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Traction Control for KTH Formula Student

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Abstract

When accelerating, traction from the tyres is necessary to move the vehicle forward. If too much torque is applied to the wheels of the vehicle, the tyres will start to spin and thereby the traction will decrease. This can occur when the driver of the vehicle applies too much throttle, but can be controlled with a traction control system that prevents the tyres from spinning and keeps the tyres at maximum traction to increase acceleration. In Formula Student competitions, every tenth of a second gained is vital and a traction control could help the driver to find these tenths of a second during acceleration.

The purpose of this bachelor thesis was to design a slip ratio based traction control for the KTH Formula Student car DeV17 with focus on the acceleration event from standing start. A problem with standing start is the launch of the acceleration which was investigated along with a PID-controller. The model was developed in MATLAB's SIMULINK and simulated with IPG CarMaker. Small improvements in acceleration time were seen with the PID-controller but the launch did not see any improvements.

Sammanfattning

När du accelererar är greppet från däcken nödvändigt för att flytta fordonet framåt. Om för mycket vridmoment appliceras på fordonets hjul kommer däcken att slira och därmed minska dragkraften. Detta kan inträffa när fordonets förare tillämpar för mycket gas, men kan styras med ett anti-sladd system som förhindrar att däcken slirar och håller däcken på maximalt grepp för att öka accelerationen. I Formula Student tävlingar är varje tiondel av en sekund avgörande och ett anti-sladd system kan hjälpa föraren att hitta dessa tiondelar.

Syftet med detta kandidatarbete var att designa ett slip-ratio baserad anti-sladd system för KTH Formula Students bil DeV17 med fokus på accelerationsförloppet från stående start. Ett problem med stående start är igångsättningen som undersöktes tillsammans med en PID-regulator. Modellen utvecklades i MATLABs simuleringsprogram SIMULINK och simulerades med IPG Car-Maker. Små förbättringar i accelerationstiden sågs med PID-regulatorn men igångsättningsmetoden såg inga förbättringar.

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1 Introduction

When a car accelerates, the power is transmitted from its motor via a gearbox to its tyres, which then applies a longitudinal force to the ground to move the car forward. The magnitude of this longitudinal force depends on how much the car's tyres are slipping. If too much torque is applied to the tyres, they will begin to slip, which means that the longitudinal force that forces the car forward will decrease and the acceleration will therefore also decrease. To avoid this, the driver can apply less throttle to reduce the applied torque on the tyres. This can also be done with the help of a traction control system and is also what this degree project will focus on. The traction control system is to be developed for DeV17, KTH Formula Student's formula car which while writing this report, is still being designed and has therefore not started being manufactured.

1.1 Traction Control

In order to maintain maximum longitudinal force during an acceleration, the tyres should not slip, which can happen if too much torque is applied to the tyres. As mentioned earlier, the driver can then apply less throttle and prevent the tyres from slipping. However, the driver may not be able to react quickly enough to prevent the tyres from slipping. Therefore the traction control system can be used to reduce the applied torque on the tyres when it senses that the tyres are slipping. The traction control system should be able to do this faster than the driver can do this.

Traction control can be used in different applications such as racing and in road cars where its purpose is slightly different. For road cars the main purpose is of safety reasons, to prevent the tyres from slipping in for example slippery and icy conditions. It is often one wheel that slips before the other tyres and this could cause the car to spin if no precautionary action is used, for example with a traction control. In racing the purpose of a traction control is rather to increase performance than safety, by keeping the tyres at the optimal grip level and thereby increase the performance of the car.

There exists different types of traction controls. One way reduce the applied torque from the motor to the wheel, which can be done with an differential distributing the torque between the wheels or by reducing the torque from the motor to the wheels. If each wheel is separately driven, each wheel can be controlled by one motor. Another way is to brake the tyre that is slipping while keeping the applied torque from the motor. This method is more common for road cars than in racing.

1.2 Formula Student

Formula Student is an engineering competition for students where universities from all over the world compete against each other in designing, manufacturing, developing and competing with small formula cars. The competition consists of three static competitions, in the form of *Business Plan Presentation*, *Cost and Manufacturing* och *Engineering Design* and five dynamic competitions in the form of *Skid Pad*, *Acceleration*, *Autocross*, *Endurance* and *Efficiency* [1].

As can be seen in table 1.1, a maximum of 75 points can be given for the competition *Acceleration*, which corresponds to 7.5 % of the maximum total score. In this report, the focus will be on this particular event.

Table 1.1: Maximum points in Formula Student competition

Static events	
Business Plan Presentation	75 points
Cost and Manufacturing	100 points
Engineering Design	150 points
Dynamic events	
Skid Pad	75 points
Acceleration	75 points
Autocross	75 points
Endurance	325 points
Efficiency	100 points
Total	1000 points

1.3 Purpose

The purpose of this study is to further develop the existing traction control in KTH formula student. The new traction control should be developed for a four wheel driven car with four separate electrical motors.

1.4 Method

From previous work by past team members of KTH formula student the traction control should be further developed. A literature study was performed to understand how a traction control system can be constructed. A model of the traction control was thereafter created using MATLAB [2] and SIMULINK and then simulated in a full vehicle model in IPG CarMaker [3].

1.5 Limitations

As this traction control was developed for a straight line acceleration event only longitudinal slip was considered and therefore no lateral slip. The report only considered a slip ratio based traction control with a PID controller. Since the traction control system was only simulated in IPG CarMaker, noise from sensors were not considered.

2 Literature study

2.1 DeV17

During the fall of 2019 and spring 2020, KTH Formula Student are designing a brand new car with new concepts. Previous cars from KTH Formula Student have had a steel chassis, but Dev17 will be a carbon fiber monocoque. This means that almost all components of the car need to be redesigned and no parameters are definitive. The parameters specified in table 2.1 are therefore only estimated values based on the design and it is not certain that these values will apply to the finished and manufactured car. The most important difference for the DeV17 compared to previous cars was that it was four wheel driven with a separate electrical motor for each wheel and traction control can therefore be applied to all four wheels.

Table 2.1: Important parameters of DeV17

Mass [kg](Including driver of 70 kg)	260
Unsprung mass [kg]	40
Center of gravity height [m]	0.26
Wheelbase [m]	1.535
Weight distribution [%]	45
Effective rolling radius [m]	0.221
Motor torque [Nm]	21
Gearbox gear ratio	15
Lift force coefficient	-4.4
Drag force coefficient	1.4

2.2 Tyres

When a tyre is subjected to a torque, the contact patch of the tyre will travel at a greater velocity than the vehicle itself due to the tyre being deformed when subjected to load. A tyre not subjected to a torque is regarded as a free rolling tyre and the velocity difference between the free rolling tyre and the deformed tyre is referred to as the slip ratio and is defined by equation (2.1). Slip ratio measures the difference between the angular velocity of the deformed tyre and a free rolling tyre of the car that is not subjected to a torque. This difference is then normalised with the angular velocity of the free rolling tyre to get a dimensionless value that defines slip ratio [4].

$$Slipratio = \frac{\omega - \omega_0}{\omega_0} = \frac{r\omega - v_x}{v_x} \quad (2.1)$$

where ω = Angular velocity of driven wheel [rad/s],
 ω_0 = Angular velocity of free rolling wheel [rad/s],
 r = Radius of wheel [m], v_x = Velocity of car [m/s]

The longitudinal force of a tyre can be described as a function of its slip ratio and reaches its maximum at a specific slip ratio. Higher slip ratio does not necessarily mean greater longitudinal force, which can be seen in figure 2.1. At a certain slip ratio, maximum longitudinal force is achieved and it is also at this slip ratio that the traction control system should regulate the torque from the motors to keep the slip ratio at this value. The tyre data in figure 2.1 was generated from modelling the used tyres with Pacejka's Magic Formula 5.2 [5].

To determine when the PID control should regulate the desired torque from the motors, tyre data is used. If the slip ration is in the area where maximum longitudinal force is generated, the control

need to regulate anything but the desired torque of the driver can be used. However, if the slip ratio exceeds the value when maximum longitudinal force is generated, the PID control should reduce the torque so that the slip decreases again. In order to continue generating maximum longitudinal force, the PID controller should regulate the torque so that the slip ratio does not exceed the maximum of the tyre curve. Data from the tyres that are supposed to be used on DeV17 are shown in figure 2.1

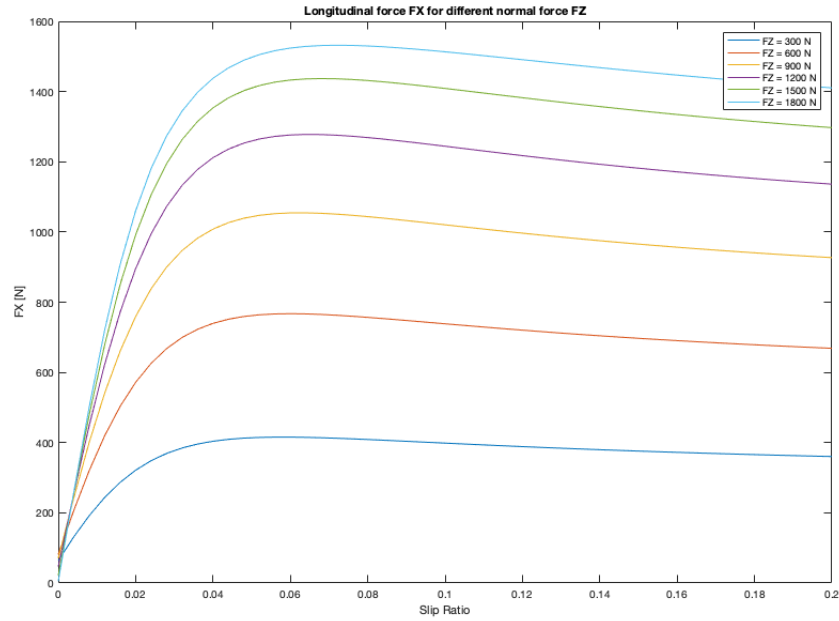


Figure 2.1: Longitudinal force as function of slip ratio for different normal forces

As can be seen in figure 2.1, higher slip ratio is required to reach the maximum of the tyre curve, the higher the normal force on the tyre. Therefore, the normal force on the tyres needs to be known. This could be calculated based on the weight of the car and the weight distribution, but as a load transfer occurs during acceleration and an increasing force is generated from the car's aerodynamics as the speed increases, a simulation was performed in IPG CarMaker to read the normal forces on the tyres front and rear during the acceleration process.

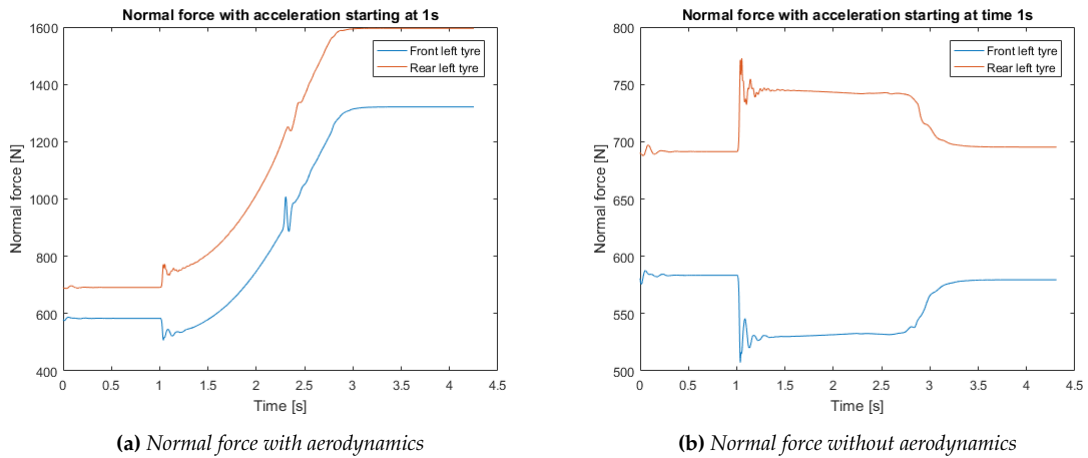


Figure 2.2: Normal forces during acceleration

The normal forces vary between 600 N and 1600 N during the acceleration process and it is therefore these curves in figure 2.1 that should be taken into account. It can then be seen that the traction control should be activated when the slip ratio becomes higher than 0.06. Notable is that the normal force on both front and rear tyres increase during the acceleration, which is due to the high downforce generated by the car's aerodynamics as the velocity increases. In comparison, the normal force distribution without aerodynamics can be seen in the right plot in figure 2.2

2.3 PID controller

The PID controller is a feedback controller which means that it compares the output signal of the controlled system $y(t)$ with a reference signal $r(t)$ to calculate the error $e(t) = r(t) - y(t)$. This error will then be used to calculate the output signal from the controller $u(t)$ with equation (2.2)

$$u(t) = K_p e(t) + K_i \int_{t_0}^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \quad (2.2)$$

Where the Proportional gain K_p , Integral gain K_i and Derivative gain K_d are the terms that can be changed to control the system and also gives the name PID controller. The output value from the proportional term will be proportional to the error $e(t)$ and will therefore have a large input on the controller performance. A larger proportional gain K_p will lower the rise time of the output signal and the controller becomes faster. A larger value will also increase instability and overshooting.

The integral term accumulates all the errors from the past by integrating the error. The control output from the integrating part will therefore be affected by the magnitude of the instantaneous error and the past errors. The integral of the error is multiplied by the integral gain K_i which make the integral term output proportional to the accumulated error. A higher K_i will make the controller faster, but also make it less stable and increase overshoot. The integral term will also eliminated the steady-state error that can be caused by the proportional term.

With the derivative term the future error can be anticipated from derivative of the error and an increased derivative gain K_d can therefore increase stability and decrease overshoot. Since the proportional and integral term increases overshoot and instability higher K_p and K_i can be chosen with an derivative term in the controller [6].

2.4 Anti-windup clamping

When using an PID-controller, integral windup can occur. Integral windup occur when the error of the PID-controller becomes bigger and bigger and therefore the command to the actuator that is being controlled is increasing as well, but usually there is a saturation in the actuator and it can not become bigger than that. The integral part will anyway try to decrease the error by sending a higher command to the actuator. When the error then starts to decrease and later switches sign, the command to the actuator should also switch sign, but since it had increased way above the saturation the sign will remain constant and the error will increase in the other direction. For this traction control, integral windup could result in a negative torque requested when it should always be positive for the acceleration.

To prevent integral windup from happening the PID-controller should never request a command above or below the actuators saturation. Anti-windup clamping can then be used. Anti-windup clamping stops the integral part from increasing when saturation of the actuator is reached but the integral error continues to add up [7].

2.5 Past traction control in KTH Formula Student

The previous traction control was a slip ratio based PI-controller applied on a rear wheel driven car. The idea was to have two thresholds for the slip ratio where the higher value of the two would represent the threshold for when the traction control should become active and start to

decrease the demanded torque from the driver. This threshold was called the In-threshold. The lower value of the thresholds would represent the threshold for when the traction control should stop to decrease the demanded torque from the driver and the drivers demanded torque would be sent to the motors again until the slip ratio would become bigger than the In-threshold again. When the traction control was active the lower of the two thresholds, the Out-threshold was used as reference for the PI-controller which led to the torque from the motors were decreased until this Out-threshold was reached. This would prevent the traction control from switching between on and off a lot.

To prevent a higher torque than the demanded torque from the driver from being sent to the motors when the slip ratio is below the In-threshold, an arbitration block was used where the lowest value of the driver demanded torque and the output torque from the traction control was sent to the motor. When the slip ratio was lower than the In-threshold a very high torque was sent out from the traction control to prevent any errors with wrong torque being sent to the motor [8].

2.6 IPG CarMaker

To test and simulate the traction control logic, full vehicle simulations was performed in IPG CarMaker. In IPG CarMaker a full vehicle model can be simulated without having to model the whole car by yourself and can instead focus on the model that you want to evaluate. The parameters for DeV17 was then implemented and the powertrain block was modified to implement the traction control model.

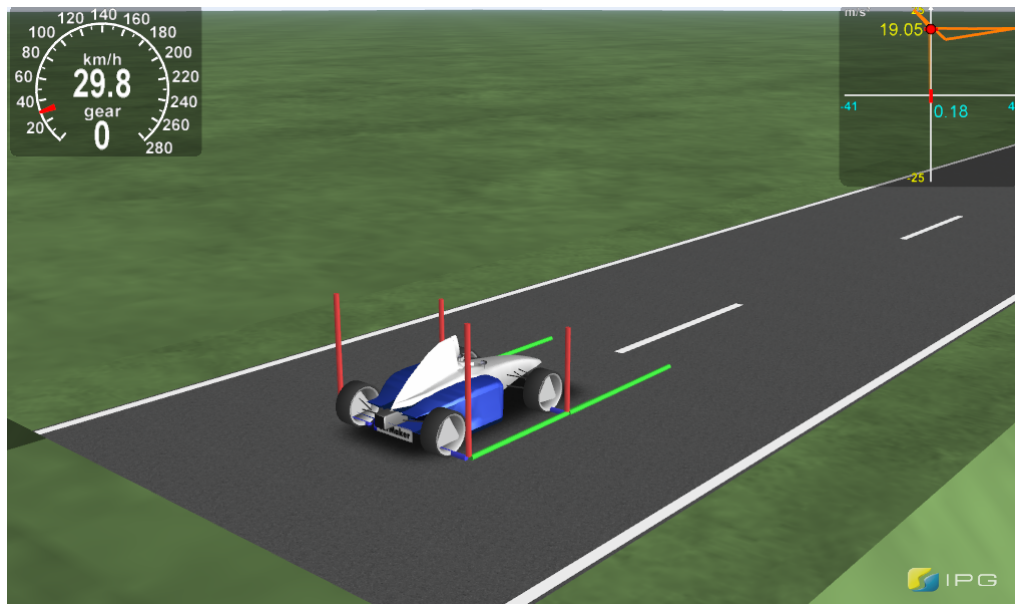


Figure 2.3: Visualisation of simulation in IPG CarMaker

3 Traction control model

3.1 PID control

Two different traction control models were designed and tested, where one used two different slip ratio reference values as in the old KTH formula student traction control and the other only used one slip ratio reference value. Apart from a difference in how the reference values were chosen, the two models used the same slip ratio calculation and arbitration block to choose the lowest value of the traction control given torque and the driver demanded torque. To prevent the traction control to send out a higher torque than the driver demanded torque, a saturation block for the PID-controller was used. The simulink inbuilt PID-controller block was used as PID-controller with anti-windup clamping and filtered derivative activated according to figure 3.1.

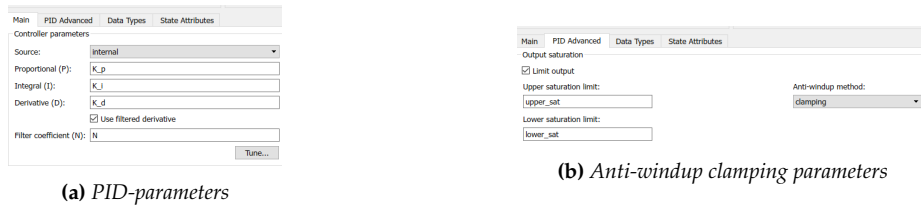


Figure 3.1: PID-controller block in simulink

To avoid division by zero according to equation (2.1) a switch was implemented where the traction control torque was not chosen if the vehicle velocity was below 0.5 m/s. The slip ratio was calculated according to figure 3.2. The whole traction control system logic can be seen in figure 3.3

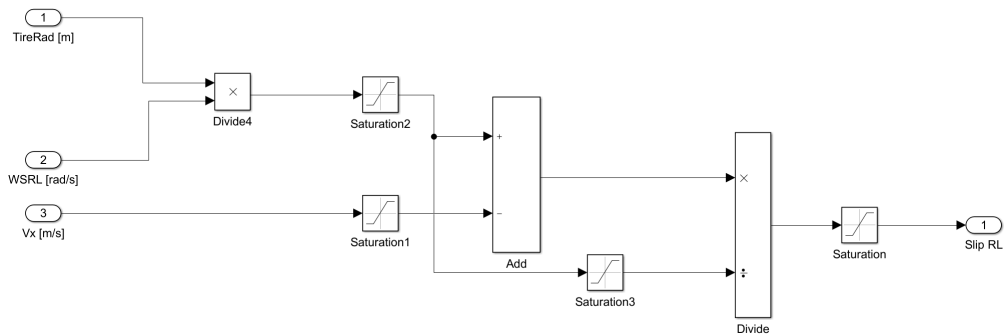


Figure 3.2: Slip ratio calculation in simulink

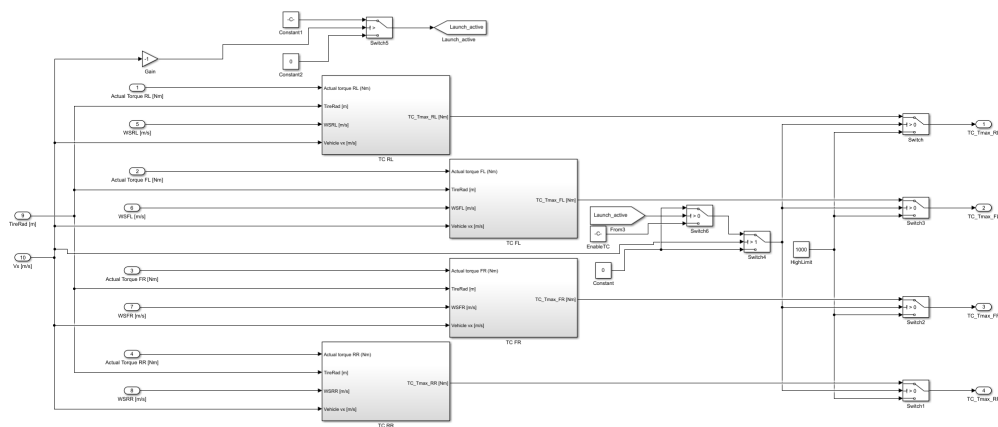


Figure 3.3: Traction control system

Two reference values

hysteresis cycle for switching logic and reference

As in the old KTH formula student traction control two slip ratio reference values were used for this version of the traction control. These reference values were also used as thresholds for when the PID-controller should be active. When the slip ratio was higher than the higher threshold, the lower threshold was used as reference value for the PID-controller. When the lower threshold was reached again, the reference value would switch to the higher threshold again as threshold. To prevent overshoot, a PID-control was used instead of a PI-control.

To decide when the traction control should be active and what threshold that should be the reference, a Matlab-function was used. The Matlab-function took the slip ratio, the driver demanded torque and the In- and Out-thresholds as inputs and a torque value and value for if the traction control was active. If the slip ratio became higher than the In-threshold, the function would send out TC-active as 1 to indicate that Out-threshold should be used as reference value for the PID-controller. A start torque would also be sent out as the torque to be lowered by the PID-controller. This start torque would be the same as the driver demanded torque at the moment the slip ratio exceeded the In-threshold and would be persistent until the slip ratio went below the Out-threshold. The Matlab-function can be seen below and the threshold switch logic can be seen in figure 3.4. The whole traction control logic for one wheel can be seen in figure 3.5

```

1 function [start_tq , TC_active] = fcn(act_tq , InThr , OutThr , slip)
2
3 persistent n start_tq_persistent
4
5 if isempty(n)
6     n = 0;
7 end
8
9 if isempty(start_tq_persistent)
10     start_tq_persistent = 1000;
11 end
12
13 if slip > OutThr
14     if slip > InThr
15         if n == 0
16             start_tq_persistent = act_tq;
17             n = 1;
18         end
19     end
20 else
21     start_tq_persistent = 1000;
22     n = 0;
23 end
24
25 start_tq = start_tq_persistent;
26 TC_active = n;
27 end

```

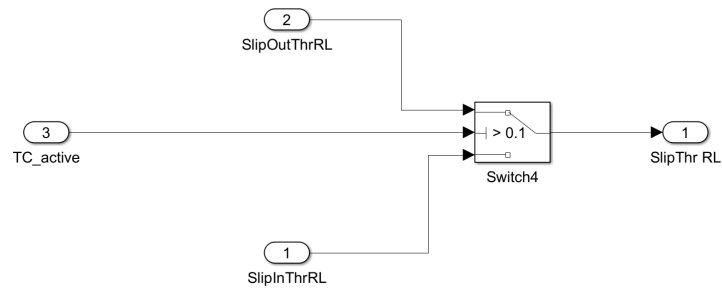


Figure 3.4: *Switch for thresholds*

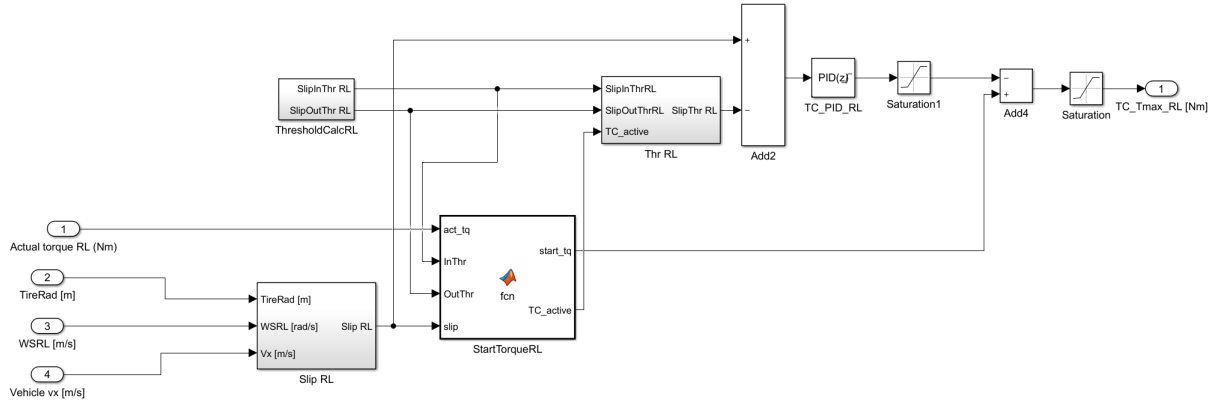


Figure 3.5: Traction control for rear left wheel with two reference values

One reference value

The model with one reference value works similar to the model with two reference values. The difference is that the reference value for the PID-controller never change and therefore the Matlab-function does not have an output TC-active. The model can be seen in figure 3.6.

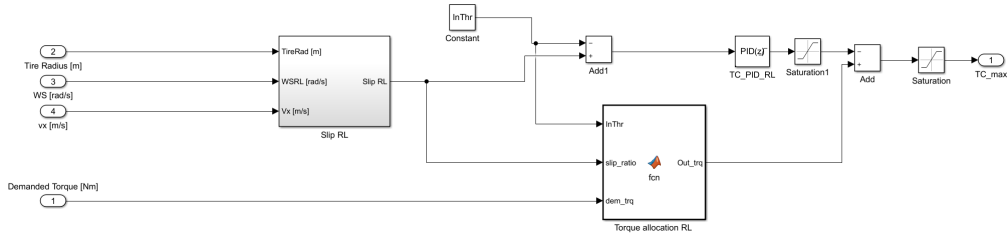


Figure 3.6: Traction control for rear left wheel with one reference value

3.2 Launch control

Feedforward control was implemented on the throttle input from the driver to the motors. The idea was that when the driver holds a launch control button and then put full throttle, launch control will be active and send a predefined throttle input uninfluenced by the throttle input from the driver. The driver have to hold full throttle during the whole launch to not break the launch. This is to prevent the predefined throttle input to go on even if the driver wants to stop the car. The launch control was implemented in simulink as in figure 3.7 where the four Matlab-functions are the different launch modes were tested. The four different launch modes were according to equation (3.1), (3.2), (3.3) and (3.4).

$$\text{Launch mode 1: } throttle_output = 0.4 + \frac{(3 \cdot Time)^2}{2} \quad (3.1)$$

$$\text{Launch mode 2: } throttle_output = 1 - \frac{1 - 0.4}{1 + 10 \cdot Time} \quad (3.2)$$

$$\text{Launch mode 2: } throttle_output = 1 - \frac{1 - 0.4}{1 + 5 \cdot Time} \quad (3.3)$$

$$\text{Launch mode 4: } throttle_output = 0.4 + 0.4 \cdot Time \quad (3.4)$$

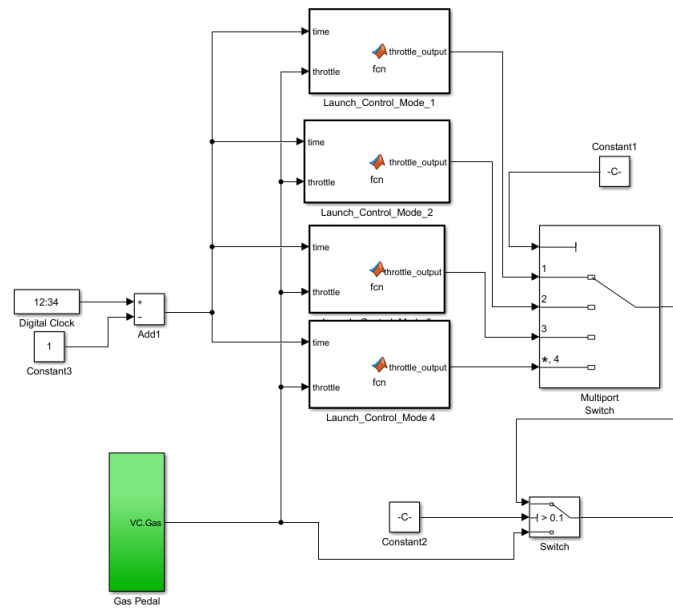


Figure 3.7: Launch control implementation

4 Results

4.1 Two reference values

For the model with two reference values the PID-parameters and anti-windup clamping saturation was chosen according to table 4.1. In figure 4.1 the slip ratio for the front left tyre can be seen without and with traction control activated. The two straight lines represent the two thresholds that the PID-controller should regulate the torque from the driver between. In table 4.2 the acceleration times is showcased. For both the simulation with and without traction control, the drivers throttle input in IPG CarMaker is set to 1 during the whole simulation, which equals full throttle.

Table 4.1: PID-parameters

Parameter	value
In_Thr	0.06
Out_Thr	0.05
K _p	700
K _i	500
K _d	10
N	100
upper_sat	315
lower_sat	0

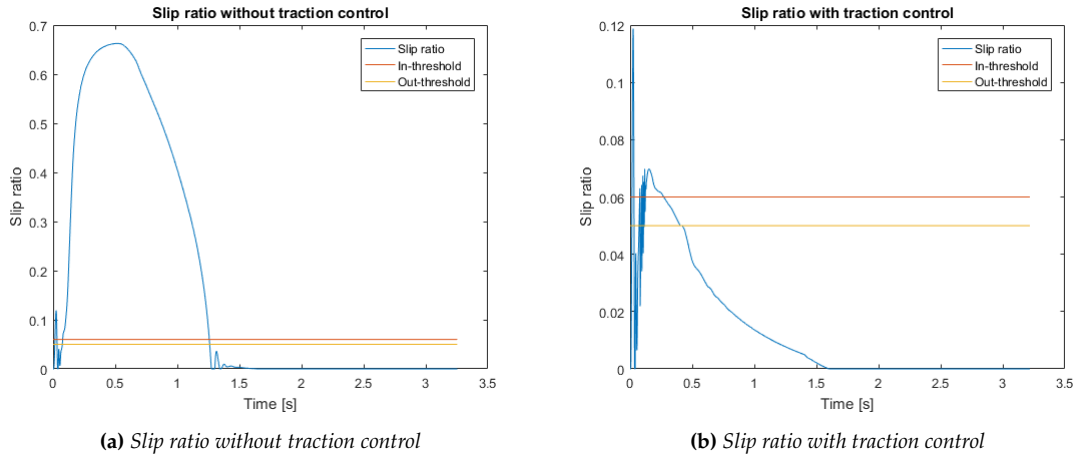


Figure 4.1: Slip ratio during acceleration

Table 4.2: Acceleration times

	Time [s]
Without TC	3.25
With TC	3.21

4.2 One reference value

For the model with one reference values the PID-parameters and anti-windup clamping saturation was chosen according to table 4.3. In figure 4.2 the slip ratio for the front left tyre can be seen without and with traction control activated. The straight line represent the slip ratio value the PID-controller should keep the slip ratio. In table 4.4 the acceleration times is showcased.

Table 4.3: PID-parameters

Parameter	value
K_p	50
K_i	100
K_d	60
N	100
upper_sat	315
lower_sat	0

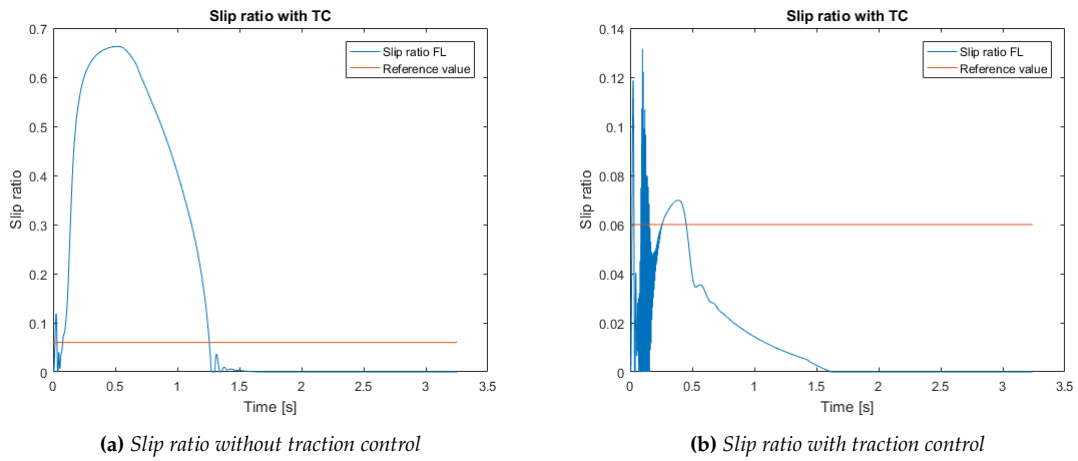


Figure 4.2: Slip ratio during acceleration

Table 4.4: Acceleration times

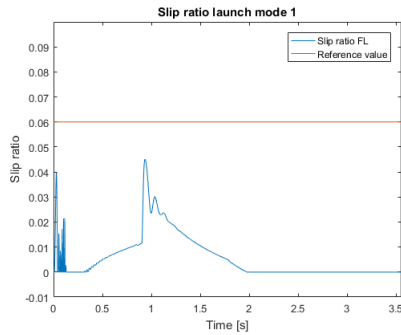
	Time [s]
Without TC	3.25
With TC	3.24

4.3 Launch Control

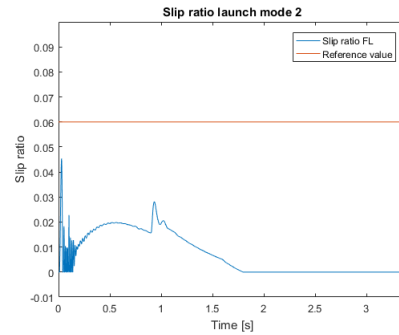
In table 4.5 the acceleration times with different launch modes is showcased and in figure 4.3 the slip ratio with different launch modes can be seen.

Table 4.5: Acceleration times with different launch modes

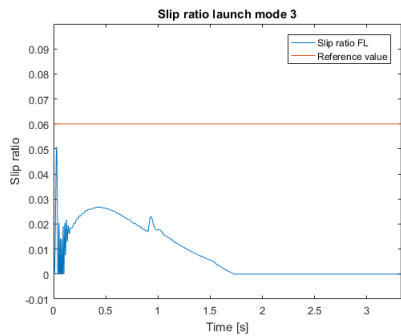
Mode	Time [s]
1	3.60
2	3.39
3	3.33
4	3.44



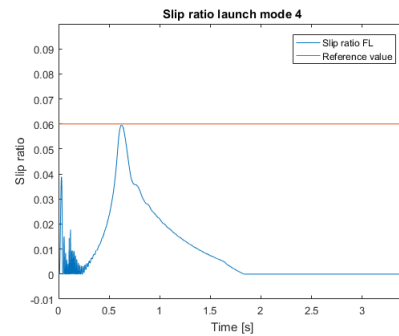
(a) Slip ratio for launch mode 1



(b) Slip ratio for launch mode 2



(c) Slip ratio for launch mode 3



(d) Slip ratio for launch mode 4

Figure 4.3: Slip ratio during acceleration for different launch modes

5 Discussion

As seen in figure ?? the traction control with two reference values significantly improves the slip ratio and keeps it closer to the desired values seen in figure 2.1. With two different reference values the controller becomes unstable and do never settle at the desired value since the reference value change. Even though it is unstable, the slip ratio is a lot closer to the desired slip ratio than without traction control. This should result in faster acceleration time but the traction control only lowered the time with 0.04 seconds compared to a driver that uses full throttle during the whole acceleration. This might be because the slip ratio is lowered to much and the longitudinal force is therefore significantly lower. While tuning the PID-controller a higher saturation of 45 led to better results than with a more reasonable saturation of around 300, since this is the maximum torque given at the wheels.

For the model with one reference value the PID-parameter gains might not have been perfectly tuned and a very unstable controller were created that did not manage to keep the slip ratio at the desired value. The time improvement was therefore only 0.01 seconds.

For the Launch control all the four different launch modes kept the slip ratio below the desired value of 0.06, but the slip ratio stayed too low so that the optimal longitudinal force was not reached. All four different modes were slower than without any traction control. More aggressive modes should have been tested.

For all simulations, ripples can be seen in the slip ratio calculations. Especially at low speeds in the beginning of the simulations this problem occurs. The slip ratio varies a lot which makes it difficult for the PID-controller to accurately regulate the torque. For the whole simulation, a fixed effective rolling radius of the tyres is used for the slip ratio calculation, while in reality the effective rolling radius will change during the acceleration. The model in IPG CarMaker considers the change in effective rolling radius, but the slip ratio calculation in the traction control does not and this could cause the ripples. The ripples could also be caused by some errors in the tyre model file used in IPG CarMaker.

5.1 Sustainability

As climate changes are one of the biggest threats to our planet as of today and energy consumption is more important than ever, reducing the energy consumption of the vehicles are of great importance. With a traction control system drivers can minimise slipping of their tyres and thereby reducing energy consumption and tyre wear. Less tyre wear will reduce the number of particles from the tyres. A traction control will also increase stability of the vehicle, making it easier to control and reducing the number of accidents on the roads. While reducing the tyre slip and number of accidents might not decrease the energy consumption much, traction control systems can be used for a autonomous vehicles to reduce the vehicle fleet. In this thesis a traction control system has been designed to find maximum accelerating traction, but the same theory can also be used to find the maximum decelerating traction and then be used for regenerative braking in an electrical vehicle.

5.2 Future work

First priority should be to solve the problems with the ripples in the slip ratio calculation before any the PID-gains can be tuned. This should be done by looking for errors in the tyre files or finding another solution. As the manufacturing of DeV17 had not started at the time of this thesis and it were still being developed vehicle parameters were not final and not validated to the real car. When the vehicle parameters are final and also when the car is validated the PID gains should be tuned again. As the the model with one reference values has a greater potential of being stable and therefore improving acceleration time, this model should be worked with further to see some

improvements. The launch modes needs to be redefined and more aggressive modes need to be tested.

6 Conclusion

In conclusion the slip ratio based traction control regulated with a PID-controller for each wheel created a small improvement of the acceleration time compared to a driver giving full throttle during the whole acceleration. The problem related to the launch solved with a feedforward control did not see significant improvement, but instead an increased acceleration time.

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A Appendix

A.1 Full model in IPG CarMaker

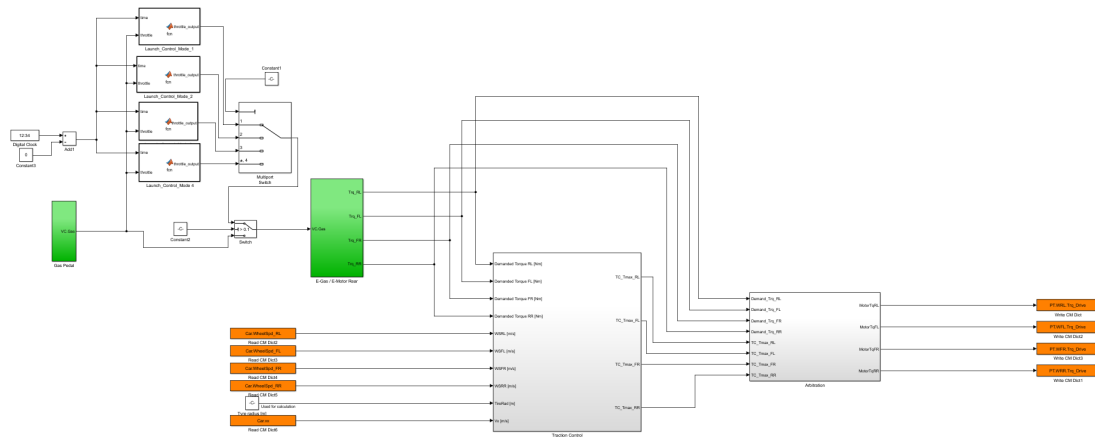


Figure A.1: Full model in IPG CarMaker

