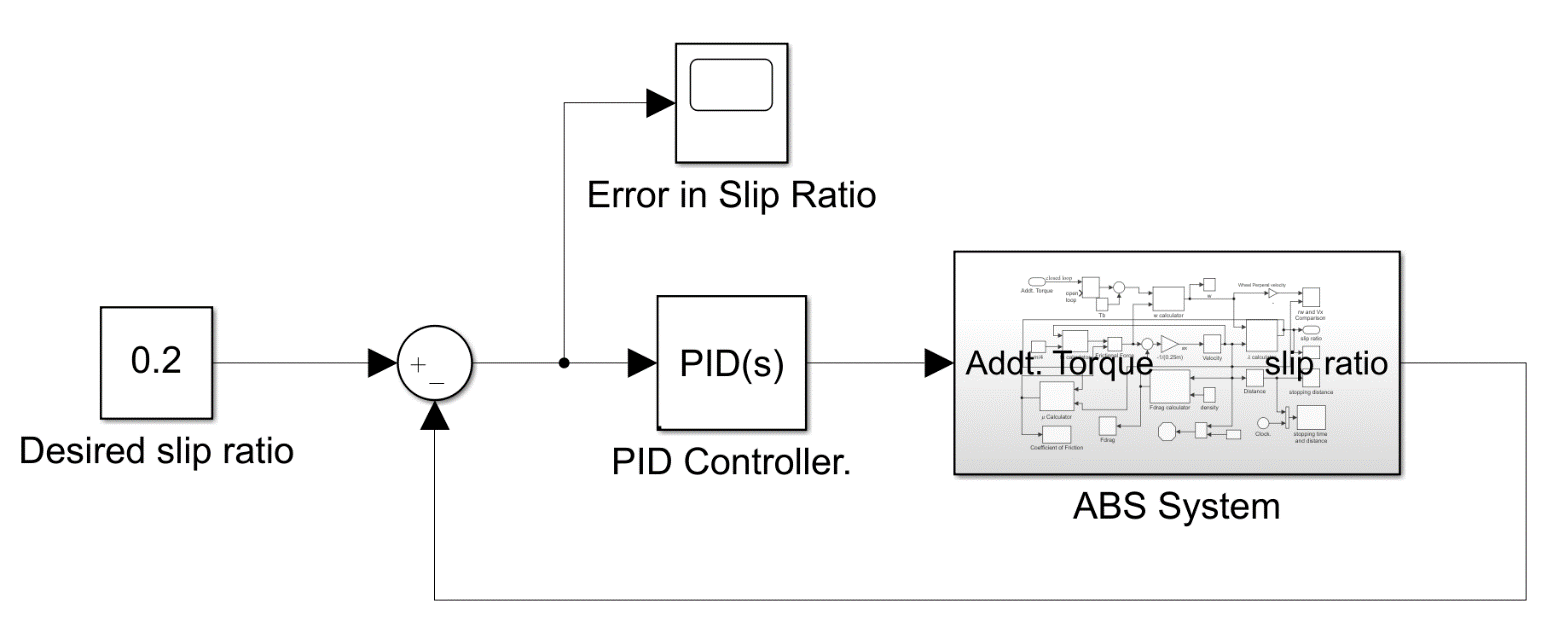


Figure The ABS Control Algorithm (PID)

The PID Tuner takes the error in slip ratio, sends the additional torques (either positive or negative), and gets the slip ratio value again. This process continues till the Vehicle velocity is less than the threshold, i.e., it is 0.5 m/s in our project. We have tuned the PID Controller manually in our project, and we have achieved the fastest response at Kp = 250000; Ki =100000; Kd =100. The Flow Diagram of the Complete Vehicle Dynamics Block of the ABS model is shown in Figure 10.

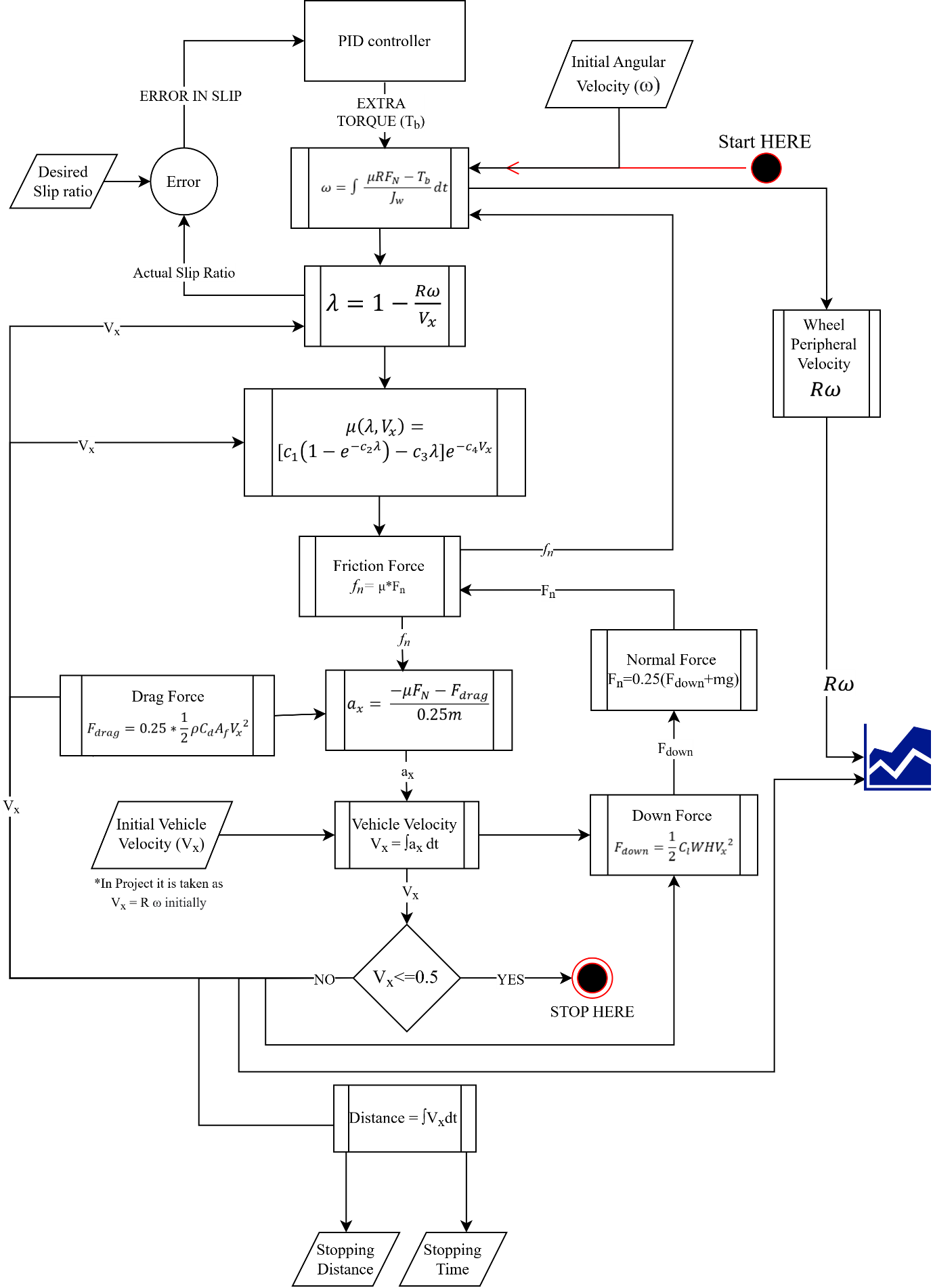


Figure 10 Complete Flow Diagram of the Simulink Model

The Simulink model of Figure 10 is as shown below. To avoid confusion, various subsystems have been made.

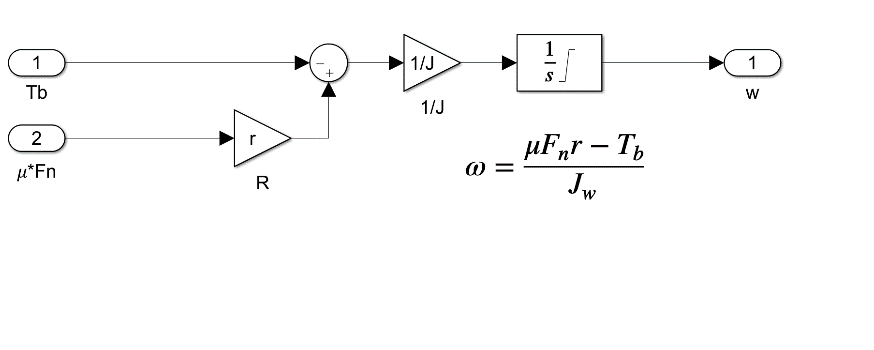
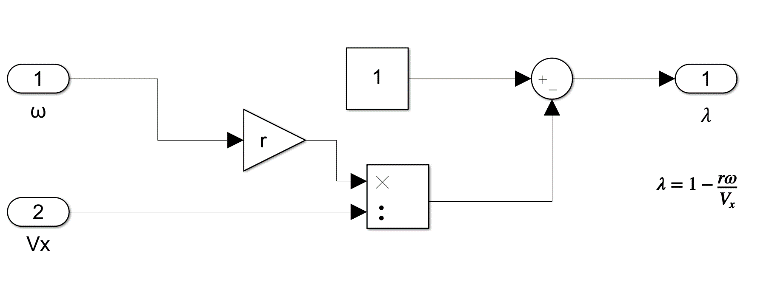
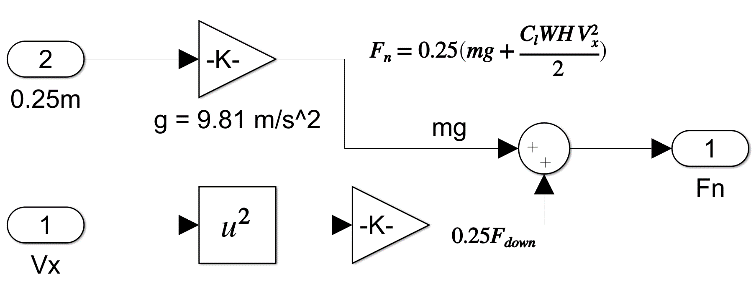
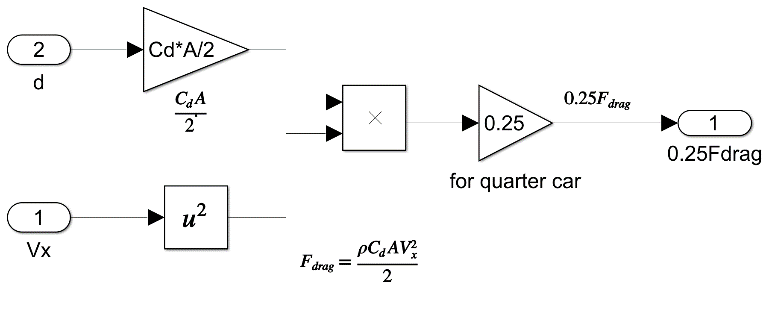
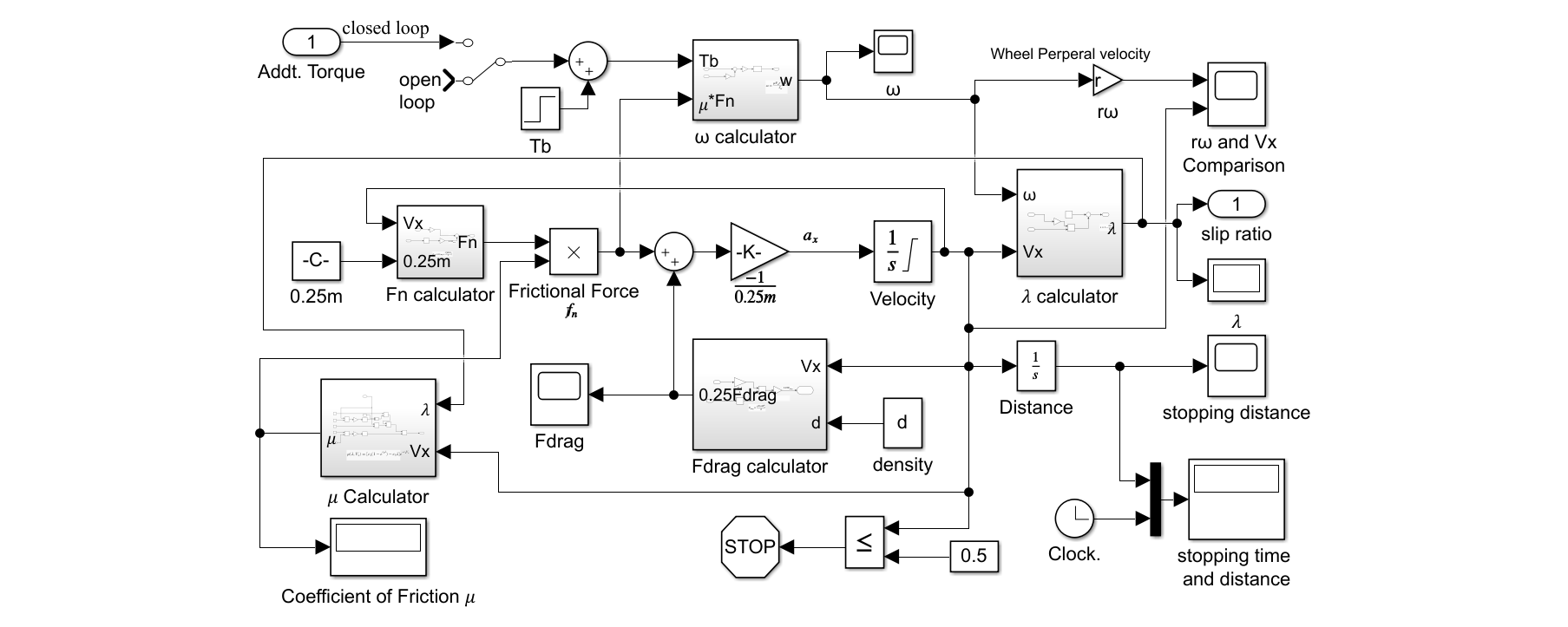
 

Figure Drag Force Calculator

Figure Normal Force (+Downforce) Calculator

Figure ω calculator Sub-System

Figure 𝜆 Calculator Sub-System

Figure Simulink Model of ABS Sub-System

The Flow diagram (Figure 10) is self-explanatory. Parameters like Downforce and Drag force are assumed to be acted on the centre of the wheel (But Practically, they are not in this way). Hence, no torque develops from them in this model.

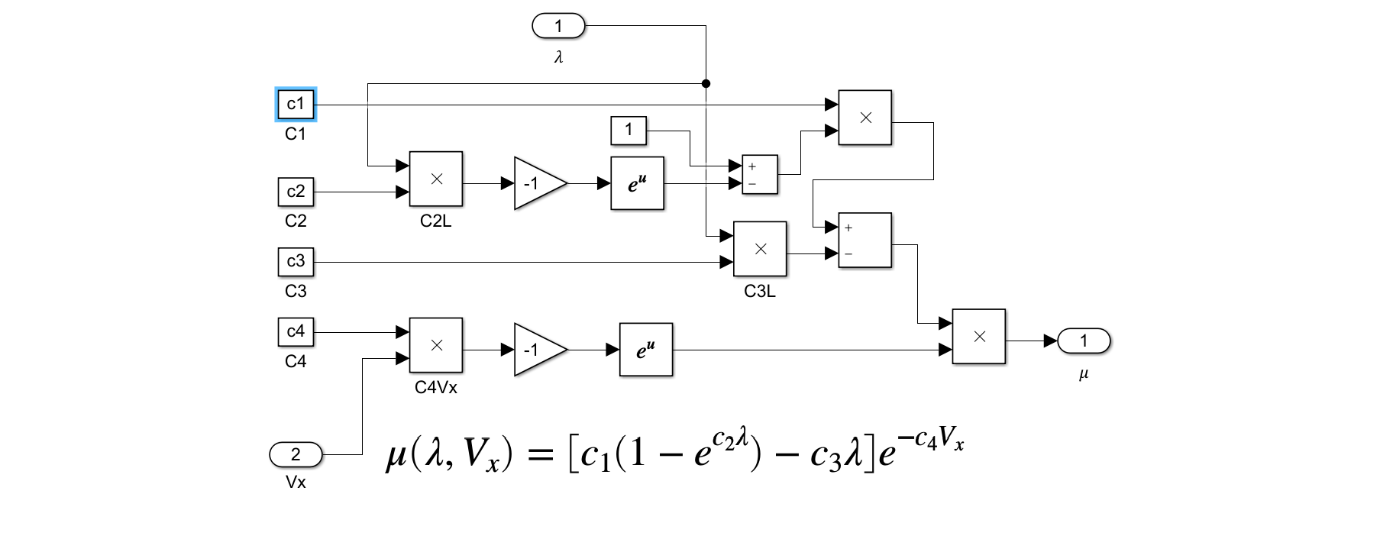
Combining all the above block, we get the final Simulink Model. A Simpler Version of the Simulink Model has been shown in the Flow Diagram.

Figure Road Friction Coefficient (Mu) Calculator

## Results and Discussion

The Simulation has been run with P, PI, PD, PID Controller and compared with Open loop System for straight line braking system. The input parameters used for the simulation are

r = 0.33 m; m = 342 kg; Jw = 1.13 kgm2; g = 9.81 m/s2; Tb = 1200 N-m;   
Vx = 100 km/hr = 27.78 m/s; ω= Vx/r = 84.14 rad/sec; λd = 0.2; Kp = 250000;

Ki = 100000; Kd = 100

The Fig is the Graph between Vx and rω in an open-loop system. We can see observer that in Figure 18, we have ω = 0 in the initial stage itself. This implies the wheel keeps skidding until Vx=0. When the wheel skids, the value of λ = 1, which is evident in Figure 17

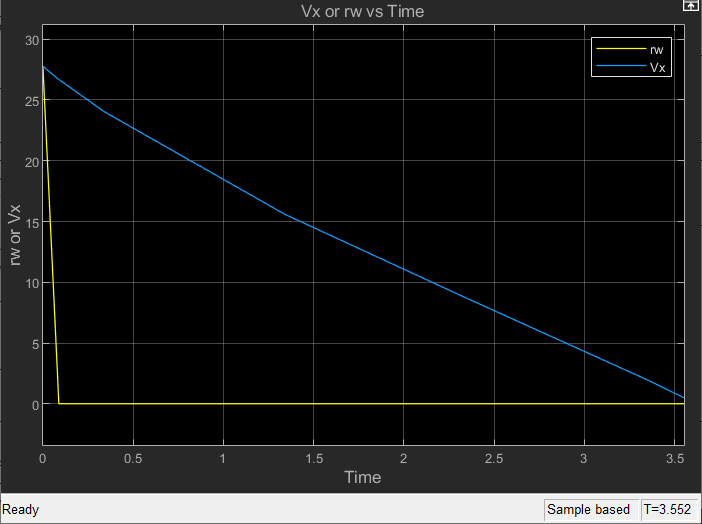
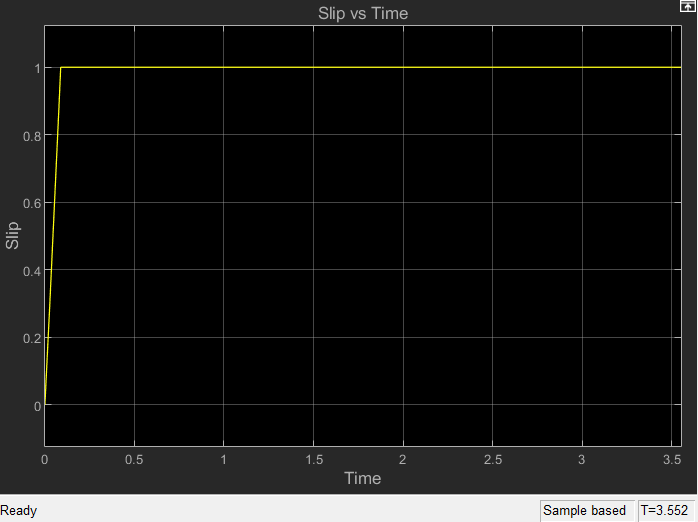
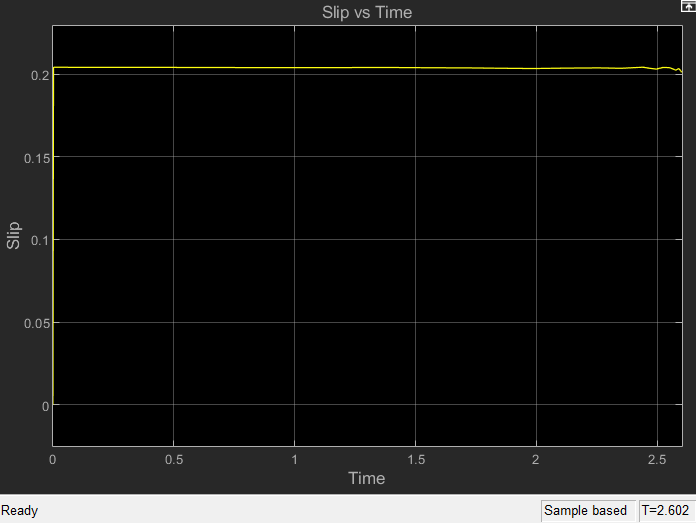


Figure Plot of Vehicle Slip Ratio (λ) v/s time (t) in Open Loop System

Figure Plot of Vehicle velocity (Vx ) v/s time and Wheel peripheral velocity (rω) v/s time in Open Loop System

In the case of the P Controller, as shown in Figure 19, we can see that initially, the peripheral wheel velocity (rω) is about to fall to zero, i.e., it was about to skid. However, due to the proportional gain in error, the wheel is made to rotate until the vehicle velocity comes reaches it threshold Vt. In, Figure 20 the slip ratio (λ) v/s time graph, we can see that there is a slight steady state error in the graph which can be acceptable and it can also be corrected by using Integrator/Derivative gains.

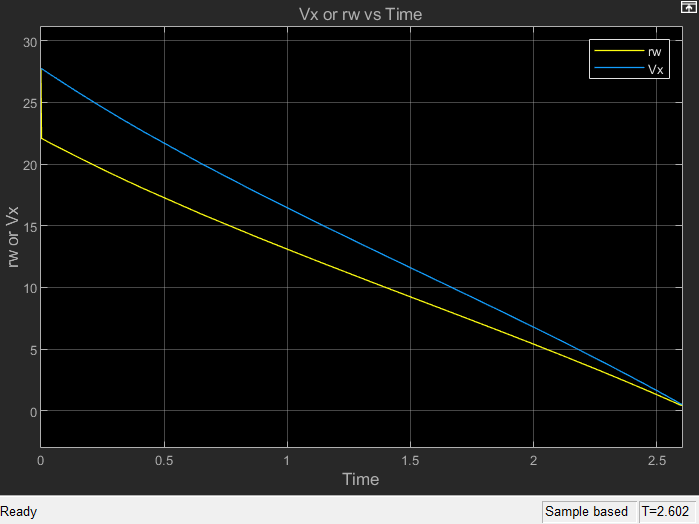


Figure Plot of Vehicle velocity (Vx ) v/s time and Wheel peripheral velocity (rω) v/s time with P controller

Figure Plot of Vehicle Slip Ratio (λ) v/s time (t) with P Controller

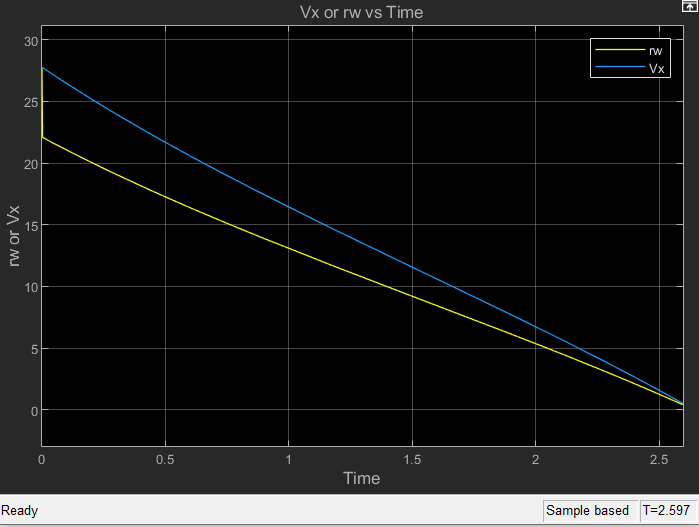
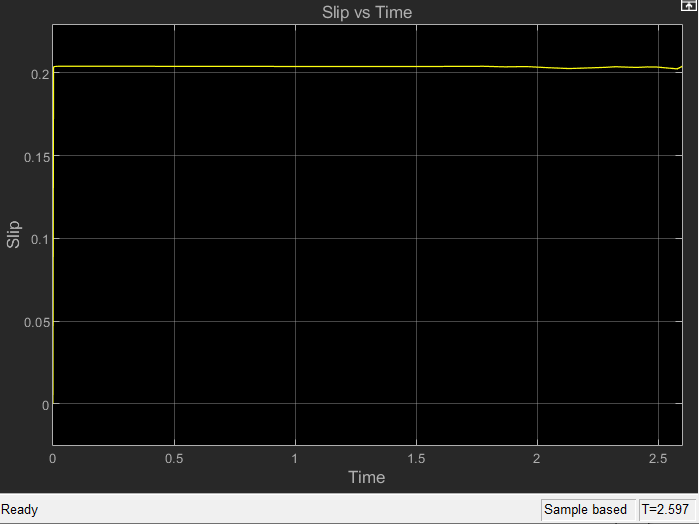
Almost Similar Results were obtained in PI, PD and PID Controllers also. There is a minute change in stopping time, i.e., in the order of 0.001 seconds. The PD Controller results are shown in Figure 22. As shown in Figure 21, The PD Controller tried to Correct the derivative error which was seen in the P controller but was not very successful.

Figure Plot of Vehicle Slip Ratio (λ) v/s time (t) with PD Controller

Figure Plot of Vehicle velocity (Vx ) v/s time and Wheel peripheral velocity (rω) v/s time with PD controller

The PI Controller results are as follows in Figure 24. The Steady-State error has been slightly corrected in PI Controller, which can be seen in Figure 23.

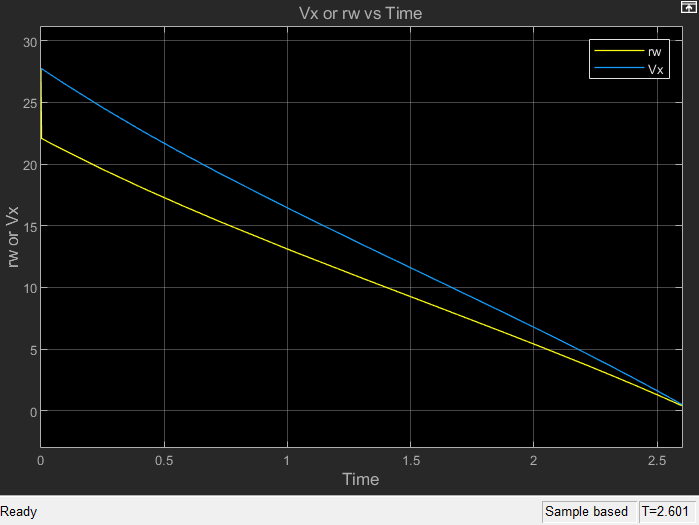
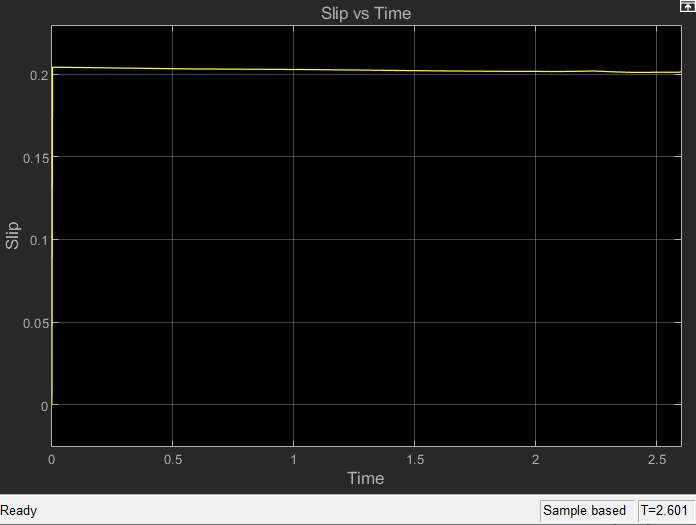


Figure Plot of Vehicle Slip Ratio (λ) v/s time (t) with PI Controller

Figure Plot of Vehicle velocity (Vx ) v/s time and Wheel peripheral velocity (rω) v/s time with PI controller

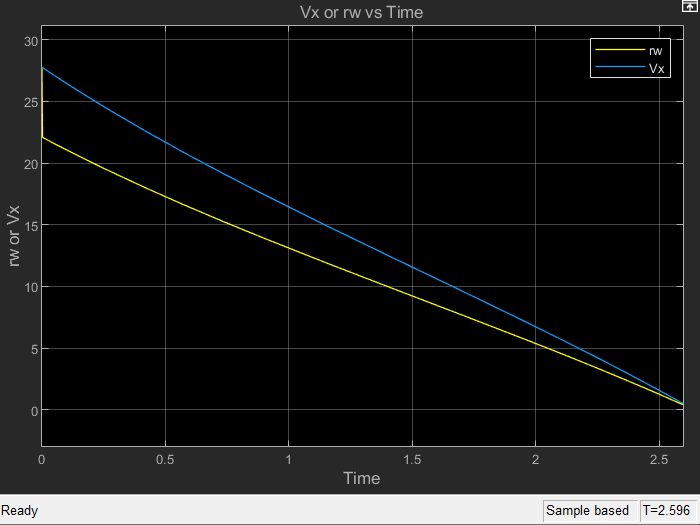
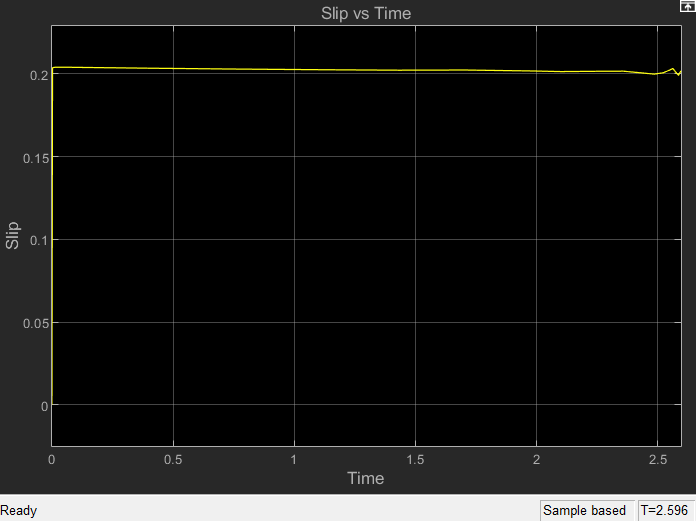
The PID Controller result is shown below in Figure 26 and Figure 25.

Figure Plot of Vehicle Slip Ratio (λ) v/s time (t) with PID controller

Figure Plot of Vehicle velocity (Vx ) v/s time and Wheel peripheral velocity (rω) v/s time with PID Controller

Although The steady-state error is corrected in Figure 25, it is good to use a P controller in this system as there is no significant change in the system. P controller can be used to be efficient and economical. The Results of all Controllers is compared with the open-loop system as shown in the below table.

Table 2 Comparison of ABS Outputs with Different Controllers

|  |  |  |  |
| --- | --- | --- | --- |
| Controller | Stopping Time | Stopping Distance | Road Friction Coefficient |
| Open Loop | 3.552 | 46.18 | 0.7488 |
| P Controller | 2.602 (-27%) | 35.66 (-23%) | 1.148 (+42%) |
| PI Controller | 2.601 (-27%) | 35.65 (-23%) | 1.148 (+42%) |
| PD Controller | 2.597 (-27%) | 35.61 (-23%) | 1.147 (+42%) |
| PID Controller | 2.596 (-27%) | 35.6 (-23%) | 1.148 (+42%) |

From the above Table 2 we can notice a 27% reduction in stopping time, 23% reduction in stopping distance and 42% increment in the Road friction coefficient with P/PI/PD/PID Controllers. It is best to use just a P controller to save costs and be efficient.

## Conclusion

In this project, an attempt is made to understand the application of the various type of linear controller used for antilock braking systems. The system was modelled with a quarter vehicle dynamic, and motions equations of motion were formulated. The slip ratio is used control as a criterion for this control work. However, a literature review was done on various types of control systems for ABS. An attempt was made to auto-tune PID using the Genetic algorithm from the global optimization toolbox in Simulink. Observations in response for slip ratio have been made using trial and error tune P, PI, PD, PID controller and comparison is also made with the open loop system.

## Future Scope

The current simulations are done for a quarter vehicle model. Future simulations can be done on a half vehicle (bicycle) model or even a full vehicle model. Other forces like Roll and Dive forces would be added in a model which consists of more than one wheel. A suspension system can be added to the Simulink model, and further tuning can be done. Also, we can integrate powertrain into this model to make it more robust. If specific to the Control system is the need, then we could also go for different auto-tuning systems like Fuzzy Logic control, Genetic Algorithm or any other available in the literature. We have a vast scope on this ABS Project, which the upcoming generations of SAE-NITK can take up.

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