SIMULINK MODEL OF ANTI-LOCK BRAKING SYSTEM

Prepared for

The Society of Automotive Engineers

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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

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:

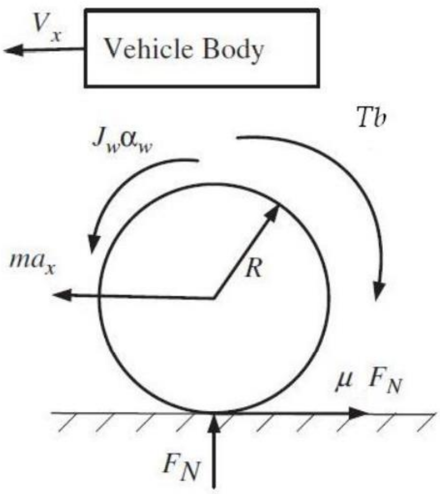

Figure 1 Quarter Car Vehicle Model

The Down Force on the vehicle is: $F_{down} = \frac{1}{2} C_l W H {V_x}^2$ (1)

The Normal Force of the Vehicle: $F_N = 0.25(F_{down} + mg)$ (2)

The Drag Force of the Vehicle

$$F_{drag} = 0.25 * \frac{1}{2}\rho C_d A_f {V_x}^2 \tag{3}$$

For a Quarter Car Model: $F'_{drag} = 0.25\, F_{drag}$ (4)

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

$$ma_x = -\mu F_N - F_{drag} \tag{5}$$

$$\Rightarrow a_x = \frac{-\mu F_N - F_{drag}}{m} \tag{6}$$

$$\Rightarrow a_x = \frac{-\mu\left(mg + \frac{1}{2}\rho C_d A_f {V_x}^2\right)}{m} \tag{7}$$

Balancing the Torque at the Wheel Centre

$$J_w \alpha_w = \mu R F_N - T_b \tag{8}$$

$$\omega = \int \alpha_w \, dt \Rightarrow \omega = \int \frac{\mu R F_N - T_b}{J_w} dt \tag{9}$$

(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 $\lambda = 1 - \frac{R\omega}{V_x}$ (10)

In the case of pure rolling, we have $V_x = R\omega$, and the value of $\lambda = 0$. On Contrast, in the case of skidding, we have $R\omega = 0$, which make the value of $\lambda = 1$.

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 μ as a function of the wheel slip λ and the vehicle velocity V_x. Researches show that the road coefficient of adhesion is a nonlinear function of wheel slip (λ) and the vehicle velocity (V_x) in a specified road condition. The road friction coefficient function is as follows:

$$\mu(\lambda, V_x) = [c_1(1 - e^{-c_2\lambda}) - c_3\lambda]e^{-c_4 V_x} \tag{11}$$

Where,

c_1 is the maximum value of the friction curve

c_2 is the friction curve shapes/slope

c_3 is the friction curve difference between the maximum value and the value at $\lambda = 1$

c_4 is the wetness characteristic value, which varies from 0.02-0.04 s/m

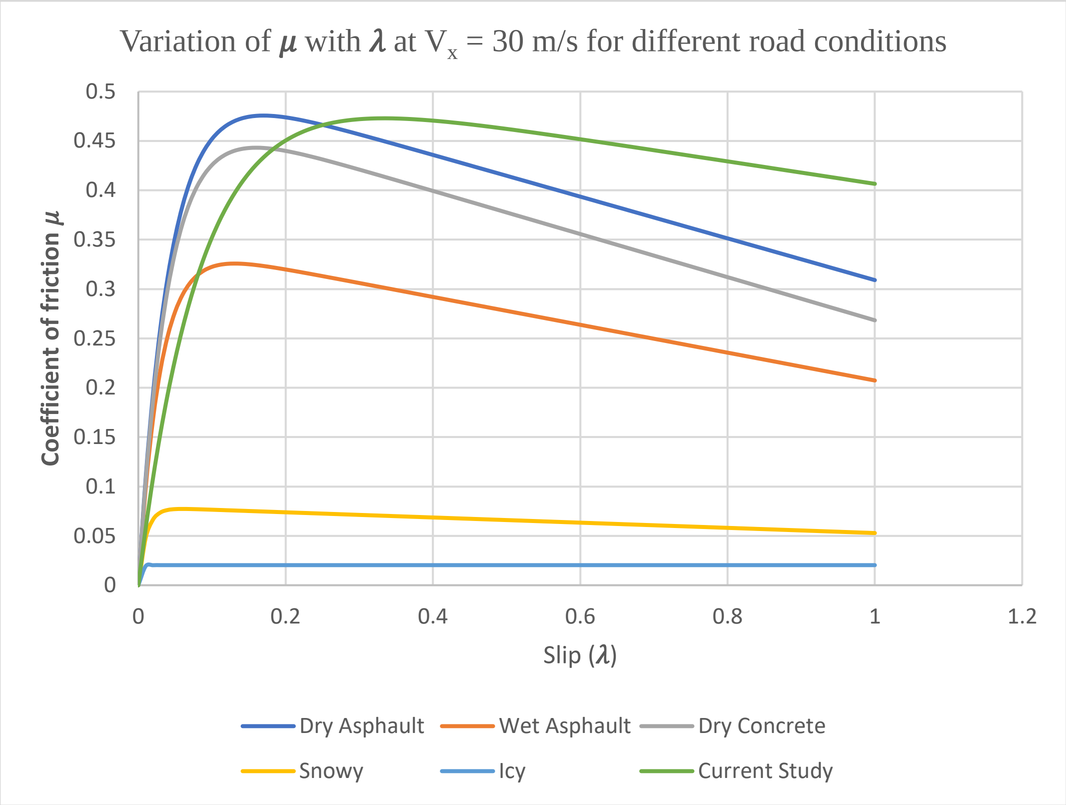

Figure 2 Road friction coefficient v/s Wheel Slip ratio at vehicle speed 30 m/s

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.

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

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

The value of c_4 varies from 0.02 s/m to 0.04 s/m, depending on the wetness of the road.

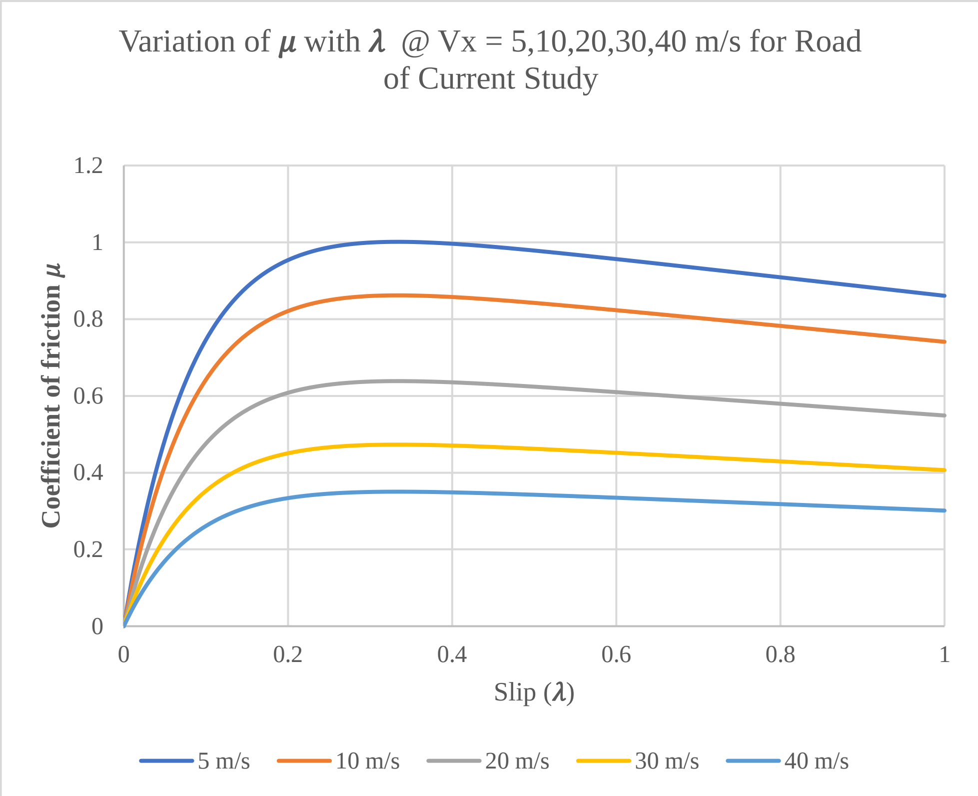

Figure 5 Road friction coefficient of road of current study at different velocities

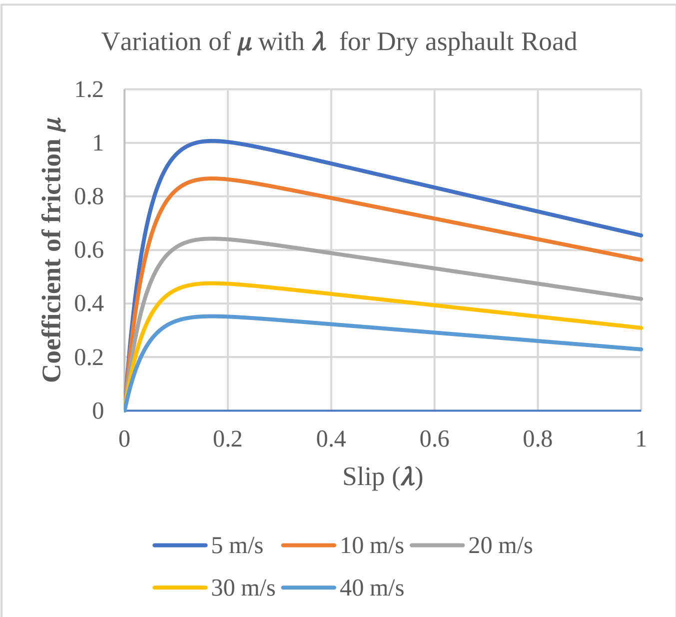

Figure 3 Road friction coefficient of Dry Asphalt road at different velocities

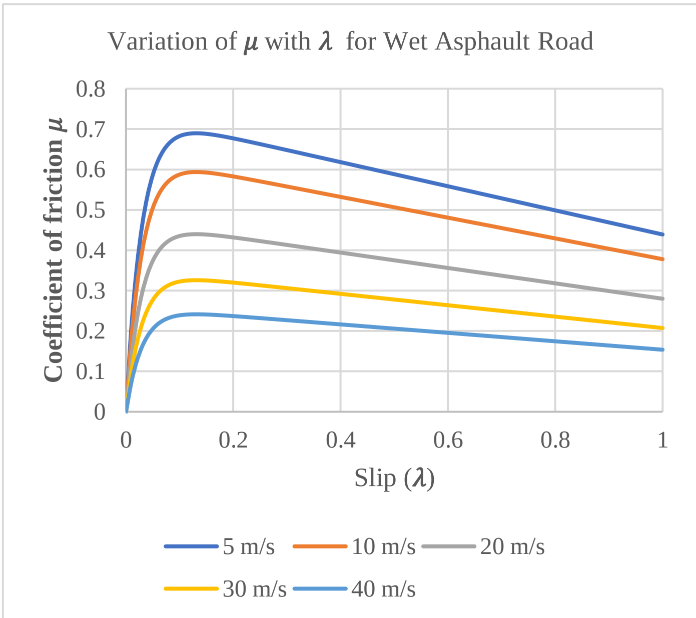

Figure 4 Road friction coefficient of Wet Asphalt road at different velocities

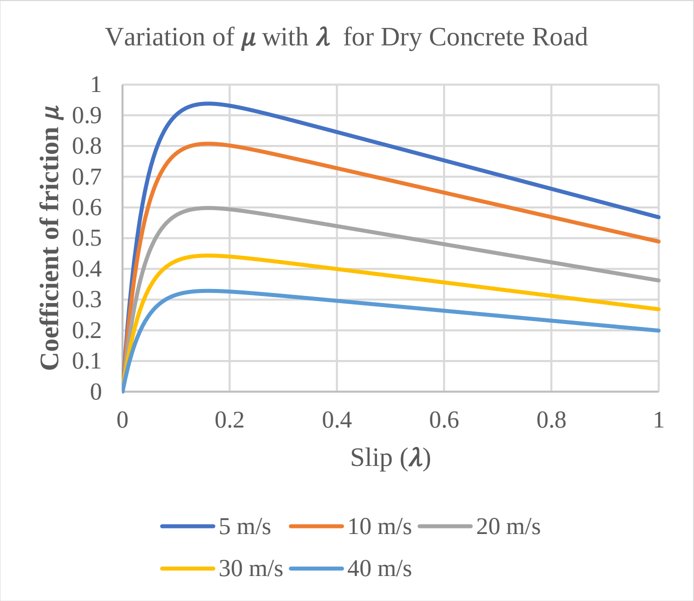

Figure 7 Road friction coefficient of Dry Concrete road at different velocities

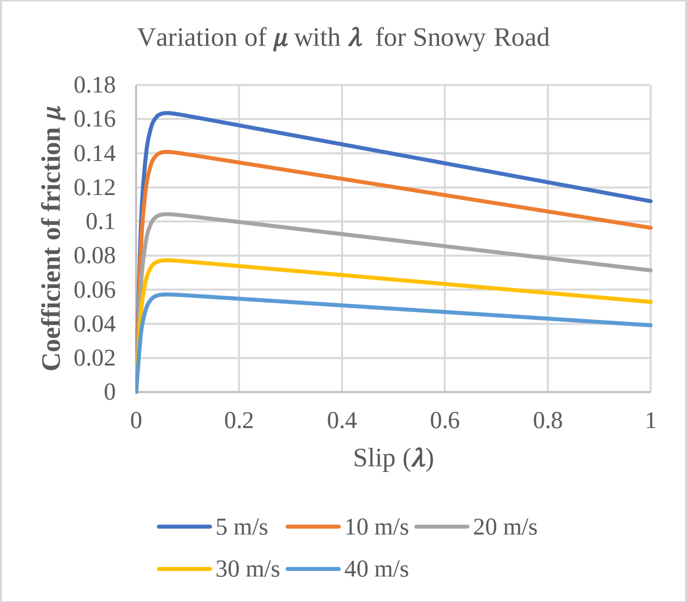

Figure 6 Road friction coefficient of Snowy road at different velocities

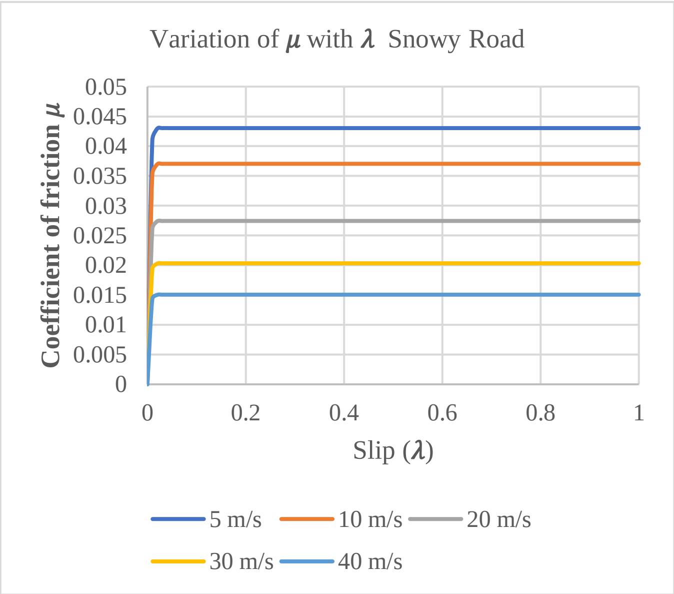

Figure 8 Road friction coefficient of Icy road at different velocities

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.

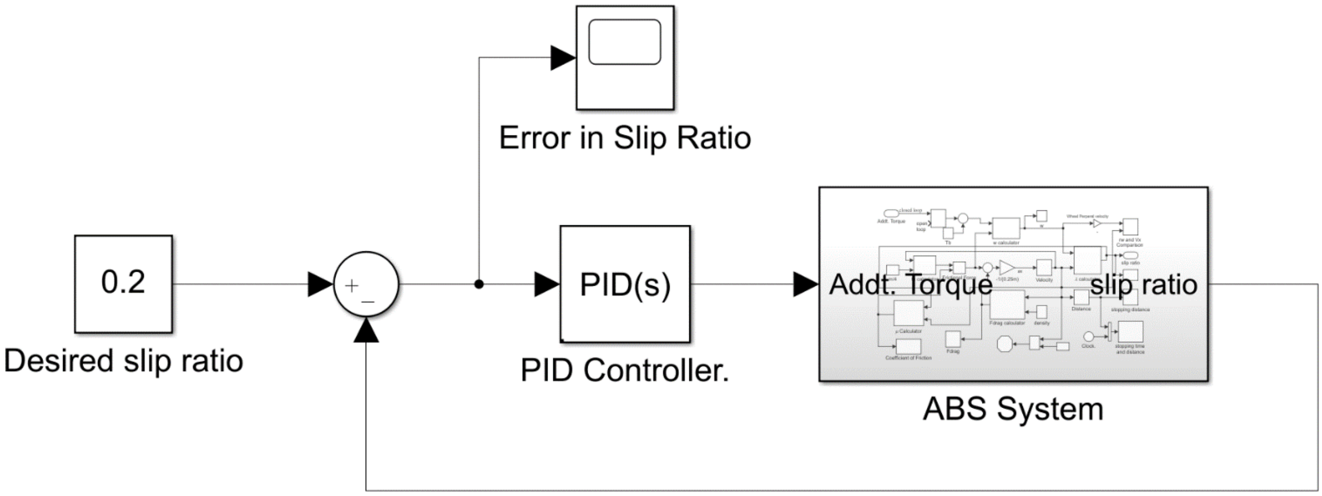

Figure 9 The ABS Control Algorithm (PID)

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 K_p = 250000; K_i =100000; K_d =100. The Flow Diagram of the Complete Vehicle Dynamics Block of the ABS model is shown in Figure 10.

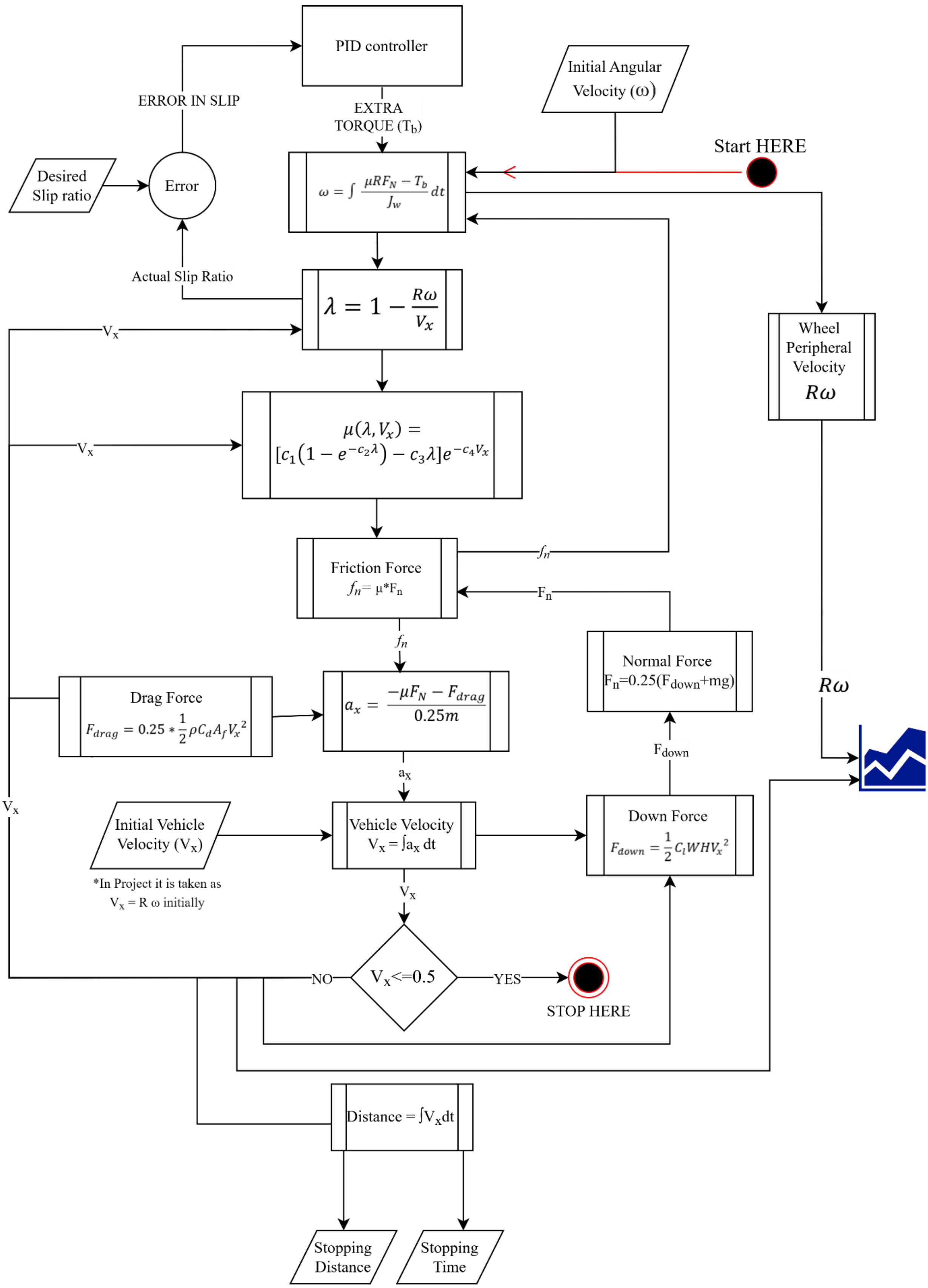

Figure 10 Complete Flow Diagram of the Simulink Model

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

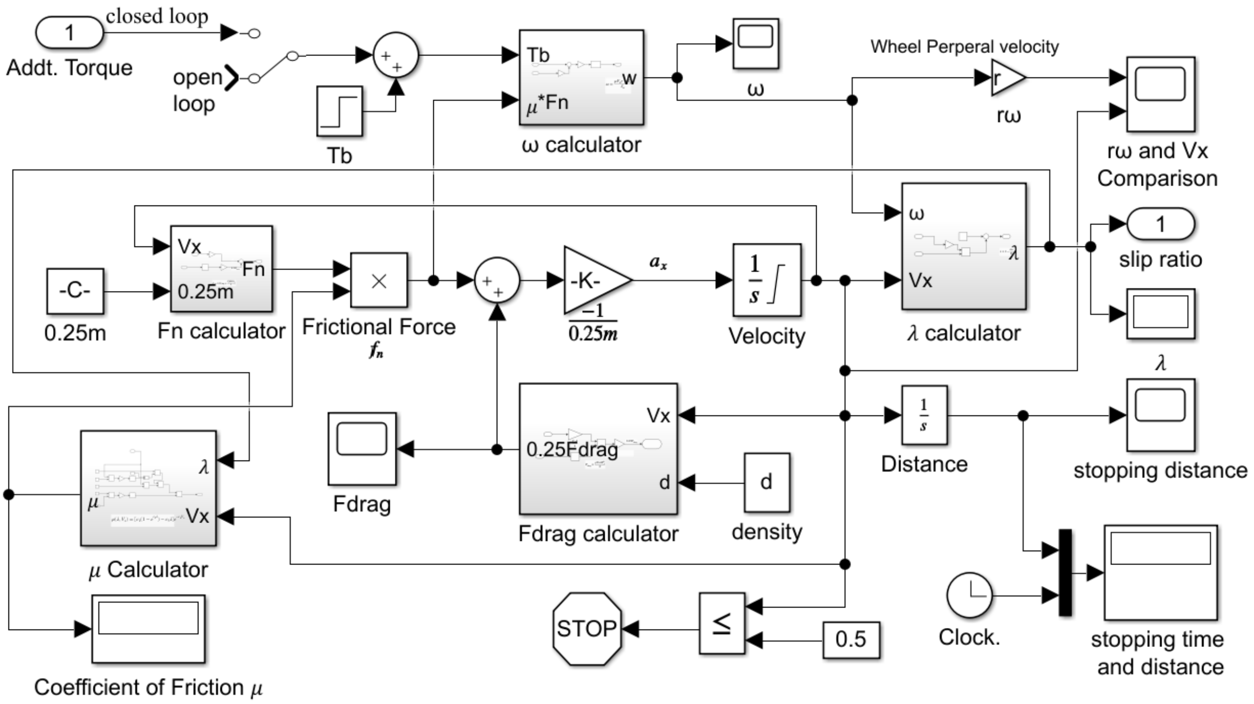

Figure 15 Simulink Model of ABS Sub-System

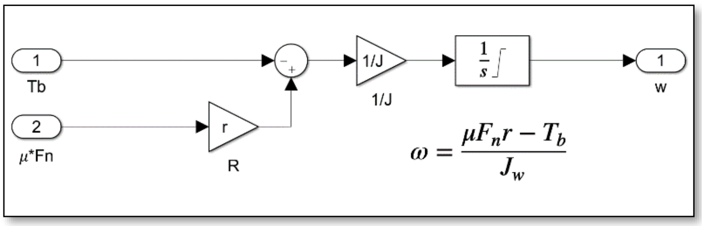

Figure 13 ω calculator Sub-System

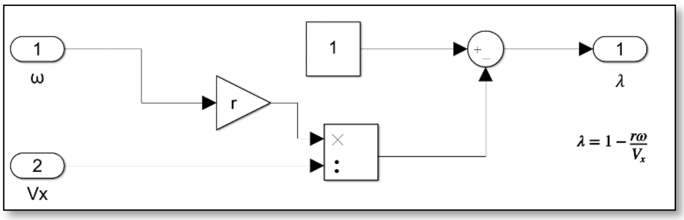

Figure 14 λ Calculator Sub-System

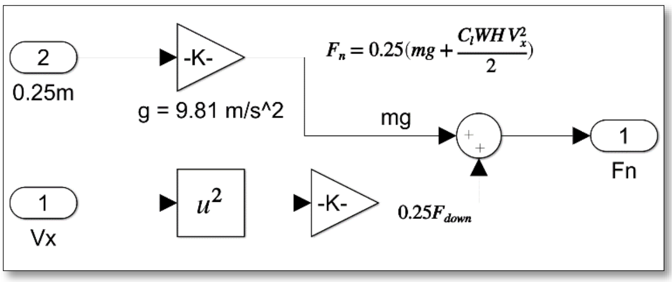

Figure 12 Normal Force (+Downforce) Calculator

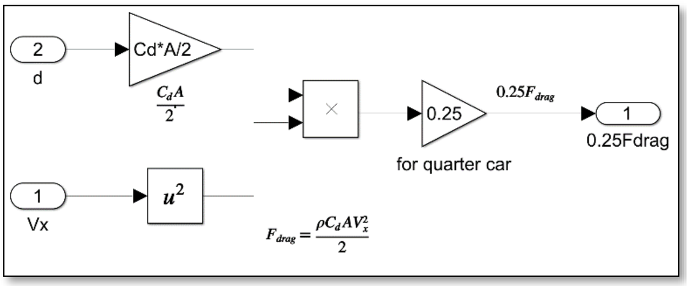

Figure 11 Drag Force Calculator

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.

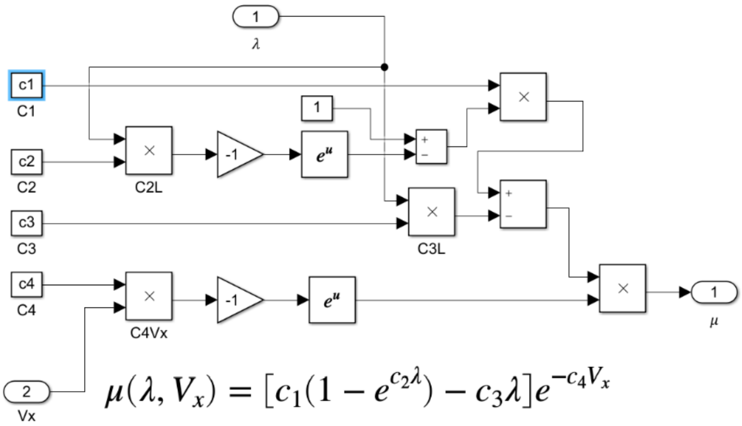

Figure 16 Road Friction Coefficient (Mu) Calculator

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.

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; $J_w = 1.13$ kgm^2; $g = 9.81$ m/s^2; $T_b = 1200$ N-m;
$V_x = 100$ km/hr $= 27.78$ m/s; $\omega = V_x/r = 84.14$ rad/sec; $\lambda_d = 0.2$; $K_p = 250000$;
$K_i = 100000$; $K_d = 100$

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

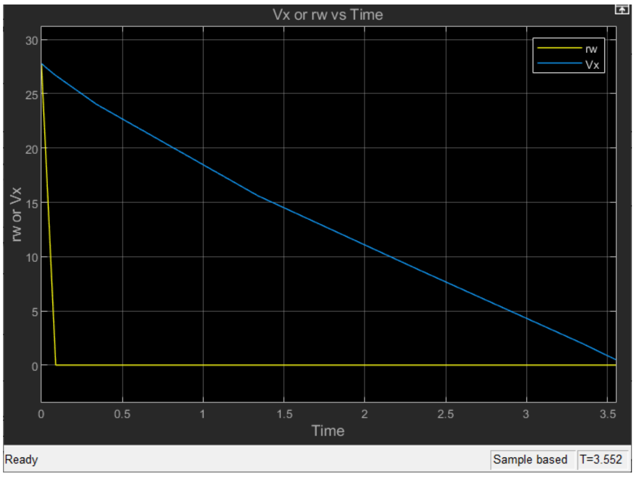

Figure 18 Plot of Vehicle velocity (V_x) v/s time and Wheel peripheral velocity (rω) v/s time in Open Loop System

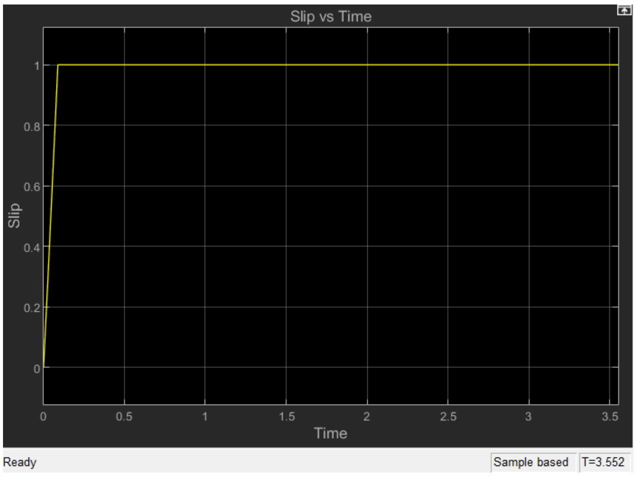

Figure 17 Plot of Vehicle Slip Ratio (λ) v/s time (t) in Open Loop System

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 V_t. 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.

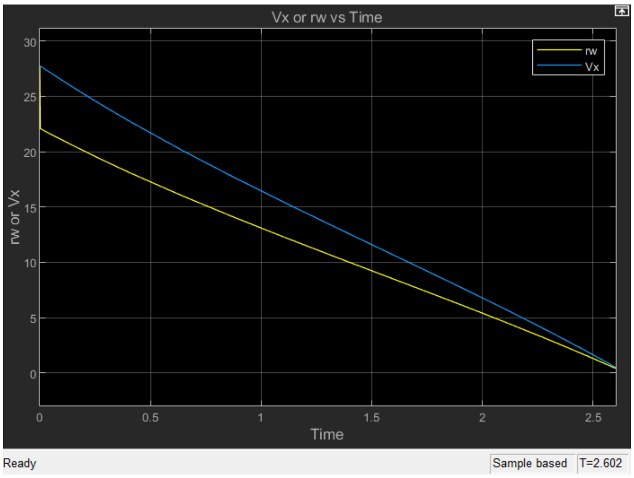

Figure 19 Plot of Vehicle velocity (Vx) v/s time and Wheel peripheral velocity (rω) v/s time with P controller

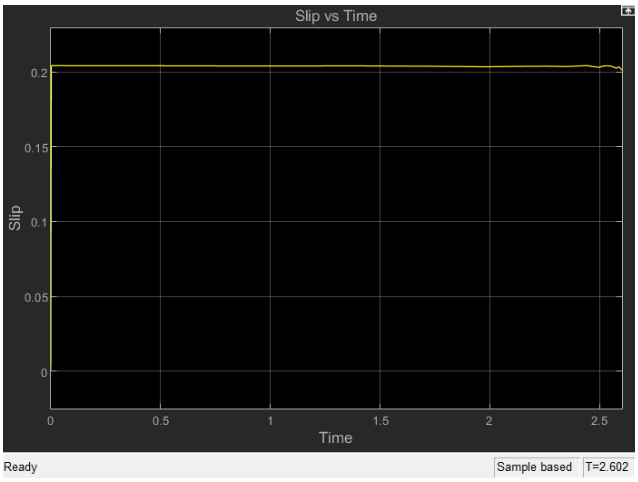

Figure 20 Plot of Vehicle Slip Ratio (λ) v/s time (t) with P Controller

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.

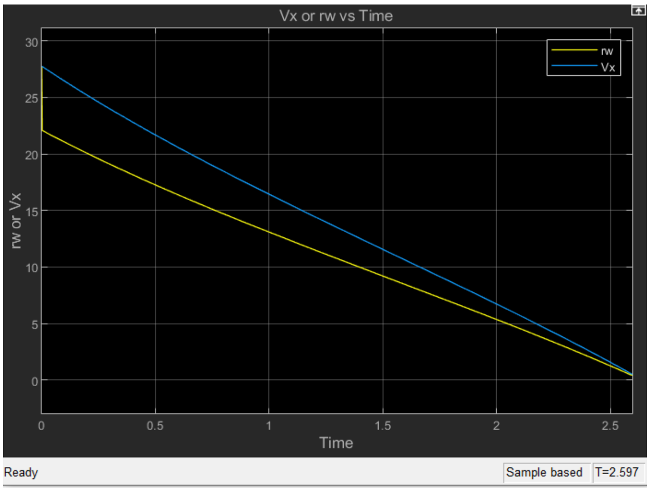

Figure 22 Plot of Vehicle velocity (Vx) v/s time and Wheel peripheral velocity (rω) v/s time with PD controller

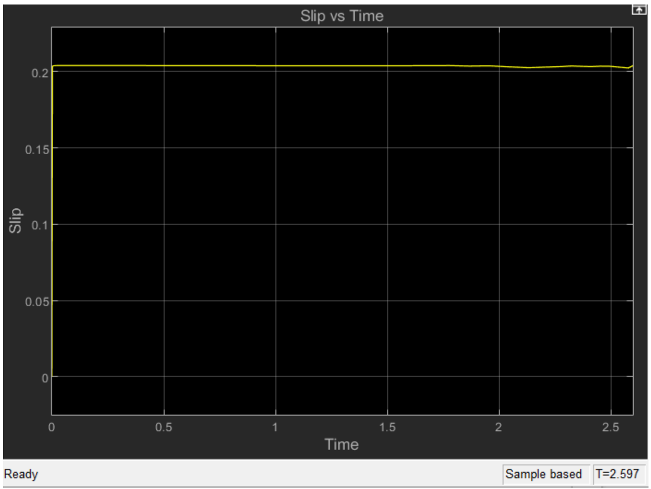

Figure 21 Plot of Vehicle Slip Ratio (λ) v/s time (t) with PD Controller

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.

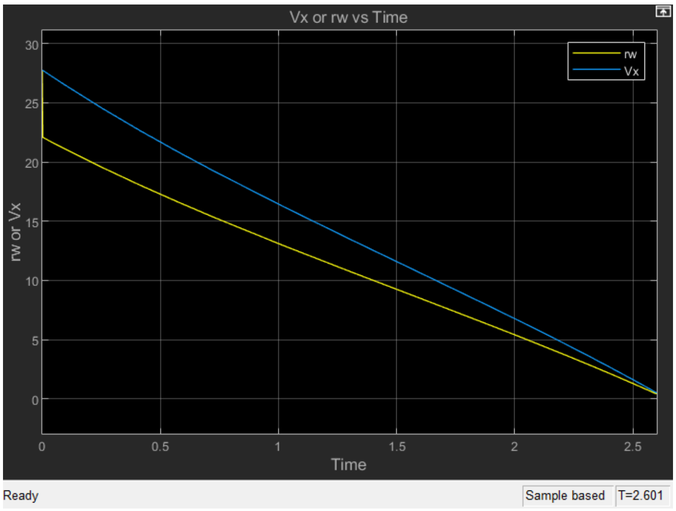

Figure 24 Plot of Vehicle velocity (Vx) v/s time and Wheel peripheral velocity (rω) v/s time with PI controller

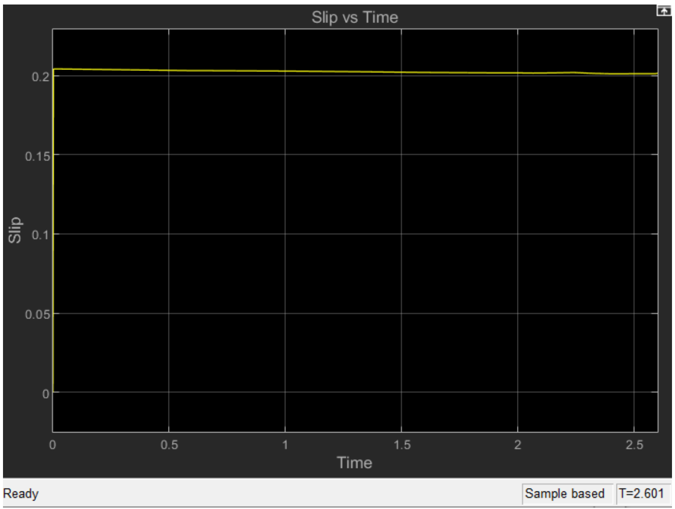

Figure 23 Plot of Vehicle Slip Ratio (λ) v/s time (t) with PI Controller

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

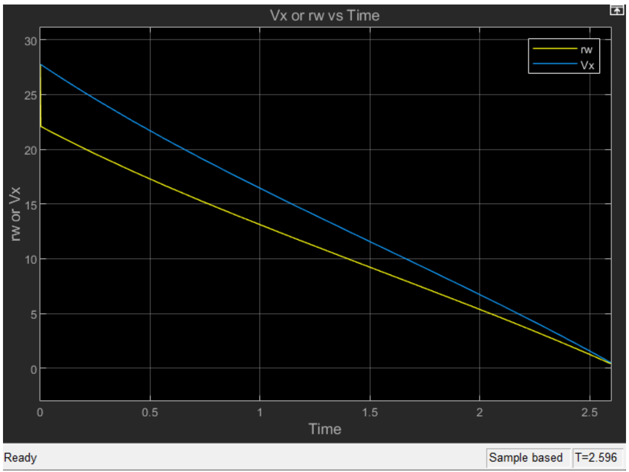

Figure 26 Plot of Vehicle velocity (Vx) v/s time and Wheel peripheral velocity (rω) v/s time with PID Controller

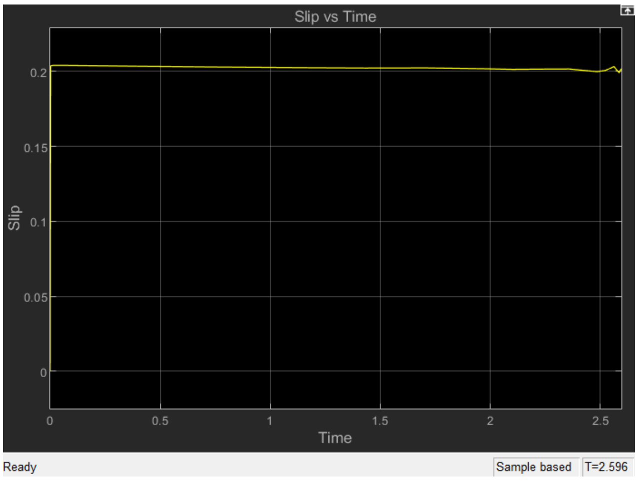

Figure 25 Plot of Vehicle Slip Ratio (λ) v/s time (t) with PID controller

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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