ROYAL INSTITUTE OF TECHNOLOGY

Lab 1: Group 17

SD2231 – Applied vehicle dynamics control

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Introduction

This assignment is aimed to gain basic knowledge of controlling longitudinal dynamics of Road & rail vehicle through implementation of Traction Control System (TCS) & Anti-lock Braking System (ABS). The road vehicle is tested for 3 different friction levels i.e. dry road, wet road and icy road along with one rail vehicle.

Various types of controllers are designed and their response studied along with their performance in acceleration (minimum time from 0 to 25 m/s) and braking (minimum distance from 25m/s to standstill) , the best designed controller is then put through testing by introducing road disturbances and an icy spot.

Task 1: Determination of control parameters

Task 1.a:

Derive the equation of motion for the single mass system in Figure 10 and build the transfer function $T(s)$=$X(s)F(s)$. Implement the transfer function T(s) in the m-file *PID_intro*. The m-file will plot the step response of the transfer function without an active controller. Sliders for each control parameter as well as for the mass, spring stiffness and damping coefficient will help you to adjust the step response.

The equation of motion for the single mass system was derived and its transfer function $T(s)$=$X(s)/F(s)$ was calculated.

Equation of Motion for a single mass system:

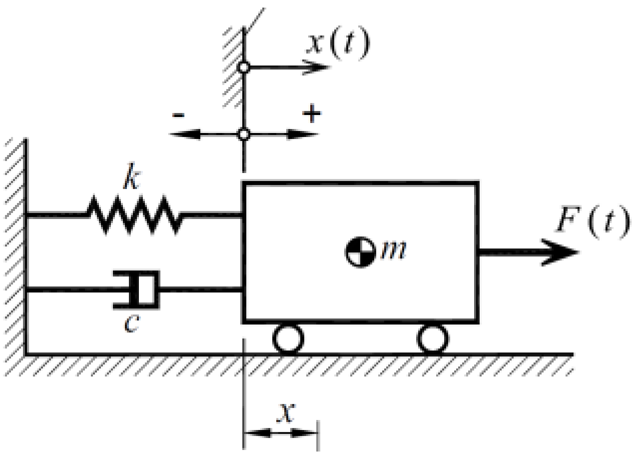

Figure 1 Single Spring-mass-damper system

Equations of motion for the single mass system with spring and damper were derived,

$$F(t) - kx - c\dot{x} = m\ddot{x}$$

Where**,**

$$x : distance\ (m);\ k{:}\, spring\ stiffness\ \left(\frac{N}{m}\right); c{:}\, damping\ rate\ \left(\frac{Ns}{m}\right);$$
$$\dot{x} : velocity \left(\frac{m}{s}\right);\ \ddot{x} : acceleration\ \left(\frac{m}{s^2}\right); m : mass\ (kg)\ and\ F(t) : force\ (N)$$

Taking Laplace transform of equation xx,

$$F(s) = kX(s) + csX(s) + ms^2X(s)$$

Transfer function is defined by Output (X(s)) divided by Input (F(s)) ,

Transfer Function:

$$T(s) = \frac{X(s)}{F(s)} = \frac{1}{k + cs + ms^2}$$

The above transfer function T(s) is implemented into the provided m-file : PID_intro ,which plots the step response of the transfer function without an active controller.

Task 1.b:

Use the model to find the control parameters that correspond to Figure 8 for a P-, PD-, PI- and PID-controller. You can use Table 1 to estimate the effectiveness of each controller parameter rather than a pure trial and error method.

The control parameters for a P, PI, PD & PID controller were found using figure 2 and table 1 as a reference.

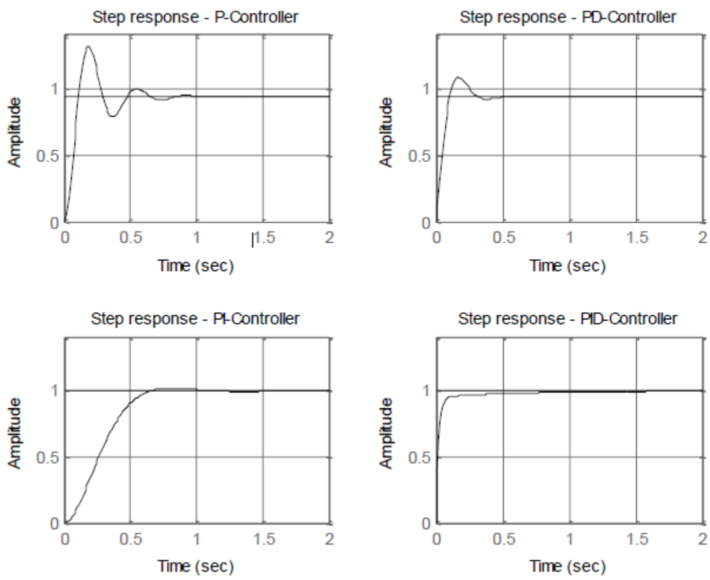

Figure 2 Step responses for different controllers

Table 1 Relation between control parameters & system characterstics

Response	Rise Time	Overshoot	Settling Time	S-S Error
K_P	Decrease	Increase	Small Change	Decrease
K_I	Decrease	Increase	Increase	Eliminate
K_D	Small Change	Decrease	Decrease	No Change

The following table summarises the control parameters:

Table 2 Control Parameters, Single spring-mass-damper system

Controller	P	I	D
P	7000	-	-
PD	7000	-	175
PI	825	1825	-
PID	4750	5500	950

The following figure shows the optimized controller response for the single spring-mass-damper system.

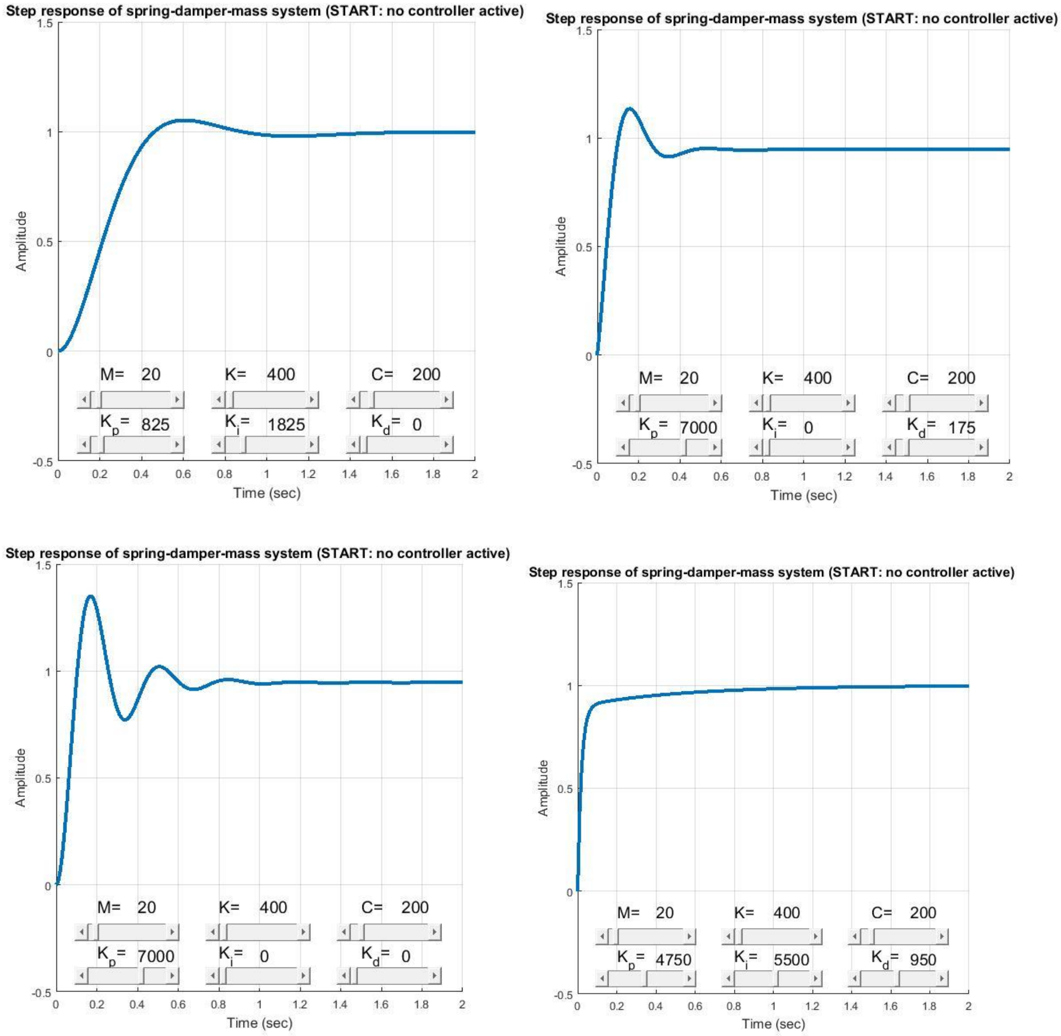

Figure 3 Optimized Controllers , PI, PD, PID & PI (Clockwise from top left)

Extra Task 1.c.

Change mass, spring stiffness and damping coefficient to typical values of a quarter car model of a passenger car. Find the control parameters for the four controllers mentioned above. Note that the slider boundaries (min and max value) might need to be adjusted in the code.

Now, the controllers were optimized for real life values of quarter car.

The following values were used:

Mass = 400 kg ; K = 20 kN/m ; C = 4500 Ns/m

The following figure shows the optimized controllers for real world car,

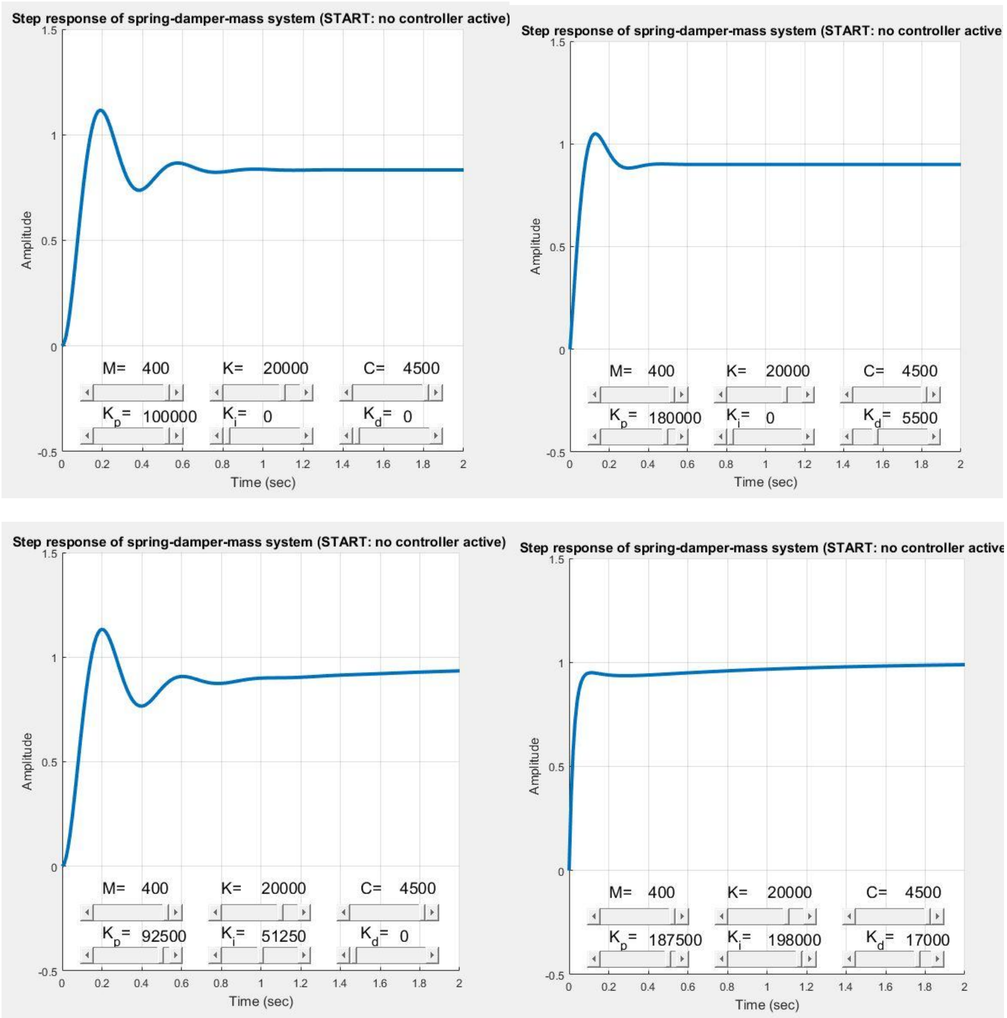

Figure 4 Optimized Controllers for real world passenger car , PI, PD, PID & PI (Clockwise from top left)

Task 2 : Integration of feed-through control

Task 2.a :

The current model will not run when pressing the simulate button. The controller block is empty and needs to be filled. The first task is the implementation of a feed-through control that translates the driver signals into actuator signals.

The given Simulink model was corrected by implementing feed-through control that will translate driver signals to actuator signals.

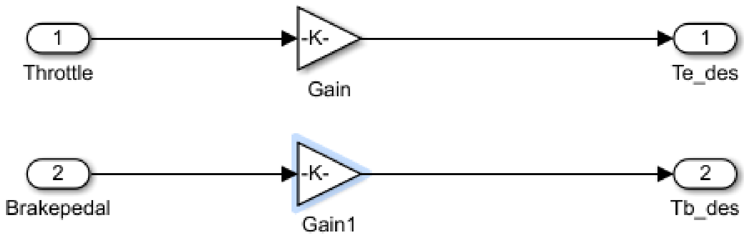

Figure 5 Implementing Feed-Through Control

Task 2.b :

Simulate both vehicles for the 3 given friction levels of the passenger car and 1 given friction level for the train. Change the friction levels and the vehicle type in the initial file accordingly and minimise the time to accelerate from 0 km/h to 90 km/h. Compare it to an acceleration run where the wheel speed is 10% higher than the optimum wheel speed which you got from acceleration minimisation. How much time do you gain or lose relatively? (Attach the graphs of both stable and unstable cases and present your results in a clear table and reflect and discuss the outcome.)

The given passenger car model was simulated for the 3 given friction level and the train for 1 given friction level. The aim was to minimize the acceleration time to reach 25 m/s from standstill.

The unstable case of 10% higher wheel speed (omega) was simulated by adding a gain of 1.10 after the wheel dynamics block.

Table 3 Optimizing feed forward gain Traction

Case	FF Gain	Minimum Time (sec)	Time with 10% extra omega	Difference
Road 1	1316	2.648	2.648	None
Road 2	920	3.741	3.741	None
Road 3	390	8.615	8.706	Increase
Rail	8800	12.841	12.817	Decrease

Comments:

There is no change in minimum acceleration time for the first two cases viz. Dry road and Wet road, this can be because the 10% increase in omega does not increase the longitudinal slip enough to change its friction utilization value. Figure x & x show the comparison between the stable and unstable cases for both the cases. The increase in omega in each case can be noted in the lower graphs.

The same line of reasoning can be applied to case 3 (icy road) that the 10% increase in omega increased slip over to the region of comparatively lower friction coefficient whereas it is interesting to note that increasing the omega in case of rail vehicle actually decreases the acceleration time, but if omega is kept on increasing the threshold will reach and wheel will start to slip.

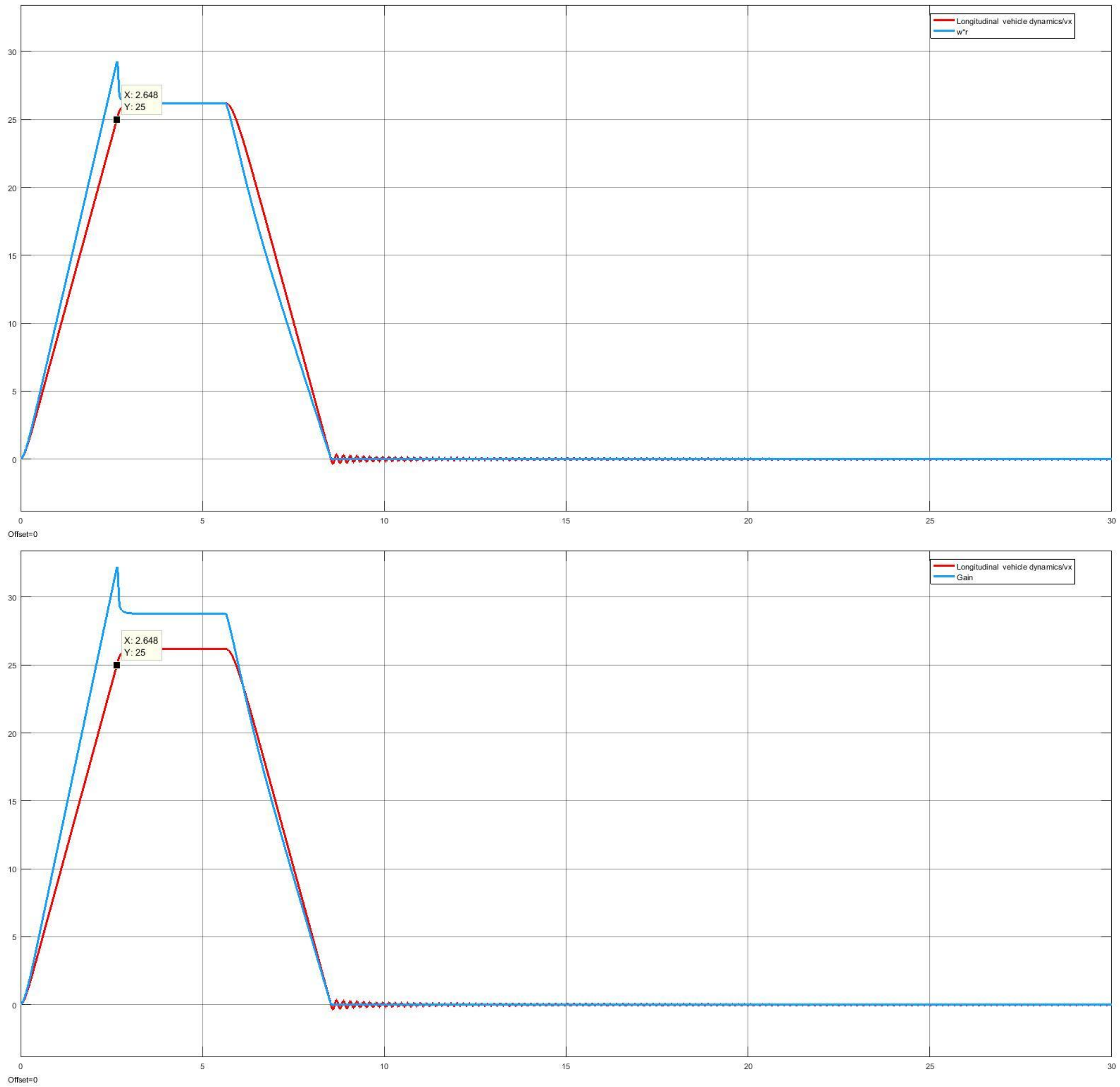

Figure 6 Road 1: Acceleration time with Optimum & 10% extra omega

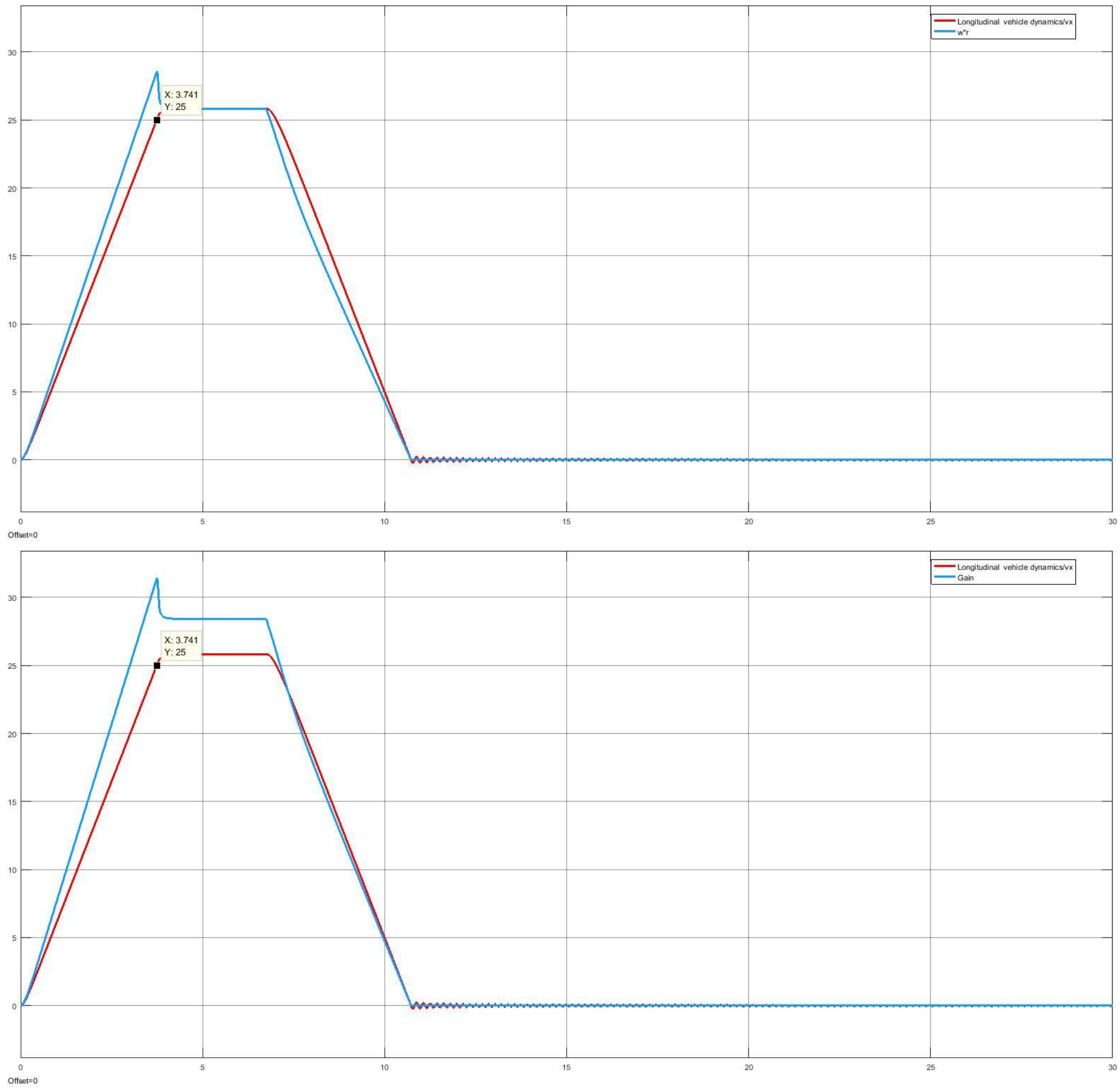

Figure 7 Road 2: Acceleration time with Optimum & 10% extra omega

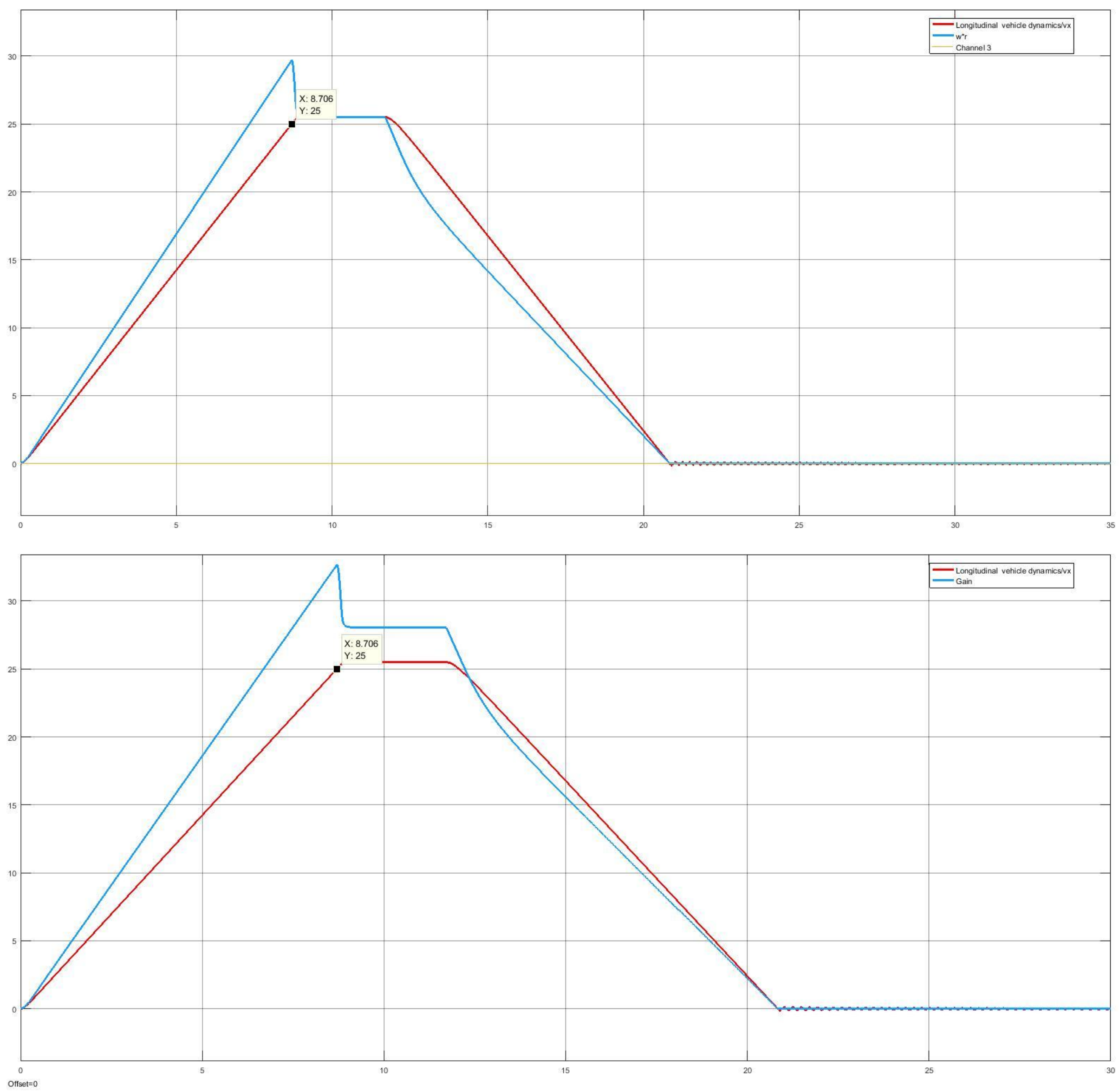

Figure 8 Road 3: Acceleration time with Optimum & 10% extra omega

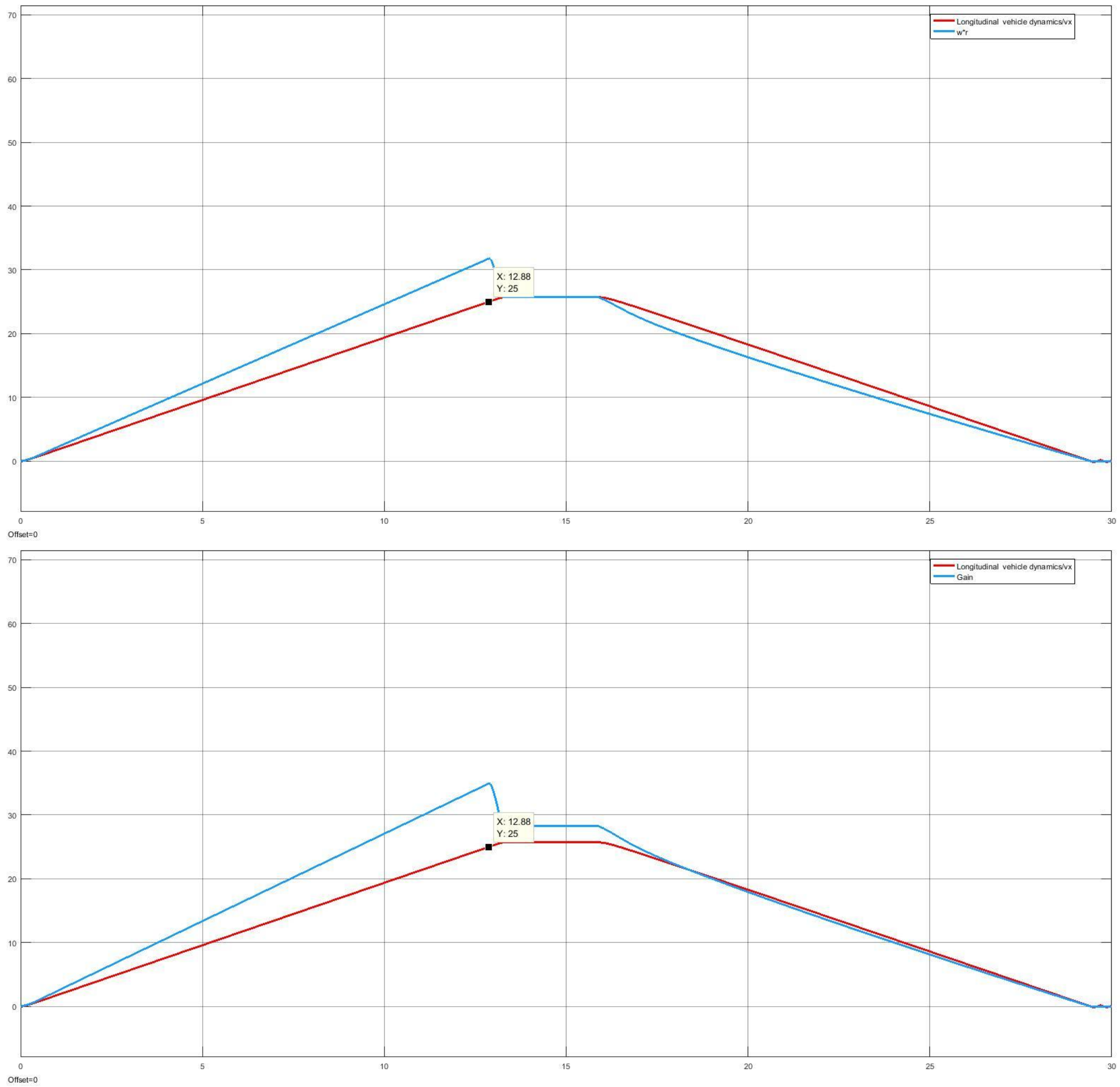

Figure 9 Road 4: Acceleration time with Optimum & 10% extra omega

Task 2.c.

Minimise the stopping distance while braking to standstill (standstill can be considered when $v_x$crosses zero the first time). Compare it to the stopping distance with a locked wheel. How many meters do you gain or lose? (Attach the graphs of both stable and unstable cases and present your results in a clear table and reflect and discuss the outcome.)

For this task the feed forward gain of the Brake pedal was optimized for minimum braking distance for each vehicle and each driving condition and was compared with unstable condition of wheel lock for each case.

Table 4 Optimizing feed forward gain Braking

Case	Gain	Braking distance	Braking Distance with locked wheel	Difference
Road 1	1297	40.1 m	47.23 m	Increase 7.1 m
2	909	54.36 m	71.78 m	Increase 17.42 m
3	387	118.7 m	113.9 m	Decrease 4.8 m
Rail 1	8493	176.1 m	171.4 m	Decrease 4.7 m

Comments:

In the first two cases as expected the locking of the wheel increases the braking distance by considerable amounts. Whereas, in case of icy road & rail the braking distance reduces, this be explained by the fact when wheels lock in case of road vehicle they dig into the snow and the snow pile-up reduces the braking distance. But it cannot be argued that the driver will have more control over the vehicle when there is no locking and also the difference between the locked and non- locked case is very less compared to actual braking distance. However, the same justification cannot be given for the rail vehicle case.

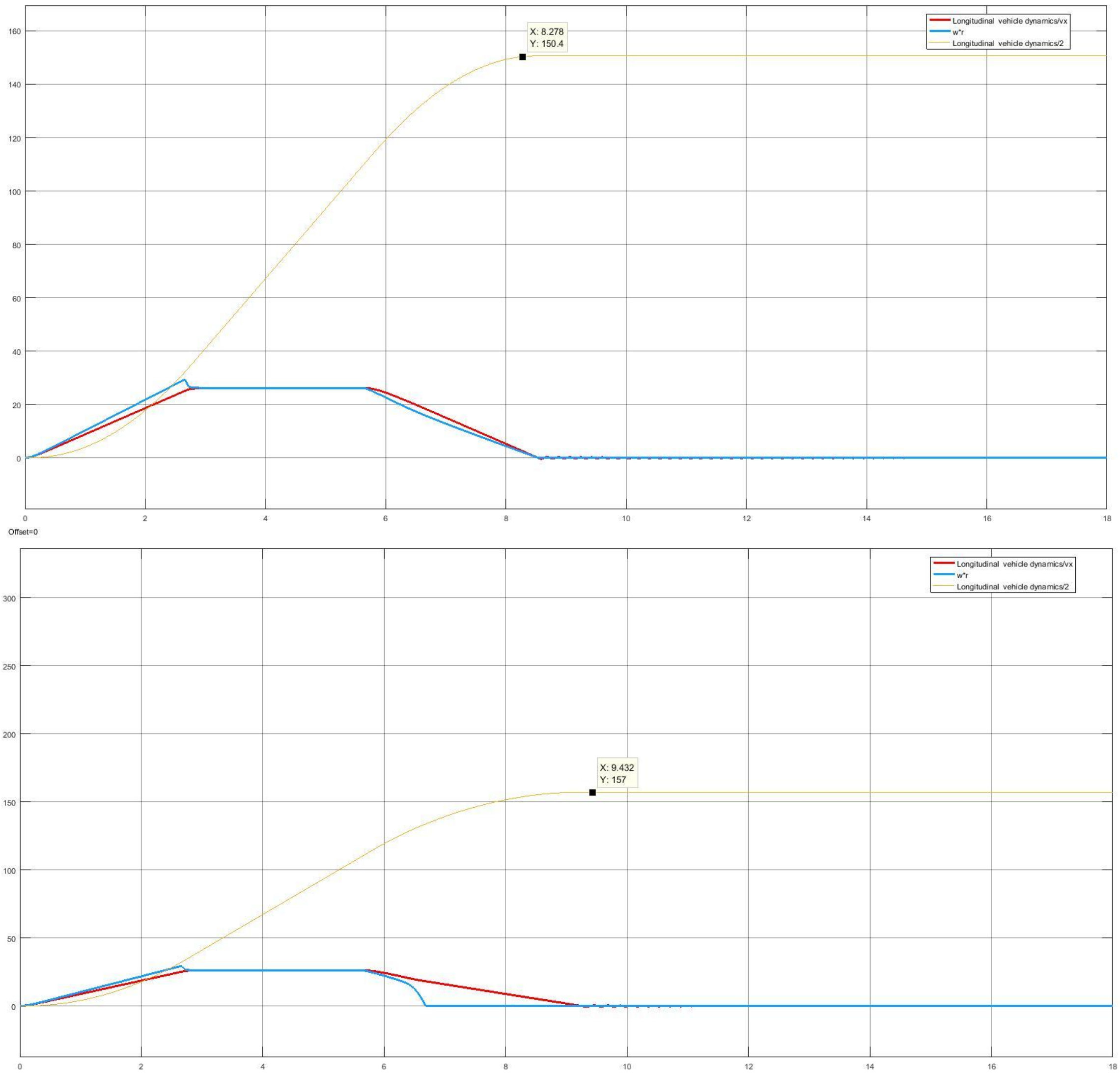

Figure 10 Road 1 :Braking Distance without and with locked wheel

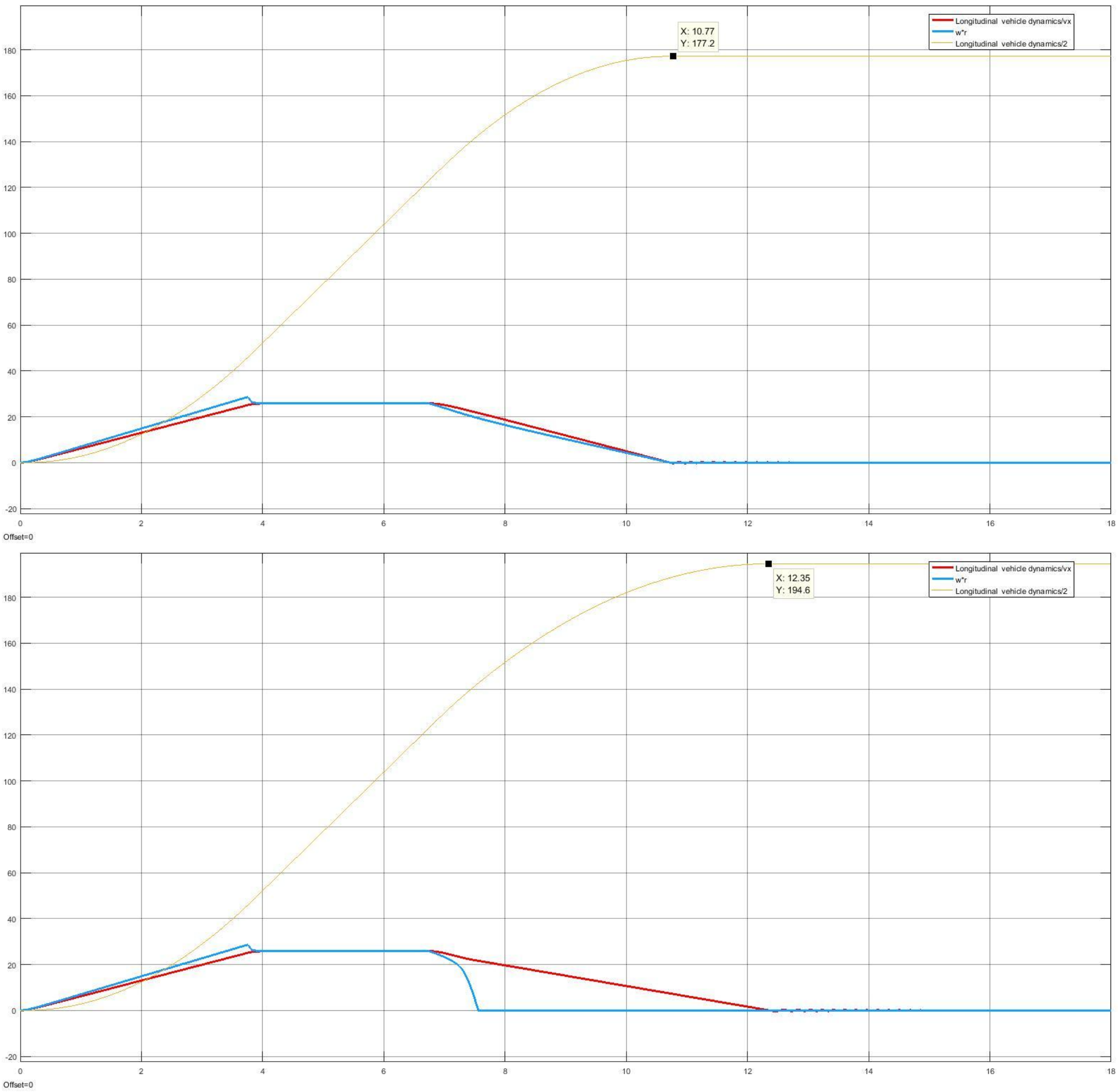

Figure 11 Road 2 :Braking Distance without and with locked wheel

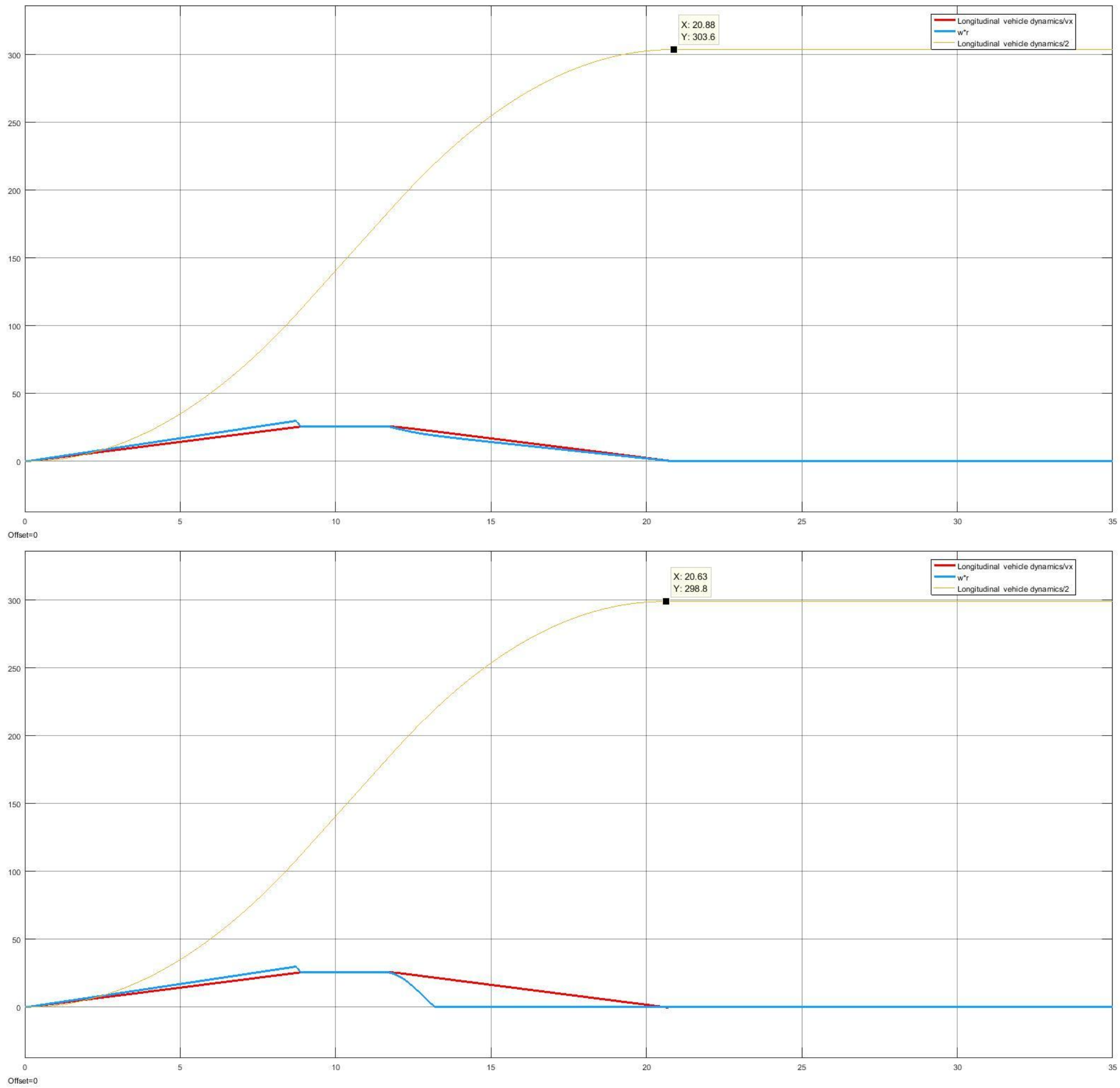

Figure 12 Road 3: Braking Distance without and with locked wheel

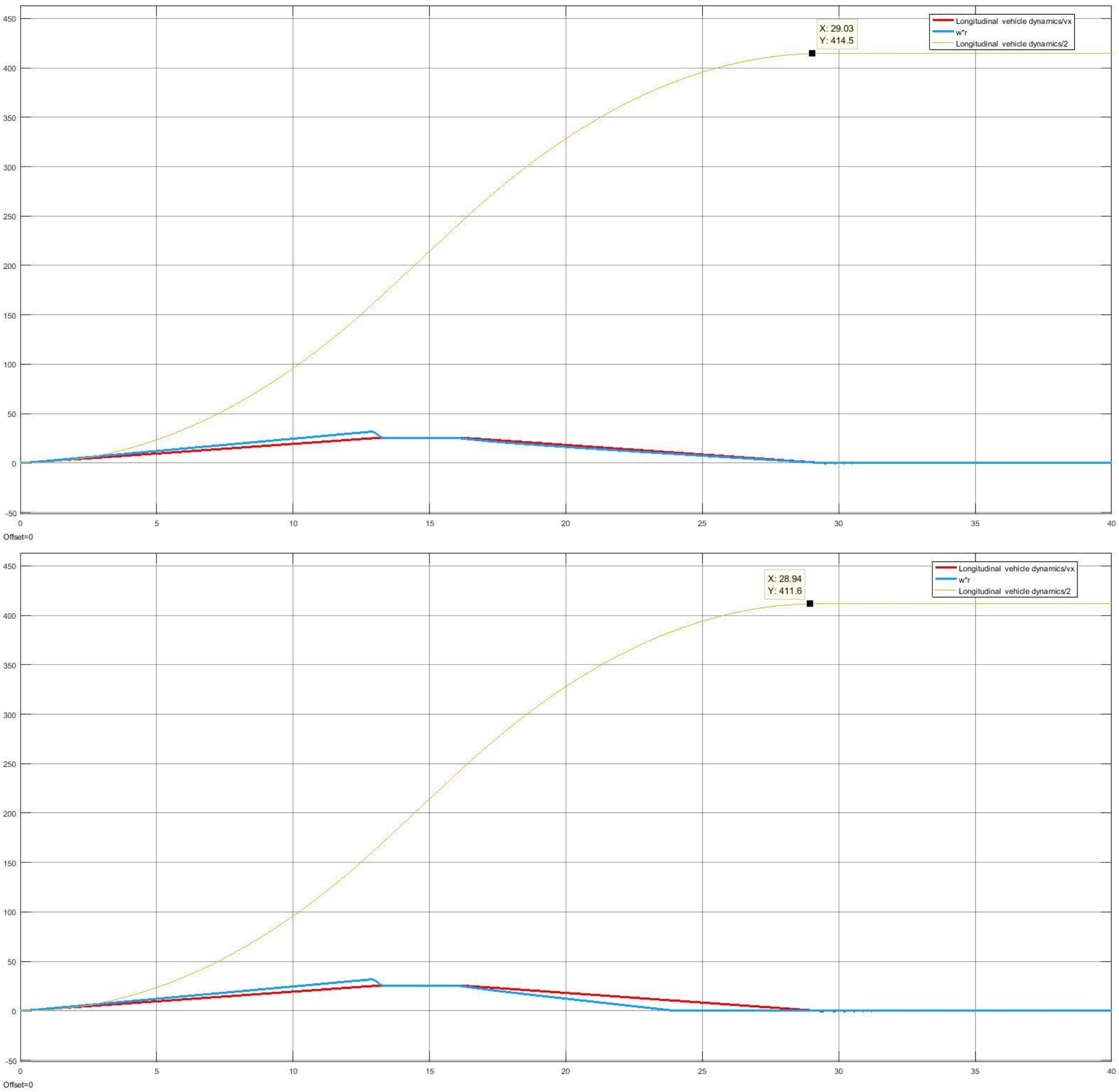

Figure 13 Rail :Braking Distance without and with locked wheel

Task 3: Designing PID Controller:

Task 3.a.

Implement the tractive and braking slip in the control block and plot the slip over time.

The tractive and braking slip were calculated using the following equations:

$$s_t = \frac{r\omega - v_x}{r\omega} \text{ and } s_b = \frac{v_x - r\omega}{v_x}$$

Where,

S_t = Tractive Slip, S_b = Braking Slip, r = wheel radius, ω = rotational speed of the wheel and vx = longitudinal speed of the vehicle

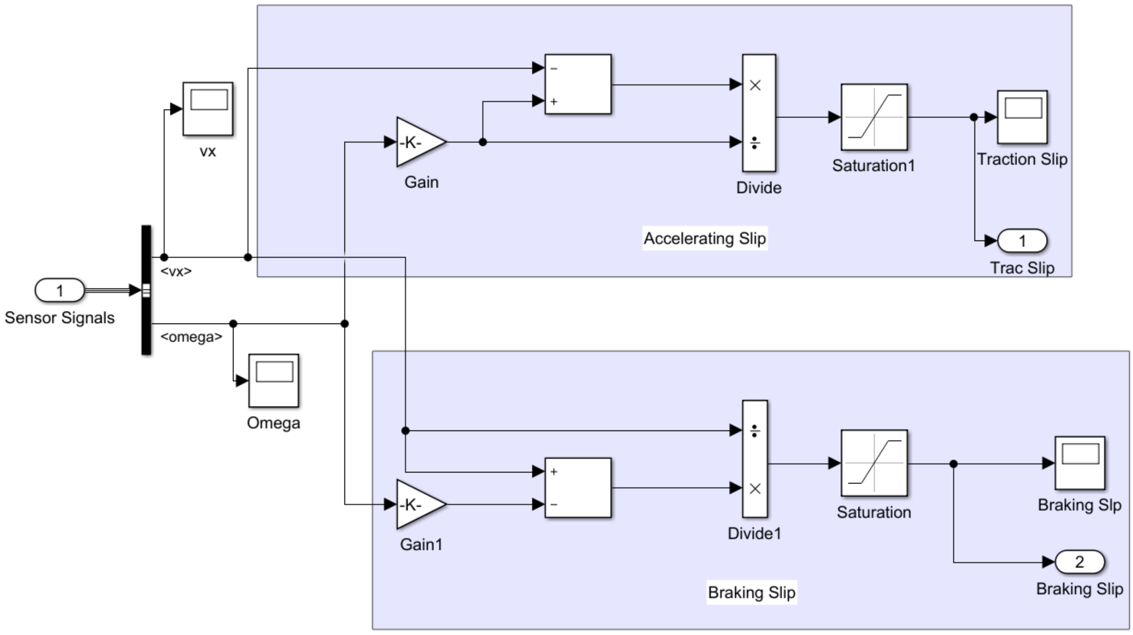

Figure 14 Traction & Braking Slip Calculation

Saturation blocks were added so that only positive values are taken.

Task 3.b.

Add activation logics for the controllers (TCS and ABS). Note that it shall work for all driver inputs (throttle and brake pedal) as soon as traction threshold is reached.

Activation logics for the TCS and ABS system were devised.

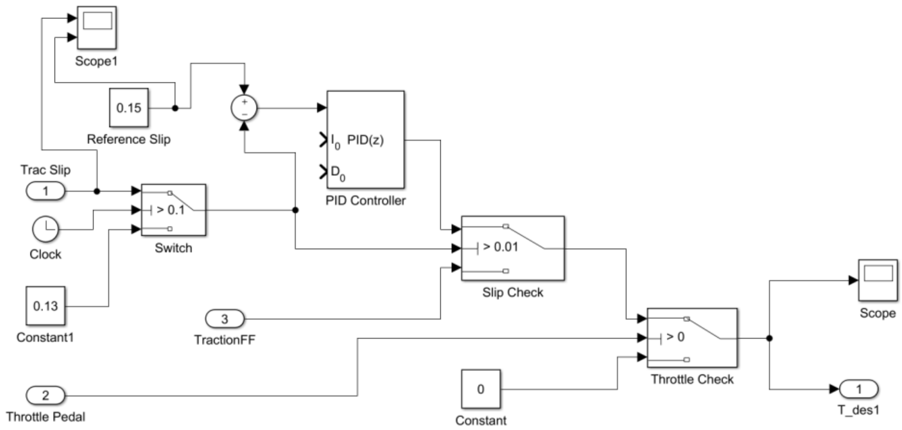

Figure 15 Traction Control System

TCS will be active only when,

- Throttle paddle is presses
- Traction slip is greater than 1%

Otherwise either the feed forward value will be taken or TCS will be off (when throttle paddle is not pressed).

Similarly, **ABS** is active only when,

- Brake paddle is pressed
- Braking slip is greater than 1%

Otherwise either the feed forward value will be taken or ABS will be off (when Brake paddle is not pressed).

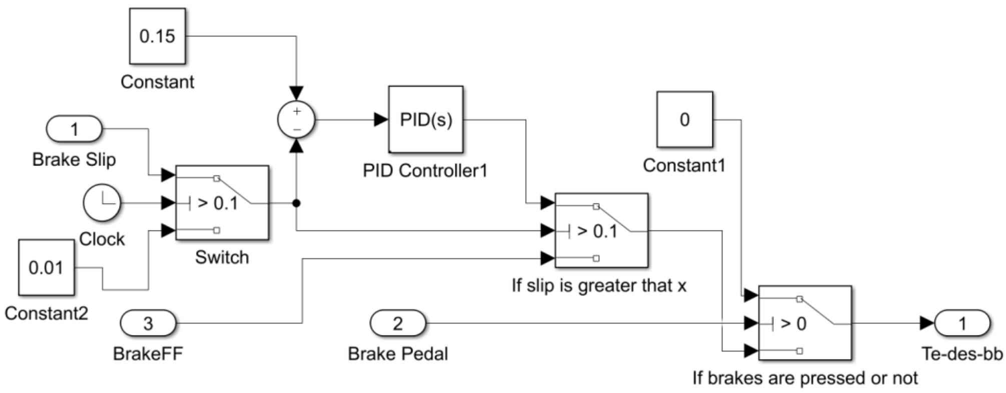

Figure 16 Anti-Lock Brake System

Task 3.c.

Design your own P-, PD-, PI-, PID-controller and compare /discuss the results for the different slip curves and vehicle types.

One PID block was implemented for TCS & ABS each. It was changed through P, PI, PD & PID controllers and their response were optimized according to reference graphs (figure 2).

A reference Slip value of 15% was chosen for both TCS & ABS for all cases. This was chosen after studying friction utilization graphs for each case, it was noted that all cases have their peak around 15% slip.

The following tables summarises the results of tedious iterative process. The slip response in studied in the next section.

Table 5 Case 1 : Road ; Friction Select 1

Case 1 : Road ; Friction Select 1								
	Throttle FF gain : 1316				**Brake FF gain : 1297**			
Controller	**TCS**			**0 to 25 time (sec)**	**ABS**			**Braking Distance (m)**
	P	**I**	**D**		**P**	**I**	**D**	
P	87997	-	-	2.612	75000	-	-	36.66
PI	110000	4000	-	2.595	30000	3000	-	36.60
PD	105000	-	1000	2.589	75000	-	10	36.68
PID	105000	10000	1000	2.584	75000	3000	1400	36.30

Table 6 Case 2 : Road ; Friction Select 2

Case 2 : Road ; Friction Select 2								
	Throttle FF gain : 920				**Brake FF gain : 909**			
Controller	**TCS**			**0 to 25 time (sec)**	**ABS**			**Braking Distance (m)**
	P	**I**	**D**		**P**	**I**	**D**	
P	70000	-	-	3.740	50000	-	-	50.02
PI	70000	400	-	3.702	60000	30000	-	52.86
PD	75000	-	500	3.696	75000	-	1400	49.86
PID	70000	40	500	3.696	78000	28000	600	51.11

Table 7 Case 3 : Road ; Friction Select 3

Case 3 : Road ; Friction Select 3								
	Throttle FF gain : 390				Brake FF gain : 380			
Controller	**TCS**			**0 to 25 time (sec)**	**ABS**			**Braking Distance (m)**
	P	**I**	**D**		**P**	**I**	**D**	
P	95000	-	-	8.652	35000	-	-	114.8
PI	100000	4	-	8.650	50000	5000	-	115.5
PD	100000	-	1000	8.651	50000	-	1000	114.5
PID	100000	4	1000	8.650	50000	10000	1000	116.1

Table 8 Case 4 : Rail

Case 4 : Rail								
	Throttle FF gain : 8800				Brake FF gain :			
Controller	**TCS**			**0 to 25 time (sec)**	**ABS**			**Braking Distance**
	P	**I**	**D**		**P**	**I**	**D**	
P	2000000	-	-	12.846	400000	-	-	162.2
PI	2500000	0.04	-	12.843	50000	7000	-	161.5
PD	2500000	-	750	12.843	400000	-	0.1	162.6
PID	2500000	4	1000	12.843	400000	3500	10	161.7

Task 3.d:

Discuss each system and compare them based on system characteristics such as settling time, rise time, overshoot and steady state error. (for each of the controllers; P-, PD-, PI-, PID-controller)

The above controllers were tuned to get minimum settling and rise times along with least overshoot and steady state error.

- **Traction Control System:**

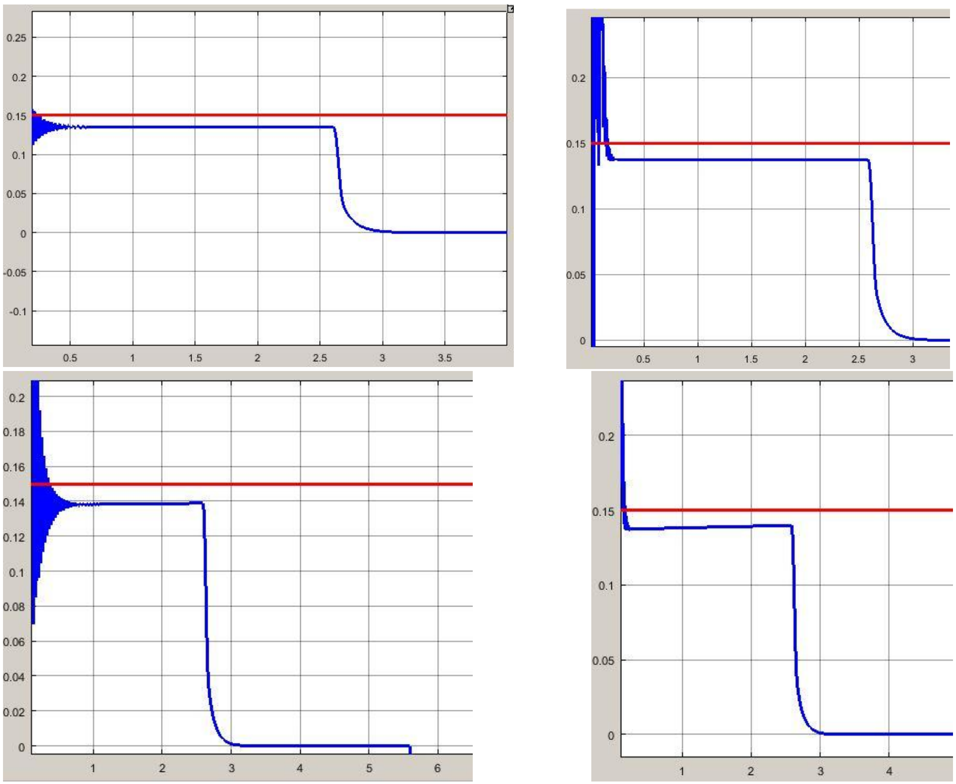

Figure 17 TCS Slip response for Road 1 for different controllers P, PD ,PID & PI (clockwise from top left)

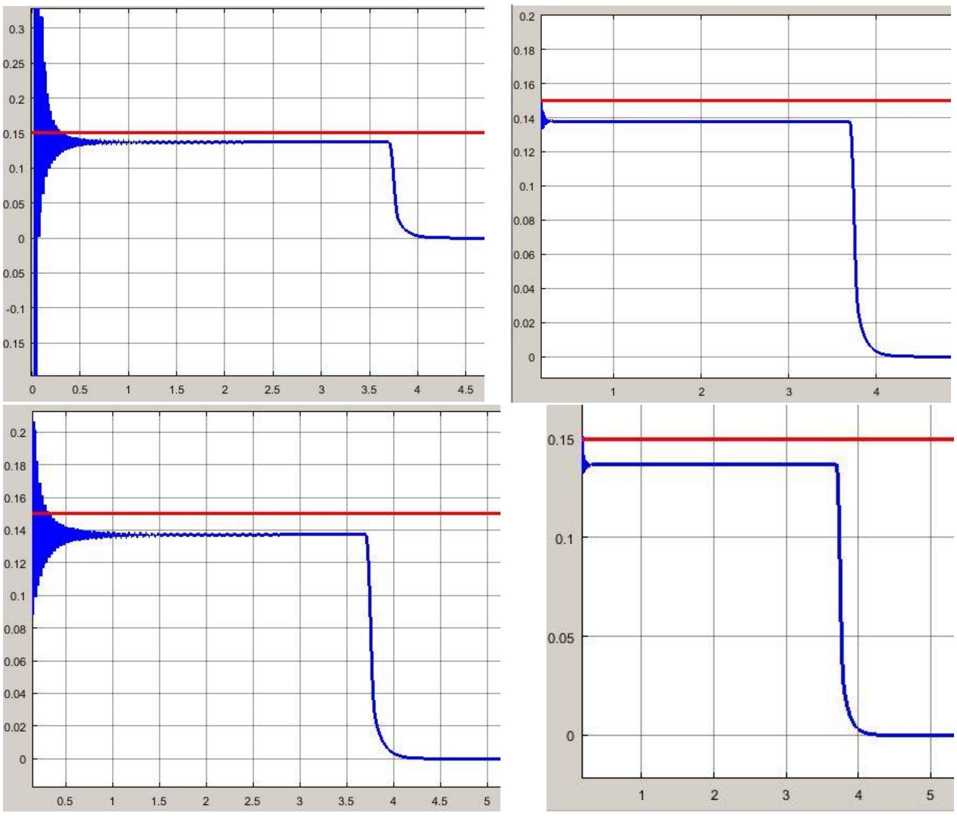

Figure 18 TCS Slip response for Road 2 for different controllers P, PD ,PID & PI (clockwise from top left)

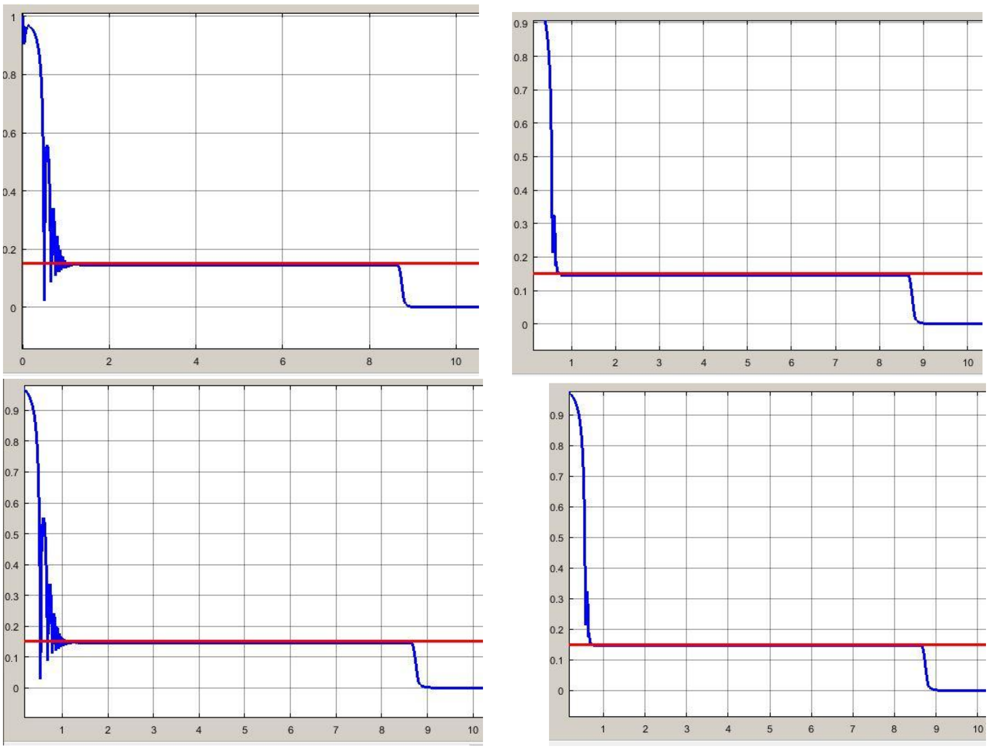

Figure 19 TCS Slip response for Road 3 for different controllers P, PD ,PID & PI (clockwise from top left)

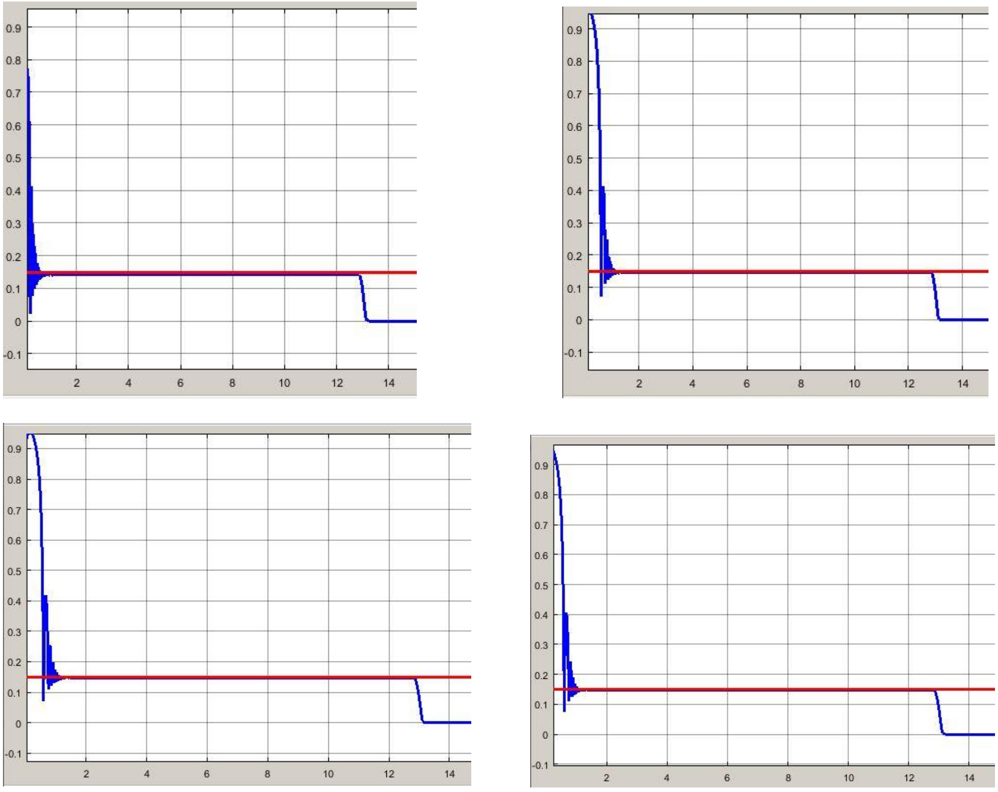

Figure 20 TCS Slip response for Rail for different controllers P, PD ,PID & PI (clockwise from top left)

The above graphs show the slip response of the traction control system, some important things that can be noted are,

- The response with P & PI controller have a high settling time.
- The settling time is reduced when derivative part is added, hence, PD & PID have a better response.
- Steady state error is very less in case of Road 1 & Road 2 where as its negligible for road 3 and rail cases. The Steady state error could have been reduced in first two cases too but it led to sharp increase in overshoot hence a compromise was made.
- The overshoot in all cases is high (reaching 1) but it is only for less than quarter of a second that too is partly due to division by zero or very low vehicle velocity (vx) at the starting of the manoeuvre.
- Rise time to steady state is very low, this can be seen by how steep the curve is.
- The response of PD & PID controller are almost identical, just that PID controller gives more flexibility in tuning.

Anti-Lock Braking System:

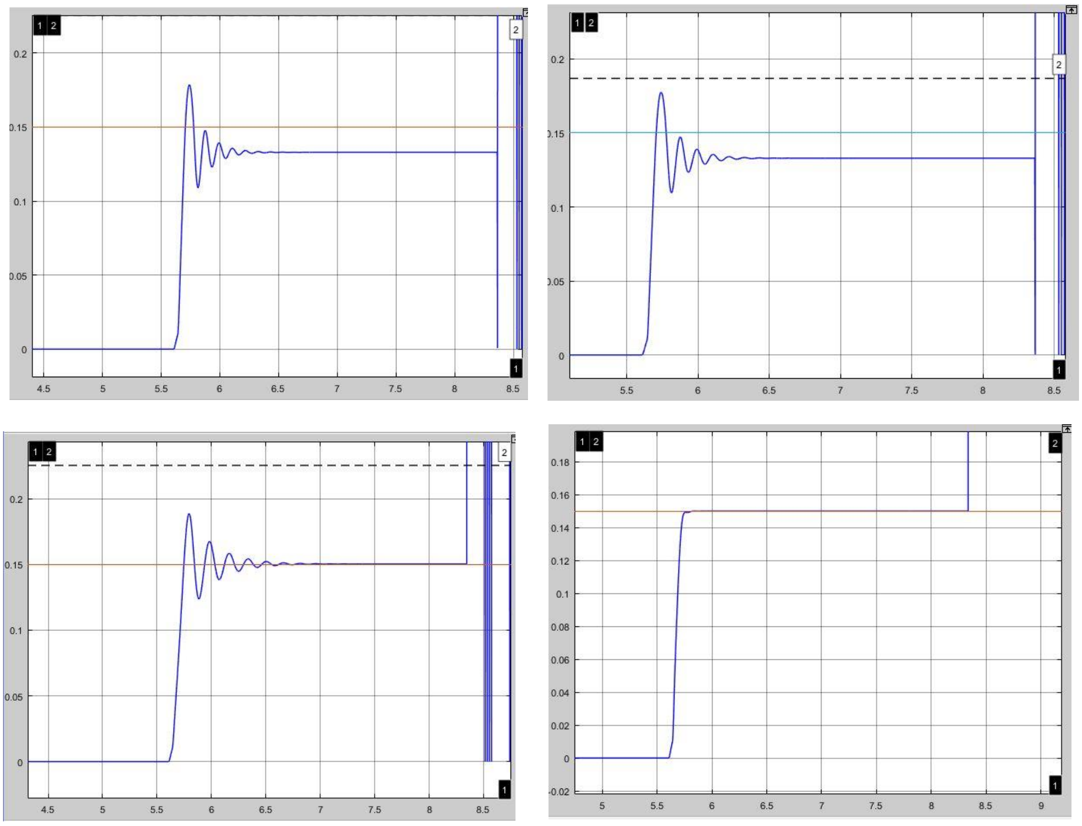

Figure 21 ABS Slip response for Road 1 for different controllers P, PD ,PID & PI (clockwise from top left)

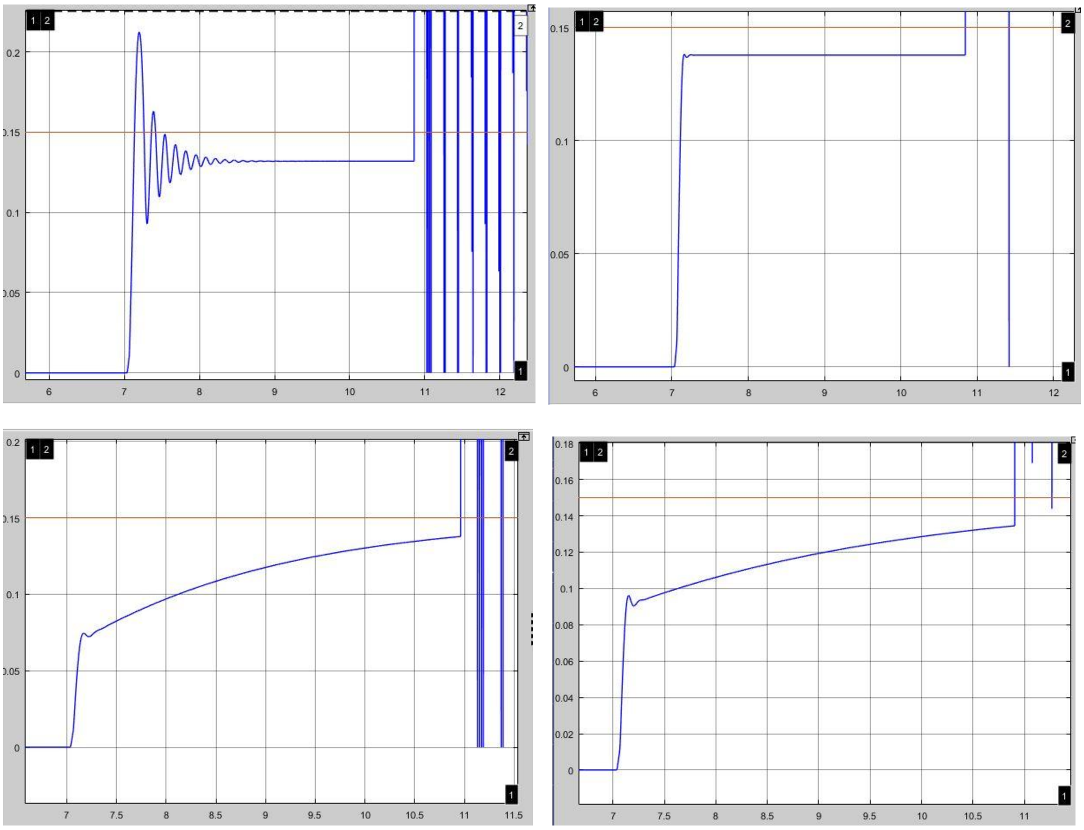

Figure 22 ABS Slip response for Road 2 for different controllers P, PD ,PID & PI (clockwise from top left)

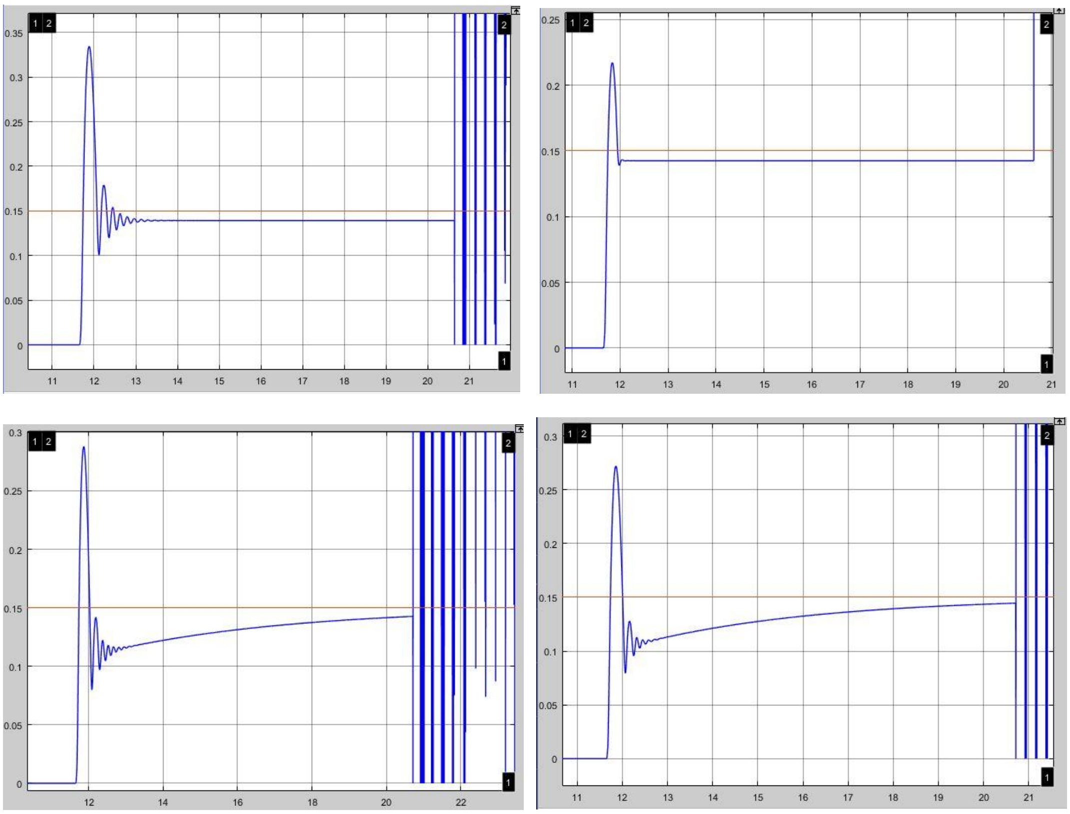

Figure 23 ABS Slip response for Road 3 for different controllers P, PD, PID & PI (clockwise from top left)

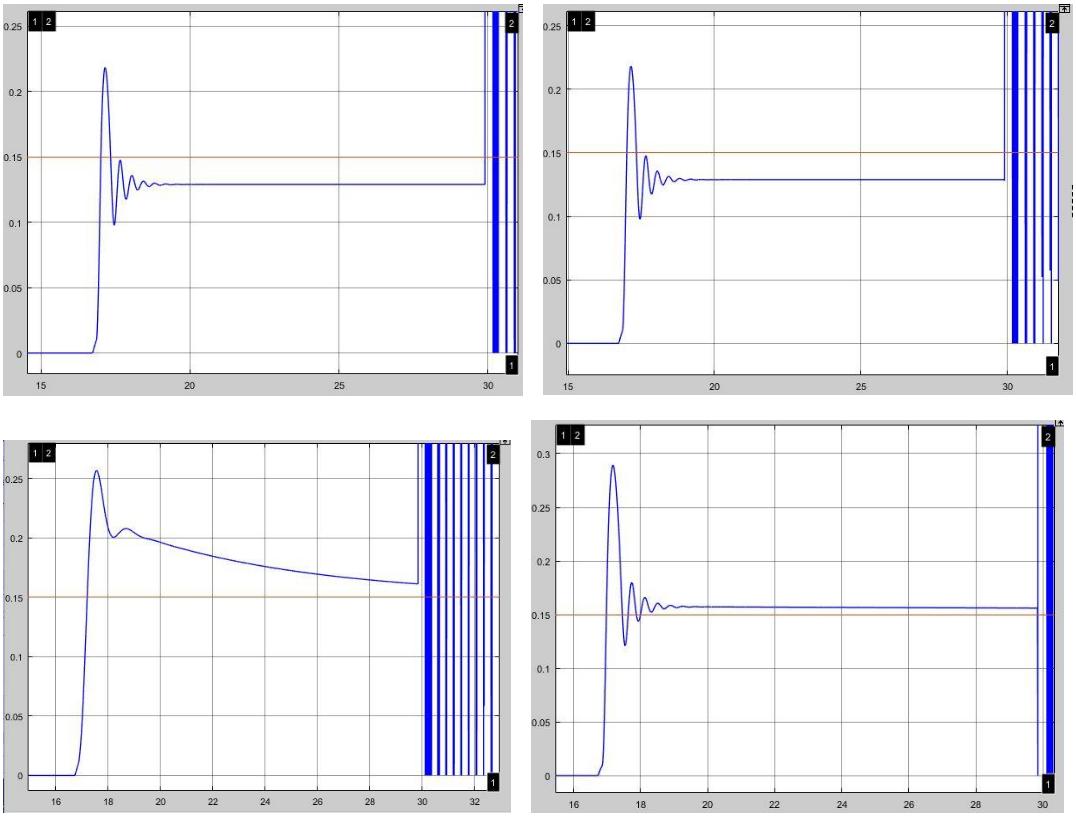

Figure 24 ABS Slip response for Rail for different controllers P, PD ,PID & PI (clockwise from top left)

The above graphs show the slip response of the anti-lock braking system, some important things that can be noted are,

- The response with P has a high settling time.
- The settling time is reduced when derivative part is added, hence, PD & PID have a better response.
- The settling time of PI controller for all cases except Road 1 is very high and is unacceptable.
- Steady state error is negligible is almost all cases except the cases where steady state hasn't been achieved.
- The overshoot is very less is all cases (about 20%) and is quickly controlled to the steady state.
- Like the TCS, Rise time of ABS to steady state is very low, this can be seen by how steep the curve is. (except PI & PID controllers for Road 2 case)
- Interestingly, PD controller outperforms the PID controller, this is also reflected in the reduction in braking distance.

Task 3.e :

Is that necessary to use all type of controllers to follow the required response? Motivate your answer.

From the above discussion and the results table in task 3.c it can be interpreted that for Traction Control System PD & PID controllers perform almost similarly, the decision between them can now be motivated by either cost or controllability, where PD controller is more cost effective, PID controller gives more controllability.

In anti-lock braking system, PD controller gives a better performance in all cases. So the obvious choice, also considering the cost factor, will be PD controller. But if one controller has to be used for all road conditions then PID controller performs better. So, PID controller is chosen for ABS as well.

Task 4 : PID Controller optimization:

Task 4.a :

Introduce the best controller that has the fastest response, least overshoot and smallest steady state error as well the best acceleration time and stopping distance. Assume that system is underdamped.

The best controller i.e. PID for TCS and ABS was introduced in the system.

The feedforward gain and controller tuning parameters were kept according to the worst case scenario that is for the Road 3 case (Icy road).

The following table shows the PID controller settings,

Table 9 Controller Settings for TCS & ABS

Parameter	TCS	ABS
P	50000	75000
I	40	5000
D	2000	900

The following table shows the acceleration time and braking distance for the above chosen controllers for each given case.

Table 10 Acceleration & Braking Distance

Case	Acceleration Time (sec)	Braking Distance (m)
Road 1	2.609	37.5
Road 2	3.912	56.5
Road 3	8.650	112.1
Rail	14.57	164.9

Task 4.b :

Is it possible to eliminate the steady state error while maintain the previous mentioned properties?

No, it is not possible to eliminate the steady sate error. To eliminate steady state error we must change the feed forward gains for each driving condition which is not possible in the real world scenario. That is why designing for the worst case scenario (icy road) is the best compromise.

Extra Task 4.c :

Estimate the utilized friction value during the manoeuvre with the given sensor signals.

The utilized friction can be estimated using the given sensor signals by taking the ratio of longitudinal tractive/braking force (Fx) & vertical force (Fz) ,

$$\mu = \frac{Fx}{Fz}$$

The following figure shows how the above formula was implemented in the Simulink model,

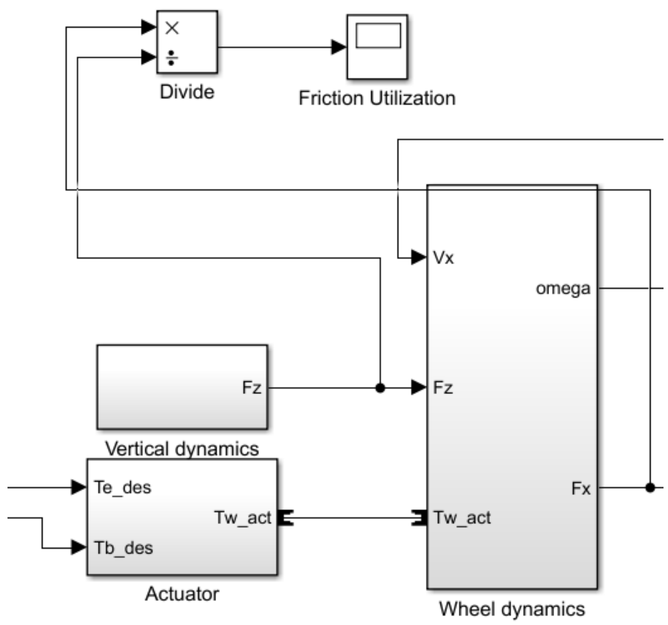

Figure 25 Implementing friction utilization

The following figures show the friction utilization for each road condition & rail,

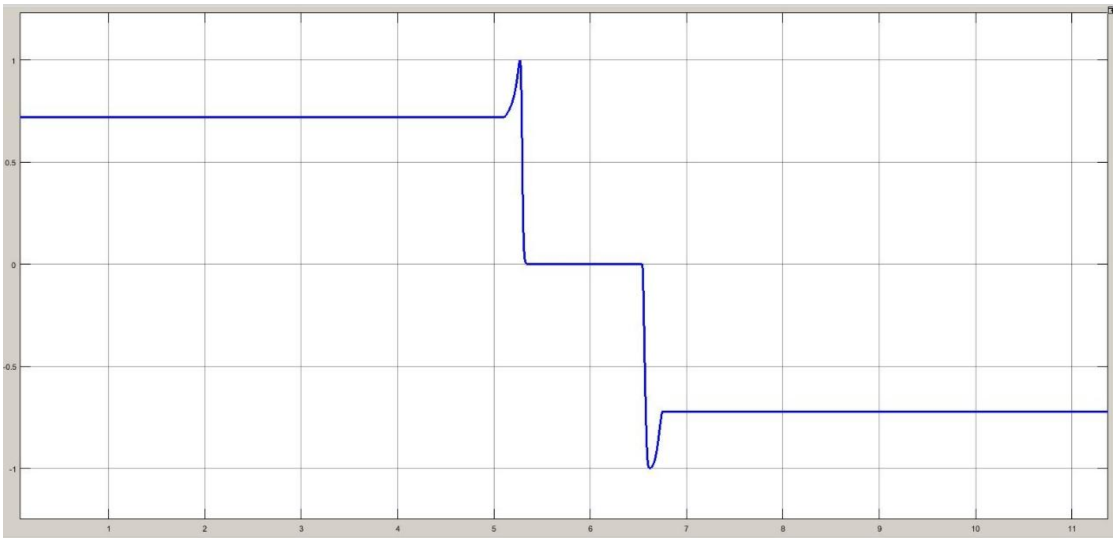

Figure 26 Friction Utilization Dry Road

Figure 27 Friction Utilization Wet Road

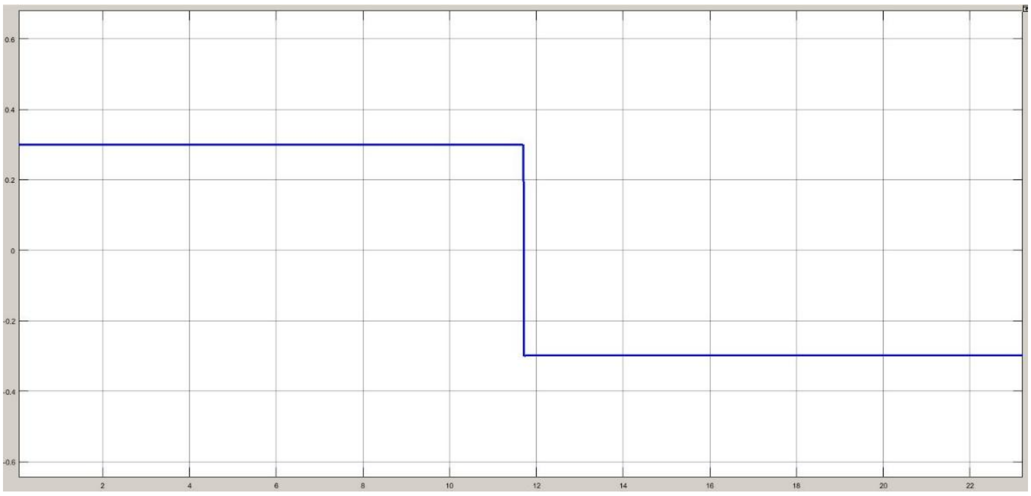

Figure 28 Friction Utilization Icy Road

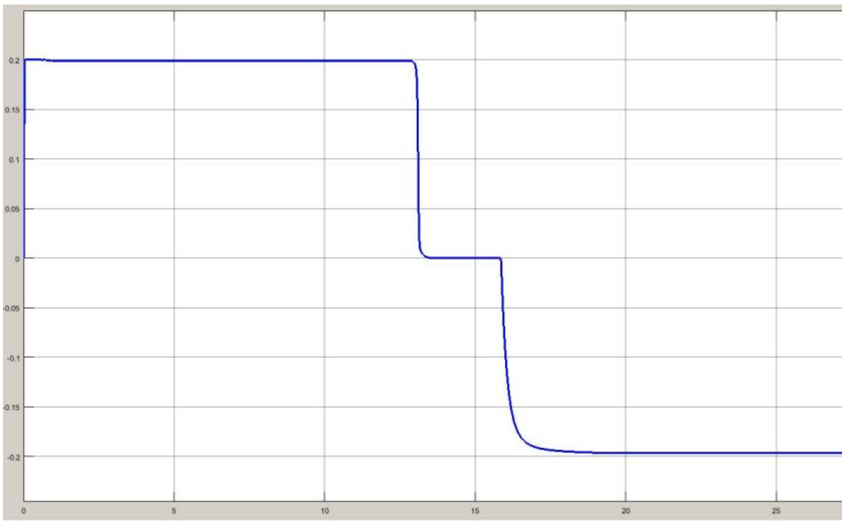

Figure 29 Friction Utilization Rail

Extra task 4.d:

Optimizing the given controller for uneven road/rail. Activate uneven road/rail disturbance in the vertical dynamics model.

Uneven road disturbance was activated in the vertical dynamics model, and the controllers were tuned for the worst case condition i.e icy road.

The following table shows the controller parameters:

Table 11 TCS & ABS control parameters for uneven road disturbances

Parameter	TCS	ABS
P	50000	75000
I	40	5000
D	2000	900
	Time= 8.545 sec	**Braking Distance = 118.2 sec**

The following figures show the slip response of the TCS (PID) and ABS (PD)

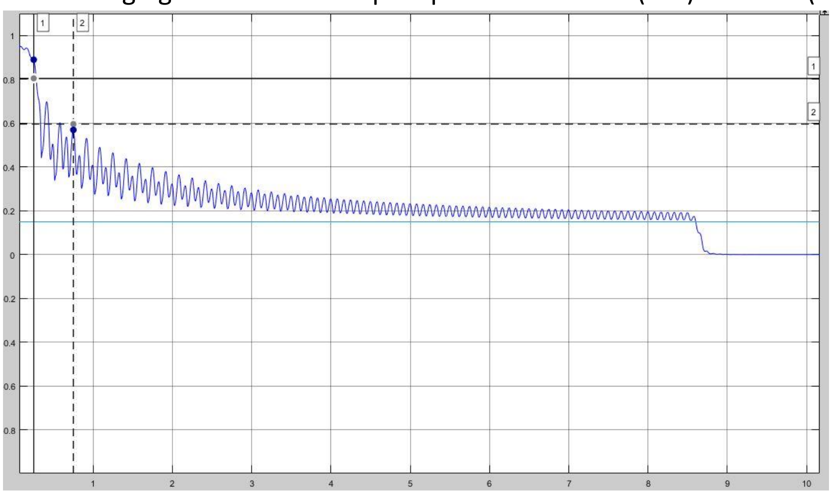

Figure 30 Slip response of PID controller for TCS for uneven road

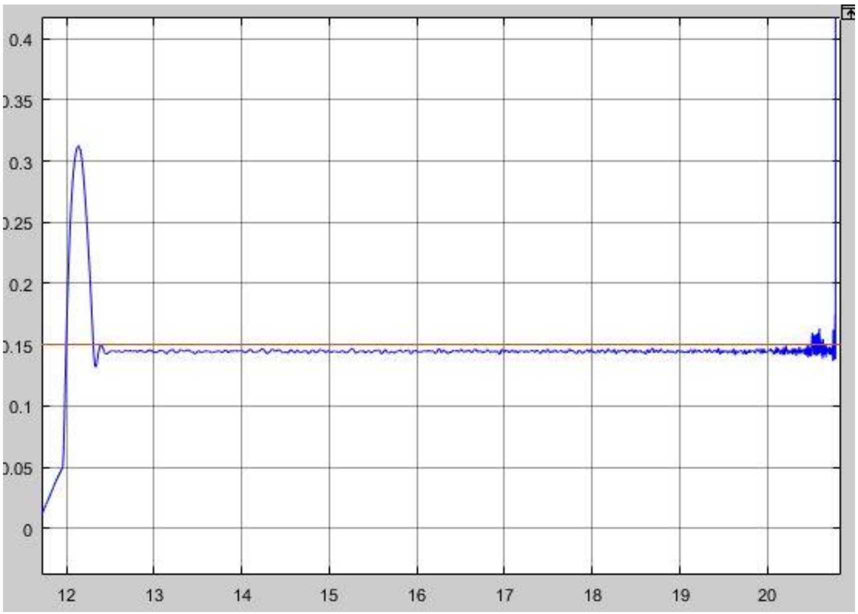

Figure 31 Slip response of PD controller for ABS for uneven road

Extra Task 5

Introduce a disturbance such as an icy spot on a wet road into system for both acceleration and braking maneouvres. How does the disturbance change the system behaviour and what has to be adopted. Propose an optimized controller which accounts for this disturbance.

The icy spot can be introduced by changing the friction coefficient value for a specific distance by altering the magic formula.

Conclusion:

The controllers and activation logics for all the given cases were designed and tested, although according to us the results are satisfactory but more time could be given to tune the controller for ABS.