University of Twente

Internship Report

Torque based anti wheel lock control at NEVS

Egbert Barels (s1200399)

National Electric Vehicle Sweden AB
Vehicle Motion Software and Control Department
Saabvagen 5
461 38 Trollhättan, Sverige
Supervisor: Mustafa Ali Arat

University of Twente
Mechanics of Solids, Surfaces and Systems Department
Drienerlolaan 5
7522 NB Enschede, Nederland
Supervisor: R.G.K.M. Aarts

September 6, 2017

Preface

This report covers a part of my work during my internship at National Electric Vehicle Sweden (NEVS). I wanted to do my internship abroad because I wanted to test if I was still able to live my life on my own, just like I did when I came from secondary school to the university, because in order to do that I had to move to another city without all my friends. A friend of mine has showed me the possibility to do an internship at NEVS. Besides that basically my intuition told me I should step outside my comfort zone with the goal to experience new things, I think NEVS vision collides with my current view of the future. NEVS is a car company that wants to make electric vehicles, not specific for particular usage as is common nowadays, but a vehicle which is for everyone, a bit like a taxi ultimately driving autonomously. Most cars today, most of the time are standing still either at home or at work taking up lots of parking space. As the amount of people is not getting less, at some point people should drive together. Also right now I think it is more efficient to have less vehicles driving more instead of more vehicles driving less. Such vehicles should be highly reliable and very robust and will probably not be as cheap like most production cars today, but they will be of more value as they can transport more people in their lifespan, making them less polluting for the environment.

Summary

In order for the driver or autonomous driver to be able to maintain control over a vehicle when braking it is advantageous to have not too many slip between the tire of the wheels and the surface of the road. This is controlled with an ABS controller which regulates the oil pressure in the hydraulic pipelines to the brake calipers, in this way the amount of friction on the friction disks can be controlled, leading to more or less braking effort. This system works great, but for vehicles equipped with an electric motor, the electric motor itself can also be used for braking. Especially for vehicles which have a separate electric motor for each wheel, it would be advantageous if the electric motor also could contain ABS to get rid of the mechanical ABS [1]. Furthermore it is highly suitable for torque vectoring applications [2]. As with electric motors the current can be measured to estimated the actual torque [3], it is investigated if it is possible to make an ABS controller which only needs this torque to be functional. This report contains two subjects, one is about the identification of a system and the other is about a control algorithm. First some effort was made to make an identification of the electric motor from NEVS which was available for testing at a test rig. There was already some dynamic model created, but it has to be sough out if this model was accurate enough since for using an electric motor for ABS more insight in the dynamic behavior might be very useful. Another company which makes in-wheel motors has provided some measurement data of demanded torques and resulted torques, to see if the identification is also applicable to their setup.

This model is used in a quarter car model, which simulates one wheel and electric motor of a vehicle. After the model of the electric motor was validated, an algorithm is created that uses the torque measurements to determine if the wheel is starting to lock up, leading to slip between the tire and the road surface. The algorithm consist of three phases, but is called a two phase algorithm, as it changes phases between two phases, a phase in which the torque needs to be increased and a phase in which the torqued needs to be decreased. The remaining phase is an initial phase, which is only active in the beginning of a braking event.

As the title of this report suggest the decision making of the phases is based on the actual torque between the wheel and the road surface. When the braking torque increases, there will be a point at which the tire starts to slip, when this happens the actual torque will be reduced hence the tire is slipping, In oder to prevent the tire from slipping the demanded torque should be reduced, however there is an optimal slipping point at which maximum torque transfer between the wheel and the road surface will be obtained, this optimum depend on many parameters and can be different for each wheel during a braking event or even change during a braking event. The challenge was to make an algorithm that was able to cope with that.

Furthermore the ABS algorithm is combined with an existing ESC controller, this is simulated in IPG carmaker. A first order model for the EM is used in the simulations regarding to the two-phase algorithm. Four simulations are performed the difference between the test cases for the simulations are the road surface conditions and the activation of the ESC. More specific a split-mu case with and without ESC, and a changing mu case with and without ESC. Also a simulation with a build-in ABS controller is carried out for validation of the performance of the ABS using the two-phase algorithm.

Contents

Abbreviations

ABS Anti lock braking system

EM Electric Machine

ESC Electronic stability control

MEA Multiple event accidents

1 Introduction

The ultimate goal is to have more control over the vehicle, not necessary more control for the driver. Current systems like ABS and ESC are not very suitable to maintain stability of the vehicle after high amplitudes of disturbances, which can be caused by an impact during an emergency incident or a flat tire. The main reference for the ESC, is derived form the drivers input. When a vehicle crashes this driver was likely unable to act correctly to accomplish a successful avoidance manoeuvre to prevent the collision. Maybe the driver is able to prevent the the initial collision but by doing this the vehicle will get into slip, creating a maybe even worse collision with other objects, this scenario is also know as multiple event accidents (MEA). So it would be preferable that the car is able to drive autonomously just before or after a crash until a safe state.

Ultimately a reference trajectory which can bring the vehicle into a safe state after a collision accident or better, prevent the collision from happening at all is desired. In order to make such a reference the vehicle must be provided with sensors to observe the surrounding, and a surrounding perception algorithm is needed to transform the data to a trajectory. A crash is happening really fast so the surrounding perception algorithm should be able to focus on certain objects and region. In this way not to much data will be sent to the reference generating path algorithm which otherwise may cause the algorithm to get stuck or behave slowly. This focus of the surrounding perception could be made variable meaning a general perception with a low frequent update, and a focused perception with a high frequent update. The general perception will than be used for determining the heading direction e.g. lane keeping and for keeping track of static objects. The focused perception will than deal with rapidly changing objects. The algorithm must diagnose and characterize objects to determine if they are rapidly changing their state or that it can be seen as a static or semi static object. This distinguish between dynamic objects and static objects will be found useful for determining the trajectory. The main trajectory will be based on the static objects and the dynamic objects will be used to deviate from this main trajectory.

During such reference trajectory the chances are very high that braking is necessary. Braking causes the car to rotate a bit, so the stability analysis of the car could be combined with a controller to accomplish a nice distribution of the brake efforts in the four wheels. With as goal preventing less down-force due to the rotation of the car, allowing to brake harder before losing grip resulting in a shorter braking distance. In some emergency situation it can be helpful to have slip of the tires to control the yaw angle of the vehicle very fast and in other situations slip is undesirable, so in order to have the best control over the vehicle the ABS, ESC and autonomously driving should be working together.

This report is mainly about a control algorithm for ABS that uses only torque information. The main purpose for only using torques is because an electric motor can be torque controlled and this fits the best with other systems like torque vectoring, which is the distribution of the torques to each wheel [5]. Another benefit is that the actual torque can be obtained from electrical current measurements through the electric motor, which makes the use of extra sensors unnecessary. Also the conventional hydraulic ABS system gives an unpleasant stuttering feel in the brake pedal, which could be more smooth.

The problem definition is given in the following section. In section 3 the control algorithm for the ABS is described in which also the results of an one wheel simulation are presented, followed with a discussion. In section 4 the control algorithm is implemented and integrated with ESC in a full car model, and the results of various simulated slip scenarios are presented, followed with a discussion. In respectively section 5 and 6 the overall conclusion and recommendations are given. Section 7 contains the appendices.

2 Problem definition and orientation

In the current ABS controllers use speed sensors in all wheels and when one of the wheels has a significantly different speed than the others the ABS will apply. For the new ABS controller the speed sensors will no longer be used as only the estimated torque will be used to determine slip.

The friction between the tire and the road depend on the slip ratio, the fiction combined with a down force and a wheel radius will determine the actual torque transfer between the vehicle and the road.

The objective for the control logic is to keep the wheels from getting locked up and to maintain the traction between the tire and the road optimal. The latter is rather complicated as the friction-slip curve depends on the road, tire and vehicle. Despite the different conditions, the similarity is that there is an optimal slipping point at which the friction is the highest. The slip ratio s is defined as in equation 1 [6].

$$s = \frac{v - \omega \cdot r}{v} \tag{1}$$

In which v denote the velocity of the vehicle, ω the angular velocity of the wheel and r the radius of the wheel. In normal driving conditions $s = 0$, while an optimal slip ratio during braking depends on the road conditions, but it is in the region of $s = 0.1$.

The following makes the design of a ABS controller challenging:

- For optimal performance, the controller must operate at an unstable equilibrium point
- Depending on road conditions, the maximum braking torque may vary over a wide range
- The tire slippage measurement signal, crucial for controller performance, is both highly uncertain and noisy
- On rough roads, the tire slip ratio varies widely and rapidly due to tire bouncing, brake pad coefficient of friction changes
- The braking system contains transportation delays which limit the control system bandwidth.

Furthermore the control problem is a highly a non-linear control problem due to the complicated relationship between friction and slip. Another difficulty in this control problem is that the linear velocity of the wheel is not directly measurable and it has to be estimated. Friction between the road and tire is also not readily measurable or might need complicated sensors.

In order to get rid of all the complex parameters like the unpredictable road conditions and actual linear speed of each wheel, the new braking strategy uses torque measurements for the ABS controller. This torque measurement, referenced as actual torque is a direct measure of the transfer between the wheel and the surface. From the changes in the difference between the requested and actual torque it can be determined if a wheel is slipping, more over the optimal torque can also be obtained regardless of the road conditions.

- Actual torque: the measured torque so the actual torque transfer between the tire and the road surface.
- Requested torque: the torque which is demanded from the actuators, it is the output of the controller.
- Braking torque: the response of the actuator models from the requested torque, i.e. the torque which is applied to the wheels.

3 Controller synthesis

3.1 Introduction

For the new braking strategy the change in torque is used for control. For example when braking with 200 [Nm] and suddenly the friction of the road changes, and the measure torque reads 100 [Nm] because the wheels are slipping. Without ABS the motor controller will try to increase the torque back to 200 [Nm], leading to more braking which makes the slipping even worse.

A control algorithm is needed to determine when and by how much the torque should increase or decrease in order to maintain an optimal slip ratio. The torque can be estimated by measuring the current through the electric motor [3]. Although the algorithm described below works with certain thresholds, it is extremely important that this signal is filtered in order to obtain a signal which does not contain false indications of a increase in torque or a decrease in torque, as the algorithm depends on the derivative of this signal. In this report the focus lies on the algorithm itself and therefore the filtering of the signal is a not further elaborated.

3.2 Two phase algorithm

As mentioned the optimal slipping point is a very unstable point, furthermore when a wheel is starting to lock up it only needs a pulse in which the braking is released to get grip again. To accomplish the this, one could try to control the derivative of the torque to zero with normal feedback control the control. In the case of an ABS application this will lead to unwanted behaviour or a very unstable system, as the control action could get very big. More importantly when changing the road surface during a brake the sign of the error alone does not tell if the torque has to increase or decrease. Due to slow response of the actuator and tire dynamics controlling the derivative of the torque with feedback control is not suitable.

The way in which an algorithm could detect increasing or decreasing slip is as follows. By lowering the requested torque the resulting actual torque will at first instant decrease, after some point the actual torque will increase this indicates that the slip is reducing, the requested torque needs to decrease more until the actual torque starts to decrease again which indicates that the optimal slip ratio has reached. At this point the requested torque can be increased again, at first there will be no increase in the actual torque but after a while the actual torque starts to increase. When the actual torque starts to decrease, it is time for the requested torque to be lowered again.

So in order to guaranty fast responses as well as stability a controller based on fuzzy logic rules is used. The goal of this controller is to maintain at the optimal slip ratio, this is accomplished by determining if the torque should be increased or decreased, and by how much. One phase is to increase the torque and the other phase is to decrease the torque. The algorithm will be in the increase phase when the slip is lower than the optimal, and in decreasing phase when the slip is higher than the optimal slip. It is not easy to determine the amount of increase and decrease in torque, because it depends highly on the friction between the tire and the driving surface. When this friction is constant during a brake it is possible to regulate the torque, but when the friction suddenly decreases it becomes far more difficult to determine how much the torque should be reduced, as the wheels get almost instantly locked.

Before it is possible to control the braking torque to maintain an optimal slip ratio, first initial braking is needed. This could also be done with the increase phase, but then it would take longer than necessary to reach the desired braking torque. The initial phase is used to get fast to the required braking torque, when this certain braking torque is reached the algorithm switches between the increasing and the decreasing phases in order to maintain the optimal torque which correspond with the optimal slipping ratio.

At NEVS already some effort was put into an algorithm which decides the current phase based on the current torque, this algorithm is depicted in figure 3.1. In the initial state the maximum braking torque is registered and stored in a variable $T_{temp} = max(T_{max} T_{current})$ if the current torque is smaller than $T_{temp} - \Delta T$ than the phase is switched from initial to decrease, ΔT is introduced in order to prevent false triggering. In the decrease phase again the maximum torque is stored in the variable $T_{temp} = max(T_{temp,prev}, T_{current})$. By comparing the current torque with the temporary stored torque it can be detected that the optimal slipping point is passed again and that the phase need to be changed to increase phase. The same holds for changing from increase to decrease phase. By the comparing of the current torque with the temporary torque the addition that the derivative of the torque needs to be below a certain value is added to exclude false triggering of a phase switch.

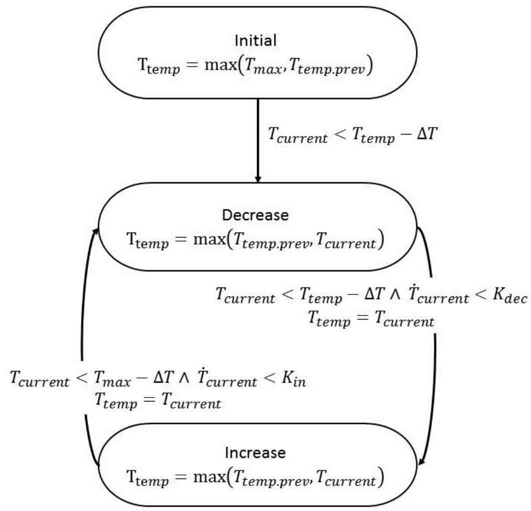

Figure 3.1: State machine control

A drawback of this algorithm is that it will only work properly when the friction of the road surface is constant, a change in friction will lead to a detection of the wrong phase, so it will either cause the wheels to lock up, or to stop them from braking at all. To get more insight in how to deal with this problem the slip-torque curve and its derivative are of interest, they are depicted in figure 3.2. In this figure the optimal slipping point is denoted with a red circle furthermore it can be seen that when the derivative of the torque is negative the optimal slipping point has past. Note that in the initial phase the slip will gradually increase with time, so the friction versus time plot will look similar. The problem with the algorithm above arises when this slipping curve is not as expected, which is the case in real life when the road surface can change. Imagine a road with a sudden transition of road cover, in this case the torque-slip curve may look like as a combination of multiple slipping curves. In figure 3.3 some slipping curves for different roads are depicted. The presented algorithm will work when the current torque is on the same side of the maximum of both slip curves, but otherwise the switching will fail dramatically, leading to either a wheel lock, or no braking at all. Figure 3.4 illustrates this problem in more detail. In order to overcome this problem some additional adjustments had to me made to the algorithm in order to get rid of these issues. With a certain threshold the algorithm will be able to choose the right phase, as it will not trigger the switching algorithm for small changes in the road surface. To make the controller stable for bigger road surface changes, at first it looks for big changes in the torque which give away a false indication of that the optimal slip ratio is reached.

To overcome the problem of different optimal slip ratios, a check has to be performed in which will be decided whether the current phase is leading to a increase in grip or not. Another check is included into the algorithm that detects sudden road changes simply by detecting a high value of the torque derivative. This increase or decrease of the torque derivative gives a false indication for the algorithm that it has past the optimal slipping point, therefore the algorithm should not change the phase during this event.

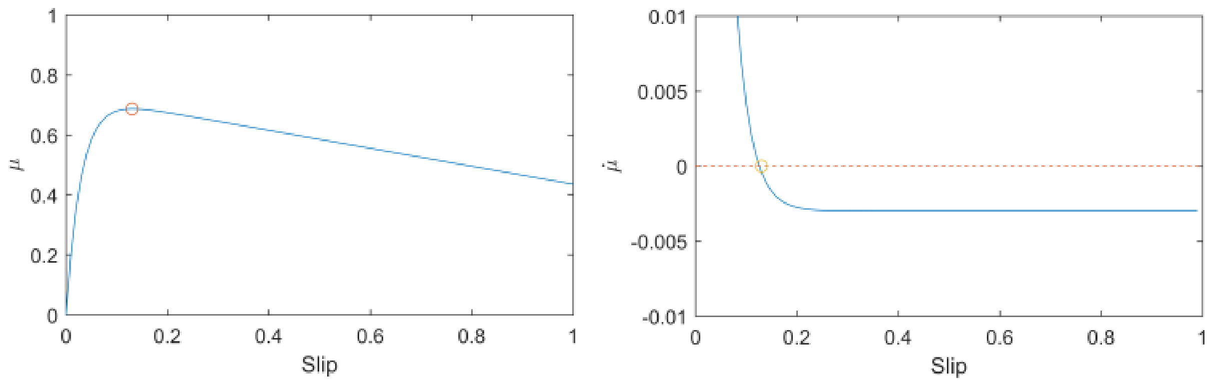

Figure 3.2: Relation between slip and torque, and the its derivative

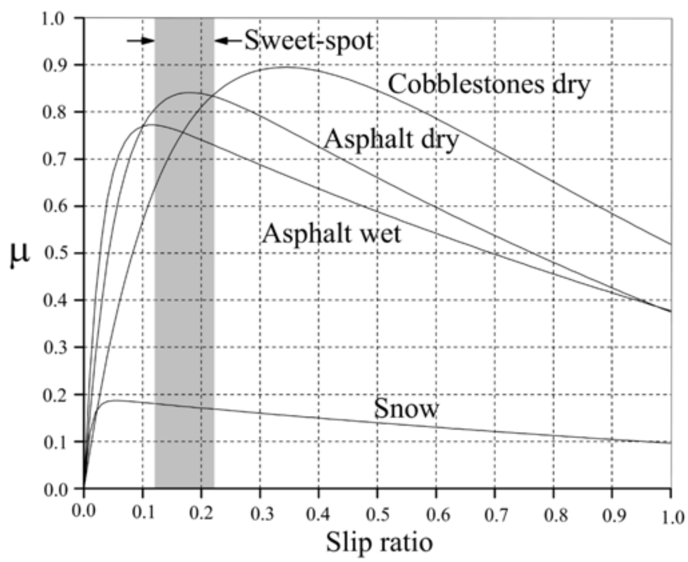

Figure 3.3: Slip-friction curves for multiple road conditions [7]

When during the brake the road changes ignoring the derivative will not lead to the correct phase in every situation, this is made clear with help of figure 3.4 in which the different possibilities for the slip curve are shown. The slip will increase when changing from high to low friction and decreasing when going from low to high friction, this is due to the inertia of the actuators. Therefore the lines are draw under an angle and not vertical, this creates more cases because when the lines are under a slight angle they can cross the optimal slipping point with should be encountered for. In other words: due to the response time of the actuators it happens that the slip increases a bit after that the phase has changed. The algorithm should be able to detect when this increasing of slip causes a passing of the optimal slipping point. There are seven different cases to distinguish which are denoted with $A - G$. In every case a high peak in the torque derivative can be detected, which indicate a big surface change.

Case A) The switch algorithm should not change the phase.

Case B) The optimum slipping point is reached due to slow response of the actuator, therefore the detection of the phase change will be false.

Case C) The switch algorithm should change the phase.

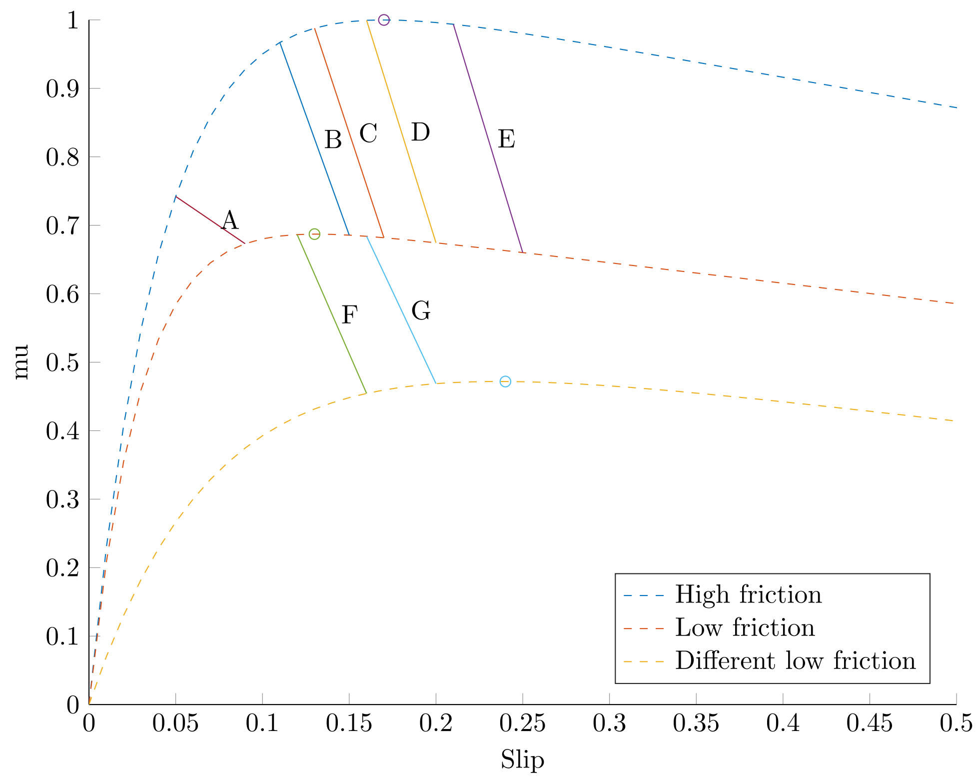

Figure 3.4: Slip-Friction curve travel routes

Case D) The optimum torque is reached due to tire dynamics or a slow response of the actuator.

Case E) The switch algorithm should not change the phase.

Case F) The switch algorithm should not change the phase, crossing an optimal slip ratio.

Case G) The switch algorithm should change the phase.

The difficulty and cause of the existence of the different cases lies in the fact that the optimal slip ratio is different for each friction curve. These cases will be described in more detail further on, first some strategy will be discussed. When currently in the increase phase, always go to the decrease phase if the derivative of the torque is strongly negative, and adjust the phase if it turns out to be the wrong phase. In this way stability is insured, because it is uncertain on which side of the optimal slip ratio peak the current torque is, it is better to maintain stability and reduce the slip towards zero, because there is the possibility to loose the grip completely. A false phase is detected by storing the torque as soon as the torque starts to decrease (detected optimum), and change the phase if the difference between the current torque and the stored torque is less than a certain negative value.

The actuators have some lag in them which causes problems, but the behaviour of the tires is also responsible for the lag in slip. Therefore increasing the torque will at first cause increasing grip and after some point it start to lose grip. A similar behaviour holds for decreasing the torque, at first this will cause losing grip and after some point the grip will increase. The reasoning above is the main cause for the need to distinguish the special cases B, D and F.

The implementation code of the algorithm in Matlab is given in the appendix in listing 1, it can be seen that there are a lot of if-statements, the main reason for that is debugging and tuning. To be able to make the tuning of the controller not to difficult a new if statement is created for every state of the wheel, in this way it is clear what the algorithm does at which point. The algorithm outputs a “foo number” which indicates this state, the meaning of these numbers will be explained further on.

3.3 Increase and decrease controllers

In this section a solution is given to the question how much the requested torque should be increased or decreased. Initial the torque is controlled as in equation 2

$$\tau_{requested} = C \cdot (\dot{\omega}_w - \dot{\omega}_v) \tag{2}$$

In which C is the controller, $\dot{\omega}_w$ the angular acceleration of the wheel and $\dot{\omega}_v$ the angular acceleration of the vehicle. For the controller a static gain is chosen $C = kp$. By taking the difference between the acceleration of the wheel and the acceleration of the car the control action will be reduced when it comes closer to the optimal slipping point.

However during testing with simulations it became clear that for hight torques a higher gain was leading to less deviation in slip from the optimal slip. So instead of using the control law above the control law is based on the actual torque with a gain and an addition as shown in equation 3. In this way also the statement of only using torques information is honored.

$$\tau_{requested} = C \cdot \tau_{actual} + K_a \tag{3}$$

3.4 Tuning

There are two parameters for the phase decision algorithm that can be tuned, i.e. one being a threshold for detecting an increase or decreasing torque and another for detecting increase or decreasing torque due to surface change. Both parameters are a certain threshold for the derivative of the torque. The latter one should be chosen significantly larger than the first one.

A disturbance e.g. due to a bump in the road can also chance the measurement of the actual torque, therefore the first threshold has to be high enough to ensure that the optimal slipping point has indeed been reached. On the other hand as the threshold is increased the performance of the braking will be reduced and if the threshold is too high the detection of a phase change will be too late and the wheels will lock up.

If the front wheels experience a disturbance from controlling the rear wheels, the algorithm might detect a wrong phase, leading to less efficient braking. Therefor a distinction in the control gain between front and rear is made to minimize the disturbance to front wheels when controlling the rear wheels, as most of the braking is done by the front wheels it is important that they keep braking the most efficient.

The tuning of the increase and decrease controller all comes down to finding the optimal value for K_p. For the increase controller the gain is $K_p > 1$. And for the decrease controller the gain is $K_p < 1$. A distinction is made between the controllers acting on the front and the rear wheels. The tuning of the addition k_a determines the relation between the control action for high and low torques, and is set to $K_a = 10$. The increase gain for the front is set to $K_p = 1.15$, and for the rear to $K_p = 1.1$, the decrease gains are both set to 0.85.

3.5 Quarter car model

Using longitudinal vehicle dynamics a model describing a vehicle as in equation 4 can be made [8].

$$m\ddot{x} = F_{xf} + F_{xr} - F_{aero} - R_{xf} - R_{xr} - mgsin(\theta) \tag{4}$$

In which:

$$\begin{aligned}
F_{xf} &\text{ is the longitudinal tire force at the front tires}\\
F_{xr} &\text{ is the longitudinal tire force at the rear tires}\\
F_{aero} &\text{ is the equivalent longitudinal aerodynamic drag force}\\
R_{xf} &\text{ is the force due to rolling resistance at the front tires}\\
R_{xr} &\text{ is the force due to rolling resistance at the rear tires}\\
m &\text{ is the mass of the vehicle}\\
g &\text{ is the acceleration due to gravity}\\
\theta &\text{ is the angle of inclination of the road on which the vehicle is traveling}
\end{aligned} \tag{5}$$

In the used model only the tire forces are implemented, rolling resistance and aerodynamic drag is neglected. Furthermore it is assumed that the vehicle is always in a horizontal position. Therefore equation 4 can be simplified as given in equeation 6. This equation can be easily changed to torques by multiplication with the wheel radius.

$$m\ddot{x} = F_{xf} + F_{xr} \tag{6}$$

During a simulation the wheel speed and vehicle velocity are calculated every step. From this the slip is calculated as defined in equation 1, this slip ratio is used in a friction estimator to estimate the friction between the tire and the road. The friction multiplied with a quarter weight of the car and wheel radius results in the the tire torque of one wheel, which is the same as the actual torque.

The following friction estimators as function of the slip-ratio s are used, the corresponding curve of these estimators are the same as depicted in figure 3.4:

$$\begin{aligned}
\mu_{high} &= \frac{1.28 \cdot (1 - e^{-s \cdot 23.99}) - 0.52 \cdot s}{1.17}\\
\mu_{intermediate} &= \frac{0.86 \cdot (1 - e^{-s \cdot 33.82}) - 0.35 \cdot s}{1.17}\\
\mu_{low} &= \frac{0.66 \cdot (1 - e^{-s \cdot 13.82}) - 0.35 \cdot s}{1.17}
\end{aligned} \tag{7}$$

The algorithm is tested on a quarter car model, the results are shown in the figures 3.7 until 3.19. In this quarter car model a vehicle starts at a certain speed and than applies full braking. In order to make it easy to see the current state of the algorithm, the foo numbers are plotted in the requested torque versus slip figures. For the same reason the phase, which indicate a decrease or increase control action are depicted in the actual torque versus slip figures, with a green triangle for increasing and a red triangle for decreasing. Note for preventing confusion that the numbers are shown at the right hand side of the line.

List which contains the description the foo numbers.

1. Detection of a sudden less friction during decrease phase
2. Decrease phase and decreasing slip
3. Detection of the optimal slip ratio during decrease phase
4. Decrease phase and increasing slip
5. Detection of a sudden less friction during decrease phase
6. Increase phase and increasing slip

7. Detection of the optimal slip ratio during increase phase
8. Increase phase and decreasing slip
9. Detection of a sudden change in friction during initial phase
10. Detection of the optimal slip ratio during initial phase
11. Stay in initial phase
12. Detection of a case A or B
13. Detection of a sudden more friction during increase phase
14. Detection of a case D or E
15. Detection of a sudden more friction during decrease phase
16. -
17. End of case A
18. No increasing of friction detected during decrease phase

The algorithm is tested for every case from figure 3.4 and the results are given in the results section in the form of a torque-slip curve. Also some time domain figures are given to give some more insight in what is going on.

3.6 Results

The results of the algorithm operating on a quarter car are given in the figures below, the first two figures show the torques against the time, the remaining figures show the algorithm for every case $A - G$. In these figures the requested torque is the torque which the controller request from the brake actuators, and the torque between the tire and the road is denoted with the actual torque.

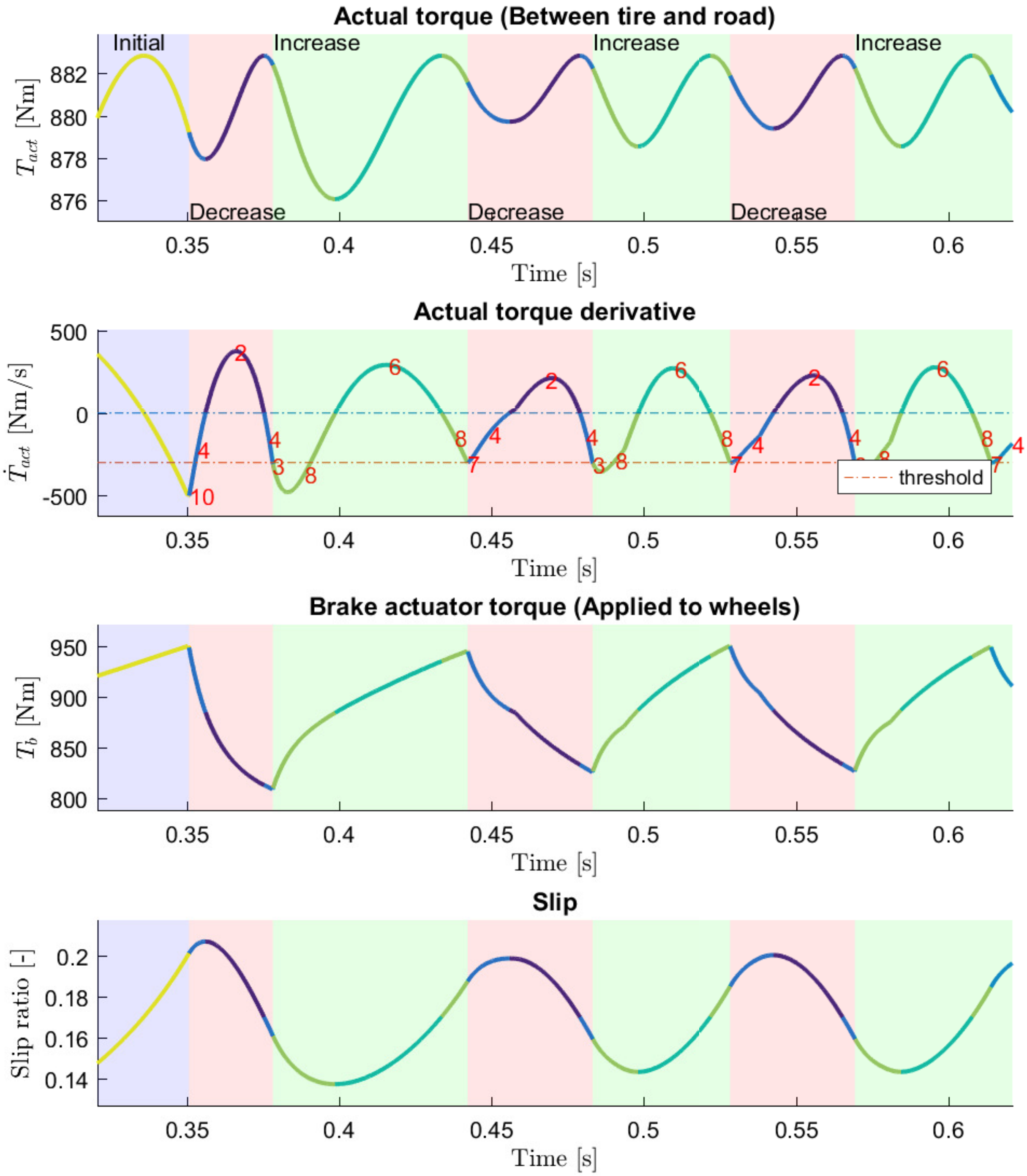

Figure 3.5: Phase decision from torque derivative

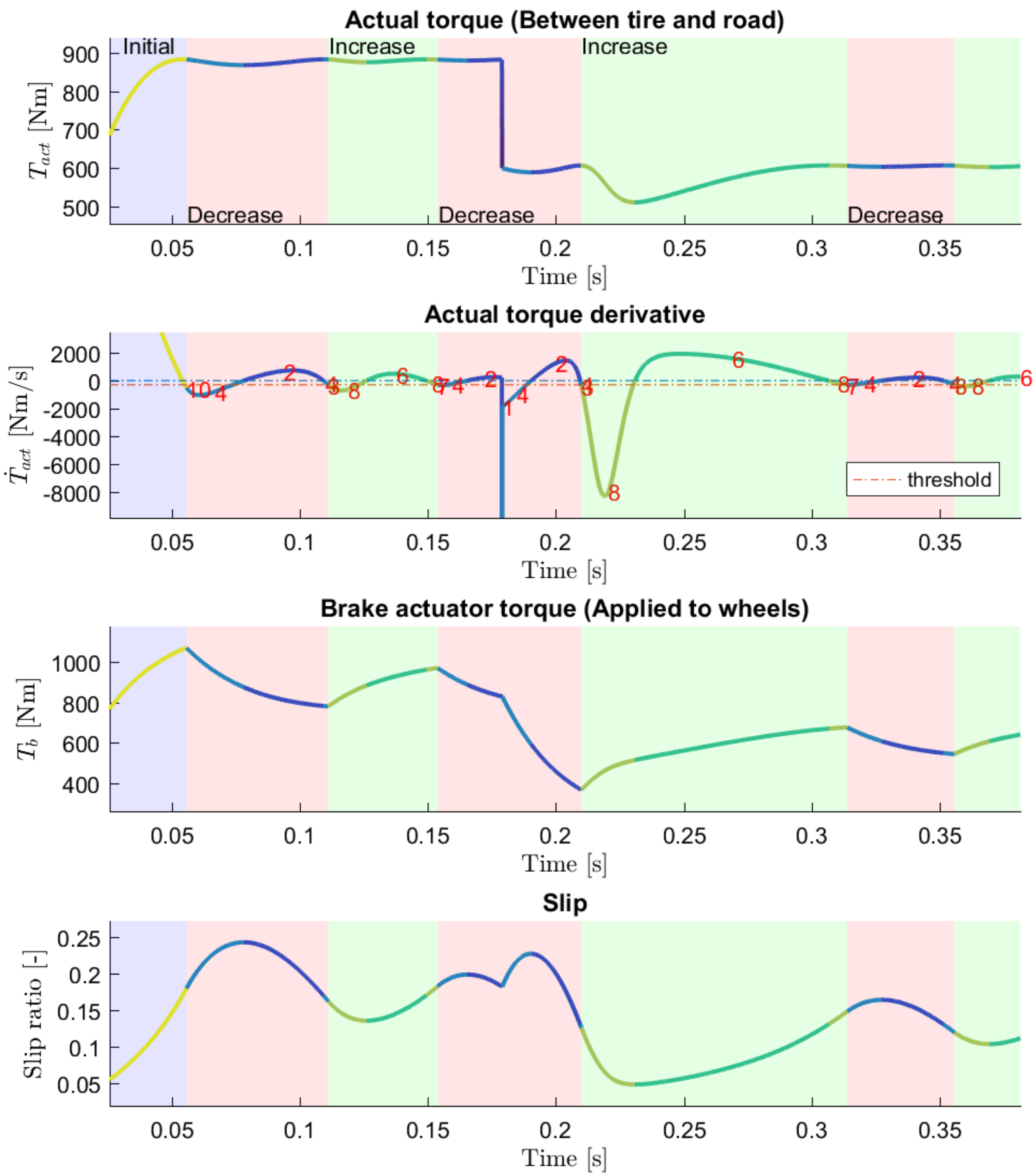

Figure 3.6: Phase decision from torque derivative

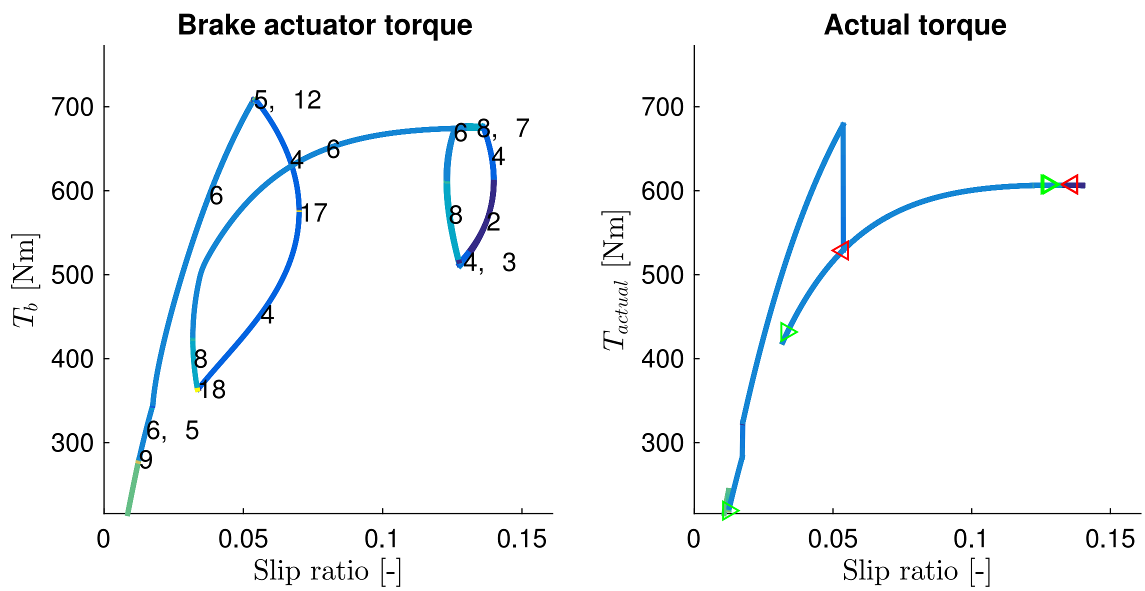

Figure 3.7: Troque-Slip curve case A, high to lower friction

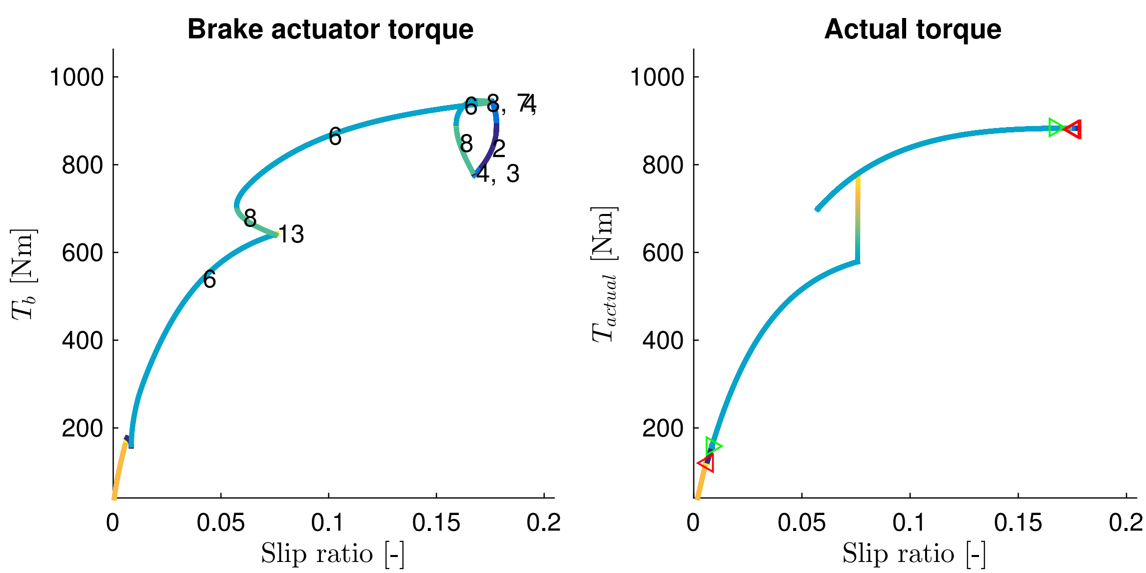

Figure 3.8: Troque-Slip curve case A, lower to high friction

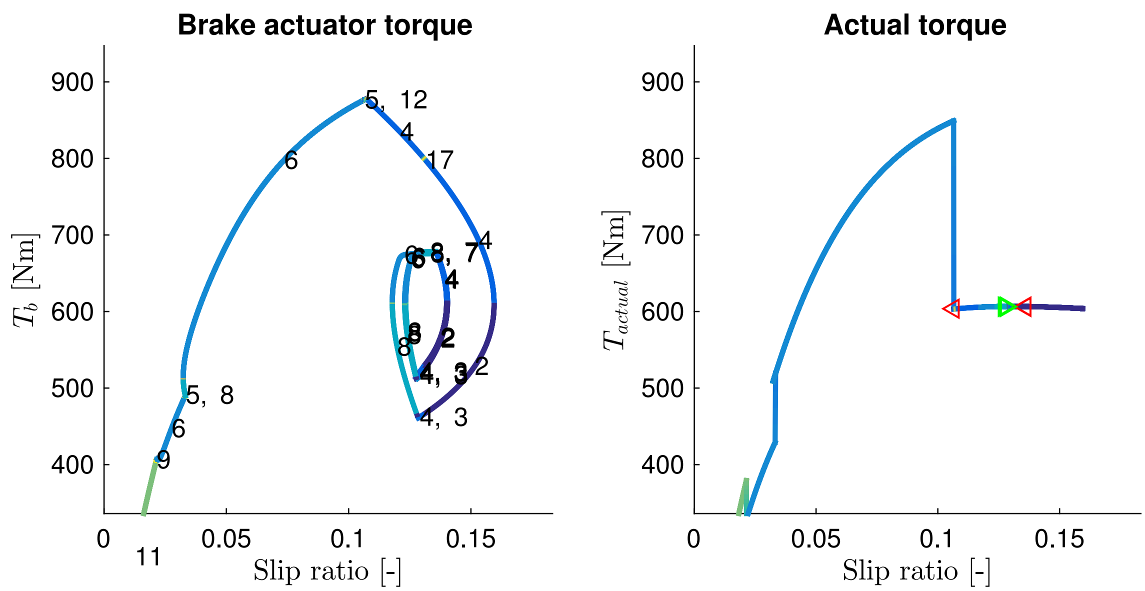

Figure 3.9: Troque-Slip curve case B, high to lower friction

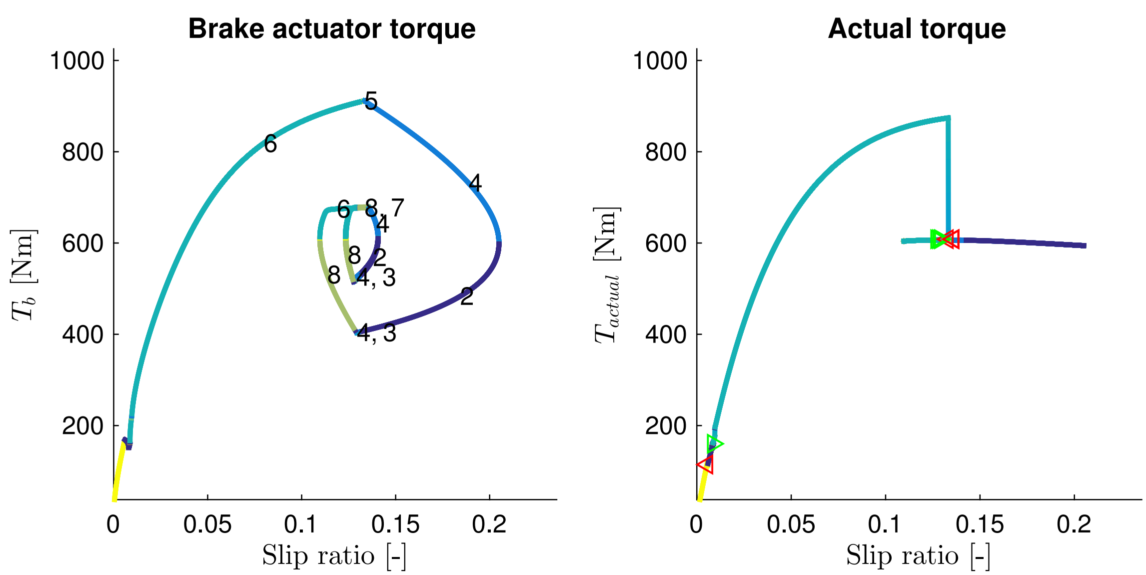

Figure 3.10: Troque-Slip curve case C, high to lower friction

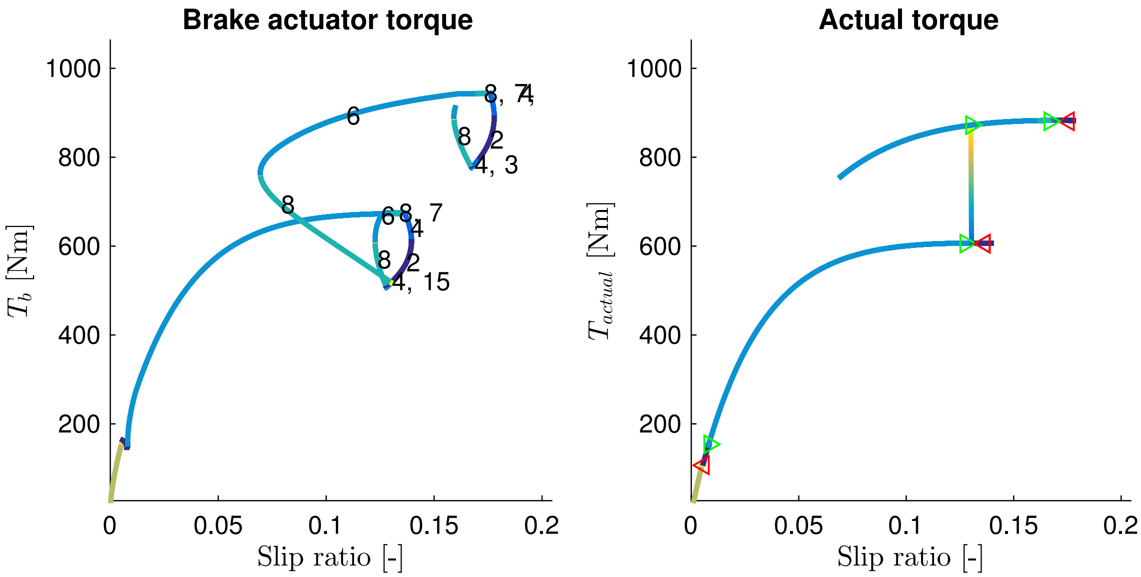

Figure 3.11: Troque-Slip curve case C, lower to high friction

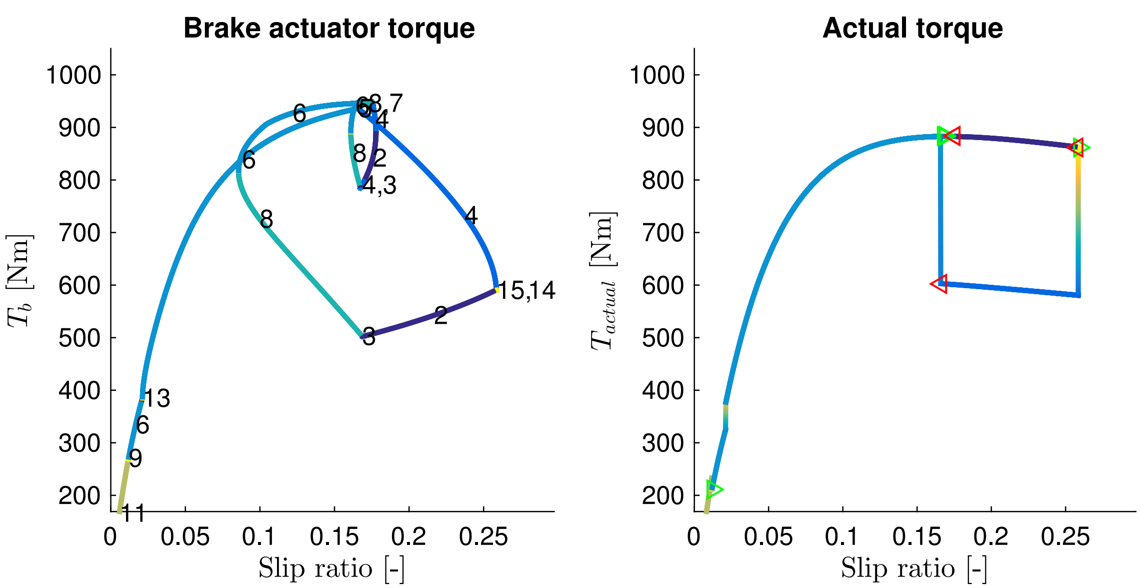

Figure 3.12: Troque-Slip curve case D, high to lower friction

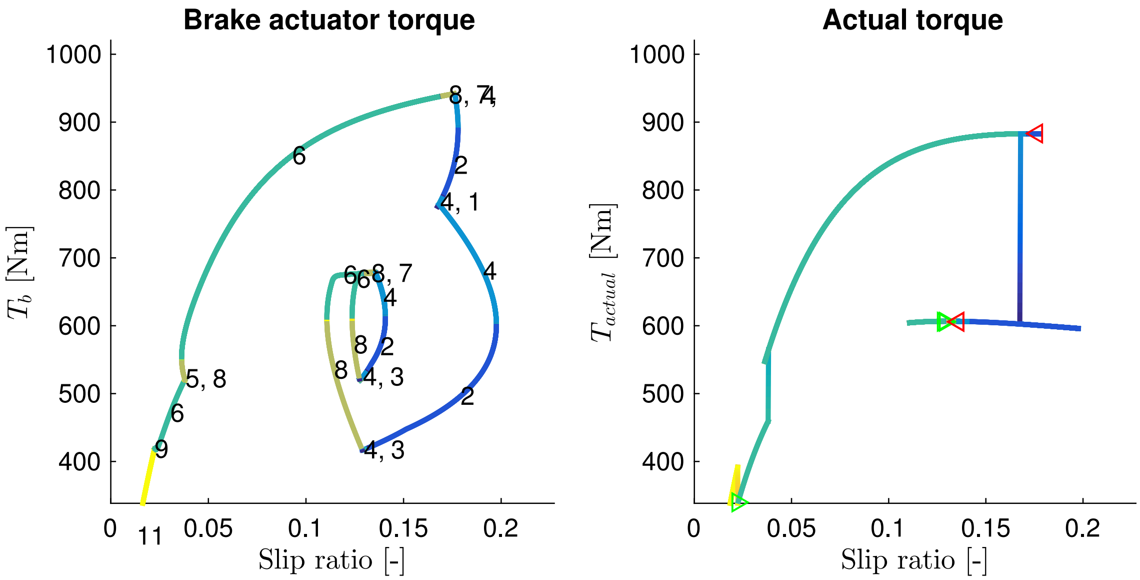

Figure 3.13: Troque-Slip curve case E, high to lower friction

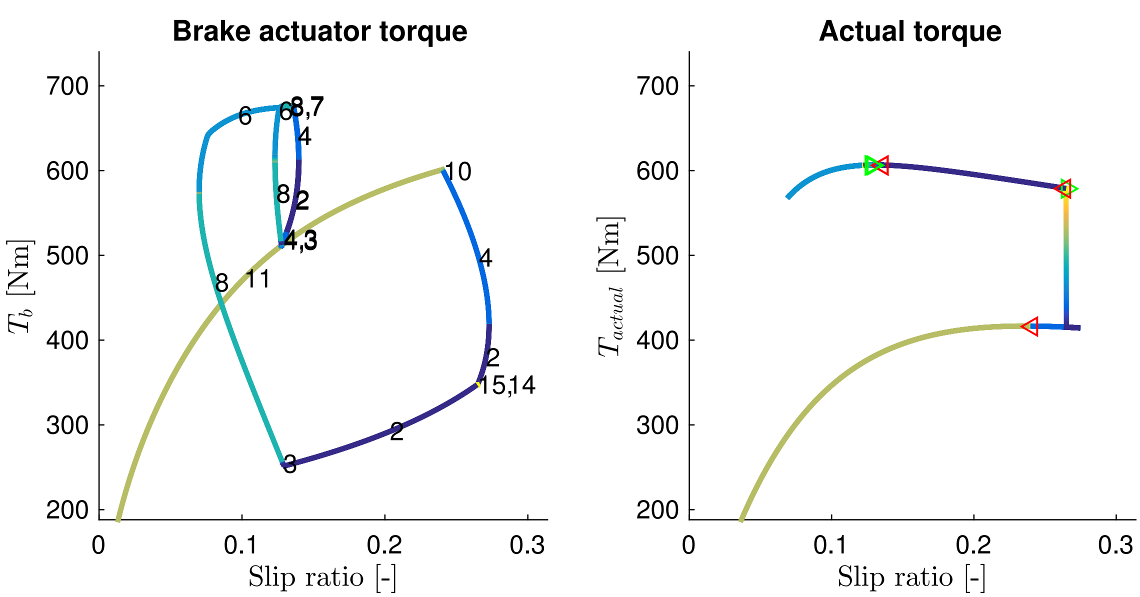

Figure 3.14: Troque-Slip curve case E, lower to high friction

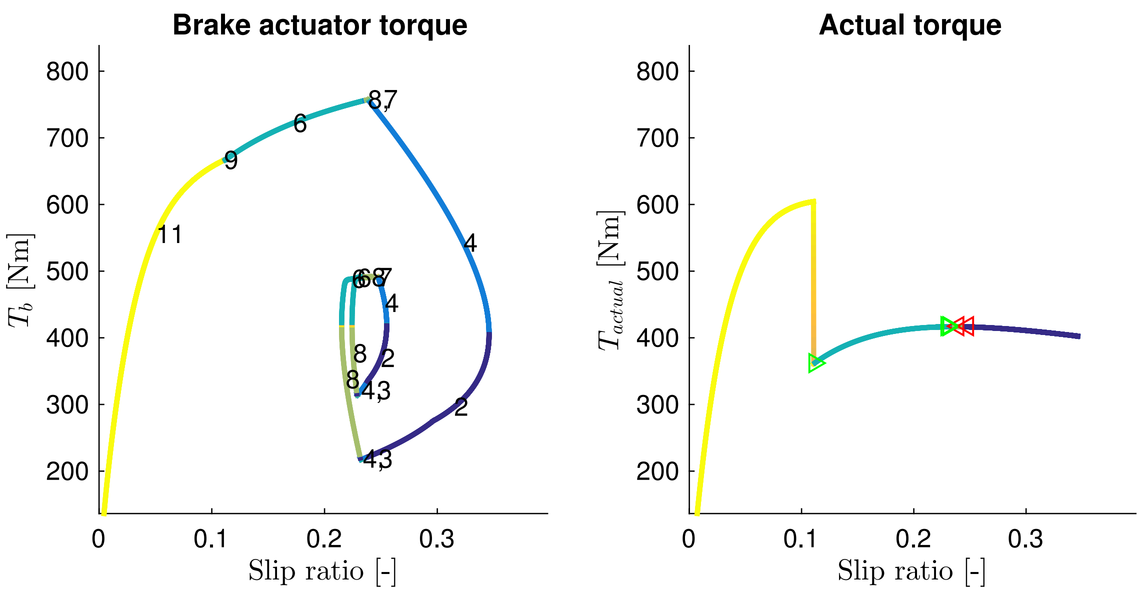

Figure 3.15: Troque-Slip curve case F, high to lower friction

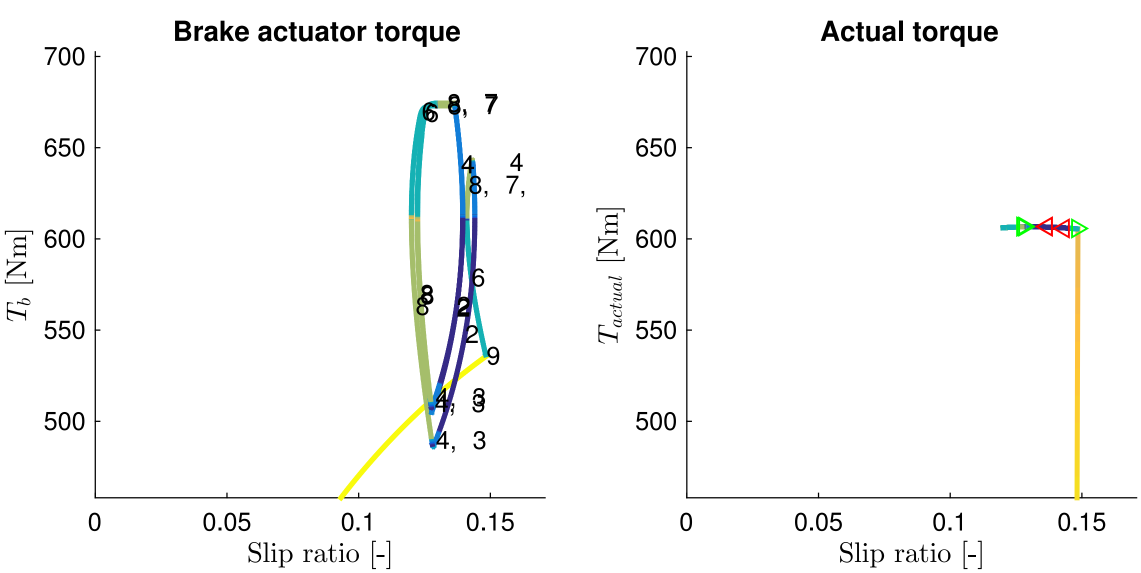

Figure 3.16: Troque-Slip curve case F, lower to high friction

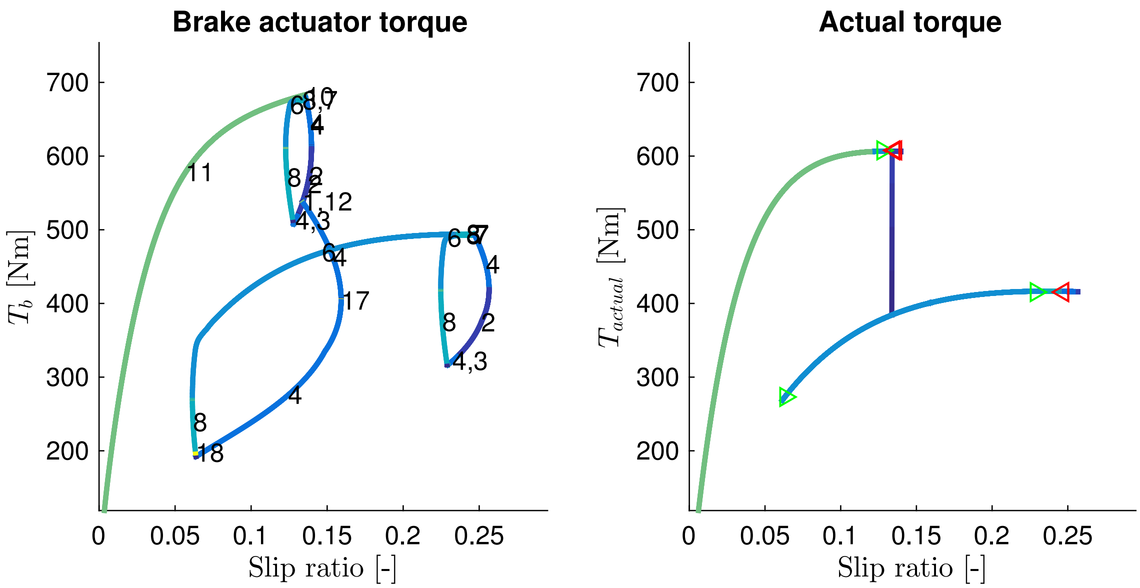

Figure 3.17: Troque-Slip curve case G, high to lower friction

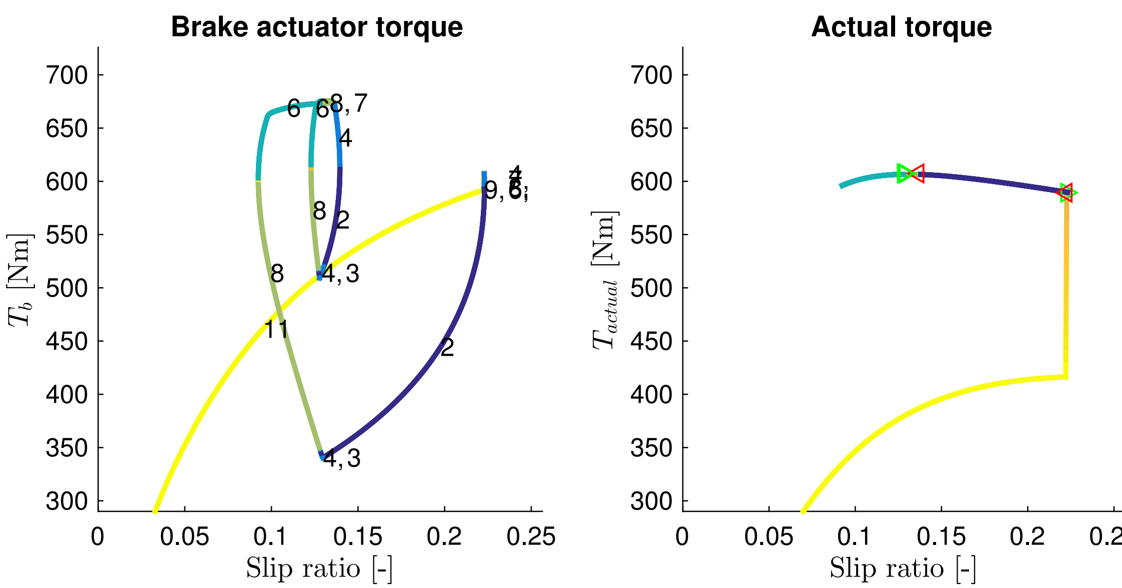

Figure 3.18: Troque-Slip curve case G, lower to high friction

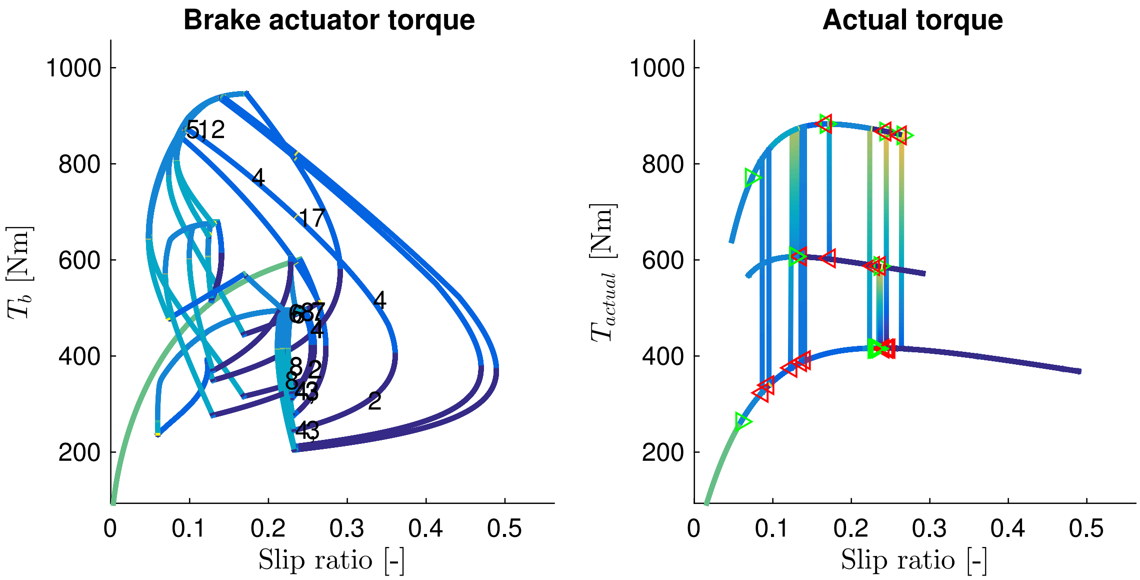

Figure 3.19: Troque-Slip curve case switchalot3, high to lower friction

3.7 Conclusion and discussion

The way in which the algorithm uses the derivative of the torque to make the phase decision is best shown in the time domain results i.e. figures 3.5 and 3.6. In figure 3.5 the road has a constant friction coefficient and in figure 3.6 the friction coefficient of the road drops around 0.17 [s].

With an initial brake torque it can be seen that the slip initially increases, and therefore also the actual torque. At a certain slip ratio 0.17 in this case, the actual torque starts to decrease, the optimal slipping point has reached. This is detected by the derivative of the actual torque passing a certain threshold, now the brake torque is decreased, as this decreasing is not in an instant the slip starts to increase a bit at this moment. The same holds when starting to increasing the brake torque again, it takes some time for the brake actuator to increase the braking and therefore to increase the slip. The threshold is free to choose, and it will influence the frequency at which the phase changes.

Due to the strategy to always go to the decrease phase when detecting a big change in the torque derivative, case B is only from high to low friction, as low to high is the same as in case C. The difference between case B and C is that in case B the torque suddenly decreases before the optimal slipping point of the low friction curve, in case B it is after this optimal slipping point. Similar but opposite to case B, case D is only from low to high friction, as high to low is the same as in case C. The difference between case D and C is that in case D the torque suddenly increases before the optimal slipping point of the high friction curve has reached, in case B this optimal slipping point has already been reached. In figure 3.17 and 3.7 a false phase is detected this can be seen at the appearance of number 18, also the number 4 before number 18 should indicate a increase in the slip according to the algorithm, but in the figure it can clearly be seen that the torque decreases. Therefore it can be said that foo number 18 maintains the stability of the algorithm here. In figure 3.19 it can be seen that the switching algorithm remains stable even when a lot of friction changes are present.

4 Integration with IPG Carmaker

4.1 Introduction

With the tuning of the control algorithm working on a quarter car model, the next task is to combine it with a full car model in the IPG Carmaker software. The model used is a backbone model which already contains the ESC functionalities and the conventional ABS functionalities. This conventional system had to be replaced with the new one, in order to do this some problems had to be solved which has to due with the differences between the ABS principles, therefore a short introduction about a conventional ABS is given first. The conventional braking system uses hydraulic pressure which is gained from the driver which has applied a force on the brake pedal. This pressure is amplified with the use of vacuum created by the engine. This amplified pressure is than transferred to the brake callipers at the wheels. As mentioned before the conventional ABS uses wheel speed sensors and vehicle speed prediction in order to determine the slip. This information is used in a modulator which controls the flow of the hydraulic fluid. In order for the ESC to work it needs to be able to brake the wheels without a driver which generates a pressure, therefore a hydraulic pump is needed.

4.2 Implementation of the torque braking method

The requested braking torque from the driver, the torque from the ESC and the torque from the ABS, has to be combined. The combined torque should follow the requested braking torque from the driver but may not exceed the torque determined by the ABS controller. The torque from the ESC is a correction torque to control the yaw angle of the vehicle. The implementation to work with the ESC works as follows. The ESC delivers forces which should be applied by the brakes, when braking the maximum braking force depends on the friction available, the vehicle already brakes with maximum torque so to be able to take the ESC contribution into account the forces should be added to the wheels on the other side of the vehicle. For example instead of braking more on the left side of the car, brake less on the right side. In this way the optimal slip ratio can be maintained and the yaw moment of the car can be controlled. As soon as the ESC demands action, the torques calculated by the ESC are simply subtracted from the current demanding torque which comes from the ABS controller, during this the torques from the ABS are neglected until the ABS calculates a torque which is lower than the previous demanded torques subtracted by the ESC torque. Note that each wheel still operates individually. Furthermore the optimal torque which is stored by the algorithm is reset when the ESC is active, in this way the mechanism of the algorithm to detect a wrong phase still works.

In the Carmaker program the vehicle which is used to do the simulations is picked randomly. Two test are performed, one in which the road friction changes in the same way for the left and right wheels, and the other in which the friction for the left wheel is always low, and for the right wheel it changes a couple of times between a low and a high friction. To test the performance of the two-phase algorithm it is compared with a build-in ABS controller from Carmaker which is denoted as Soft ABS.

Not only the friction for the left and right wheels are different, also in the driving direction the friction changes. So this test is a combination of a split mu and a mu change test. The results of the split-mu test are given in figures 4.11 until 4.18.

It is tested if the controller is capable of handling a road change which affect the same for the left and right side of the vehicle. The results are given in figures 4.1 until 4.8.

Also the Two Phase algorithm is compared with a Soft ABS controller from Carmaker. Where the Soft ABS controller needs the slip and wheel rotation speed information, the Two Phase controller only needs the torque to be functional.

4.3 Results

4.3.1 Change in friction

The results for the ability to deal with a change in friction, in the time domain for all four wheels, are given in the first four figures of this section. In the following four figures the same torque results are plotted against

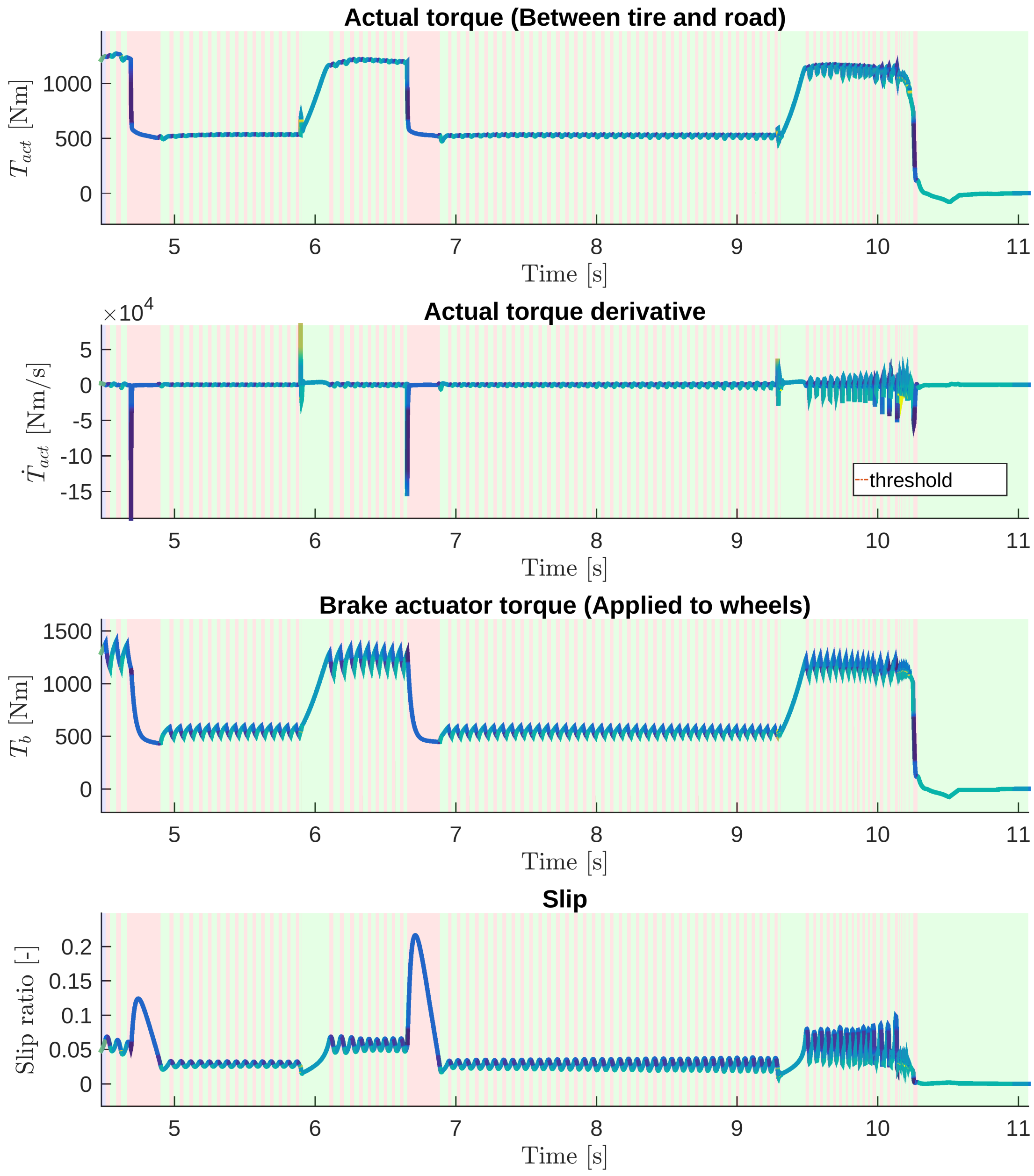

Figure 4.1: Torque and slip vs time, Front left

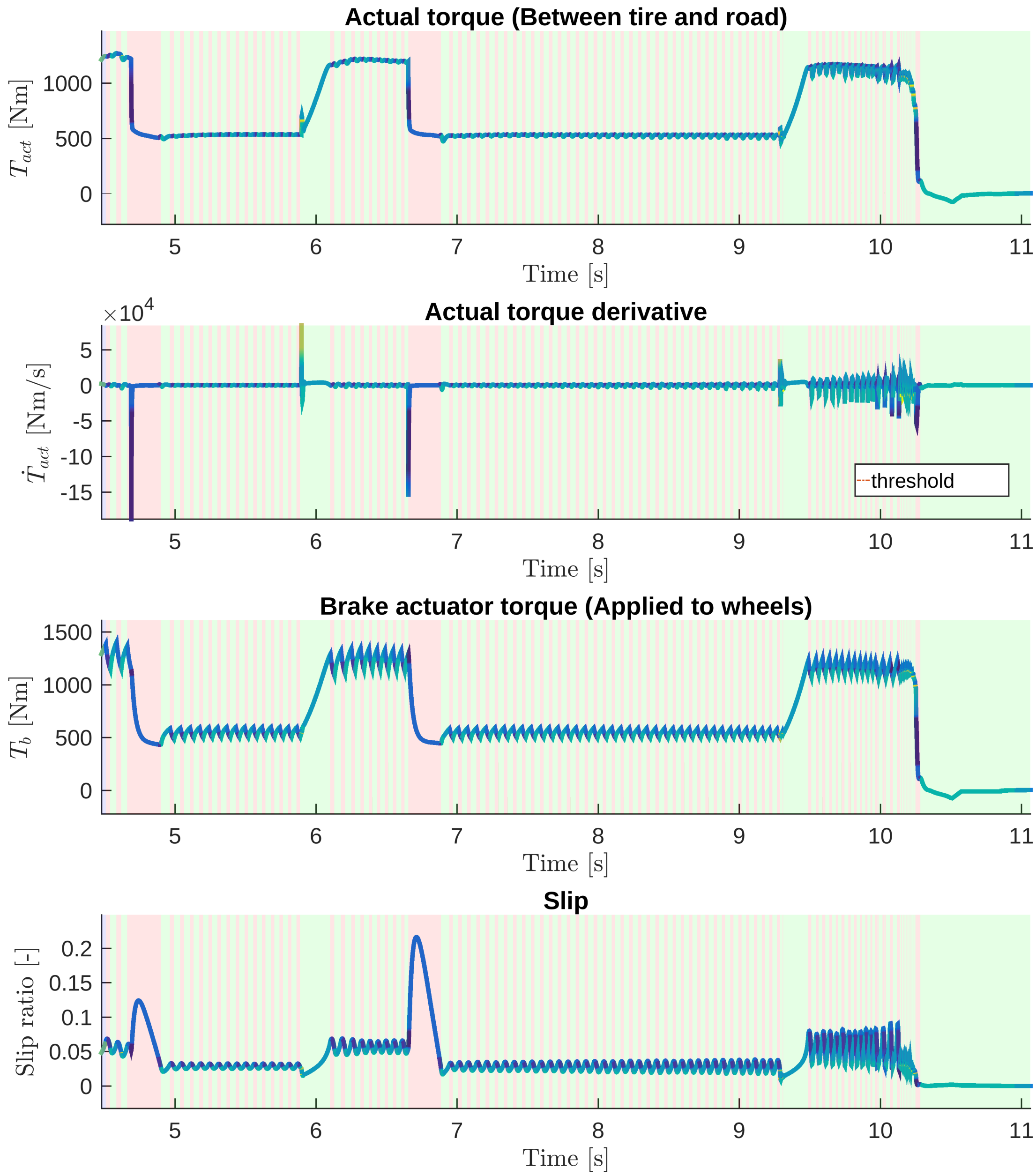

Figure 4.2: Torque and slip vs time, Front right

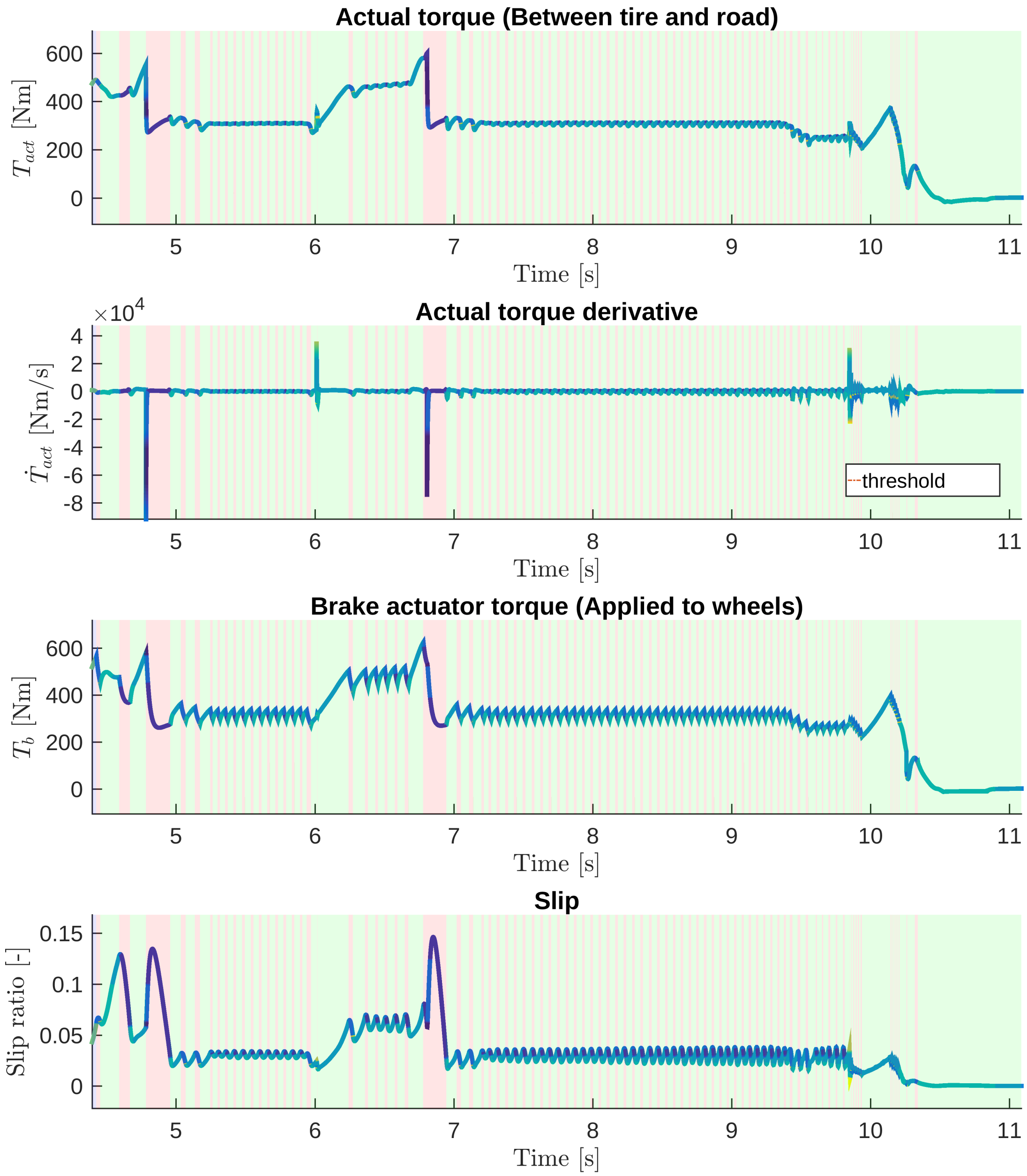

Figure 4.3: Torque and slip vs time, Rear left

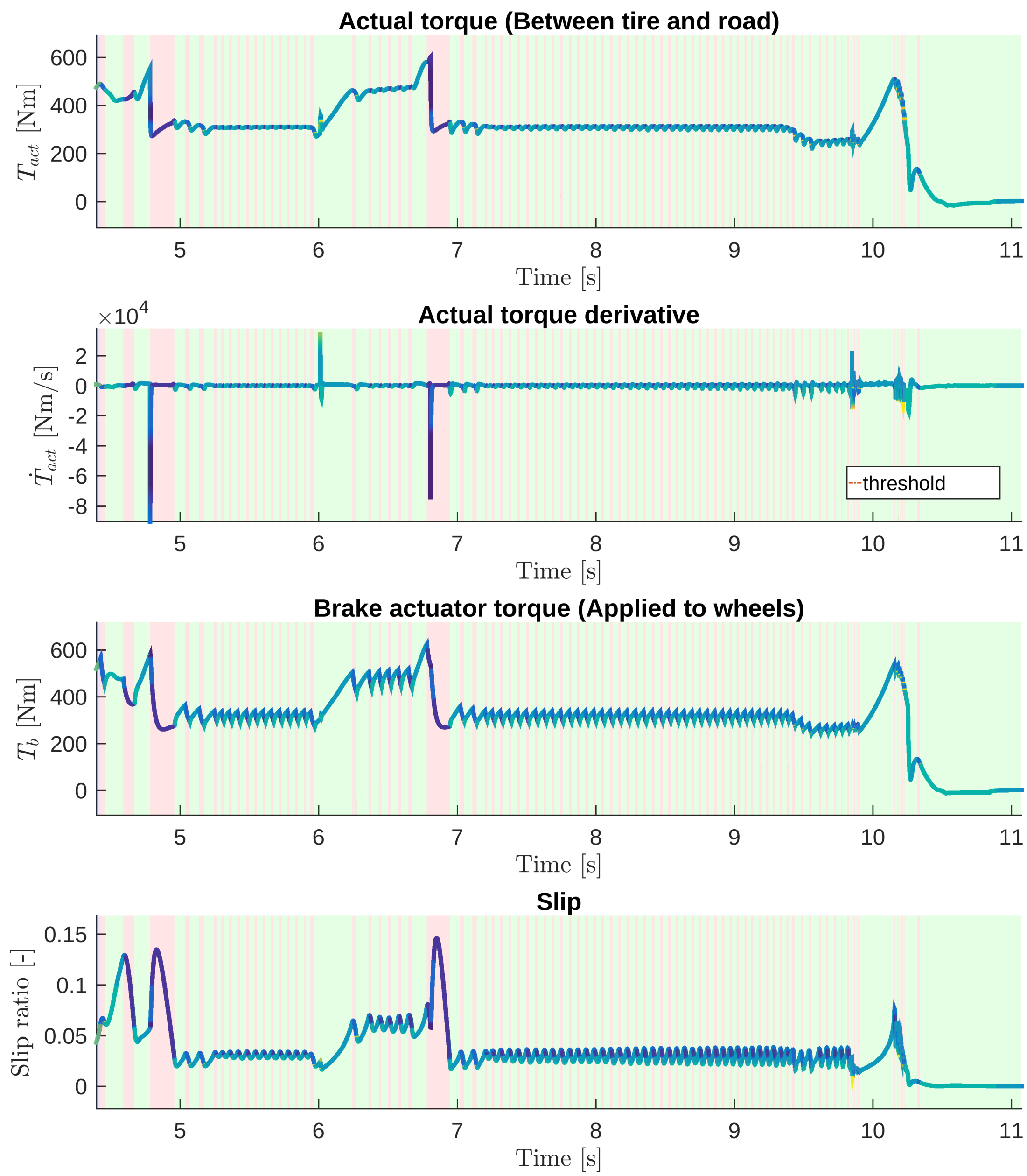

Figure 4.4: Torque and slip vs time, Rear right

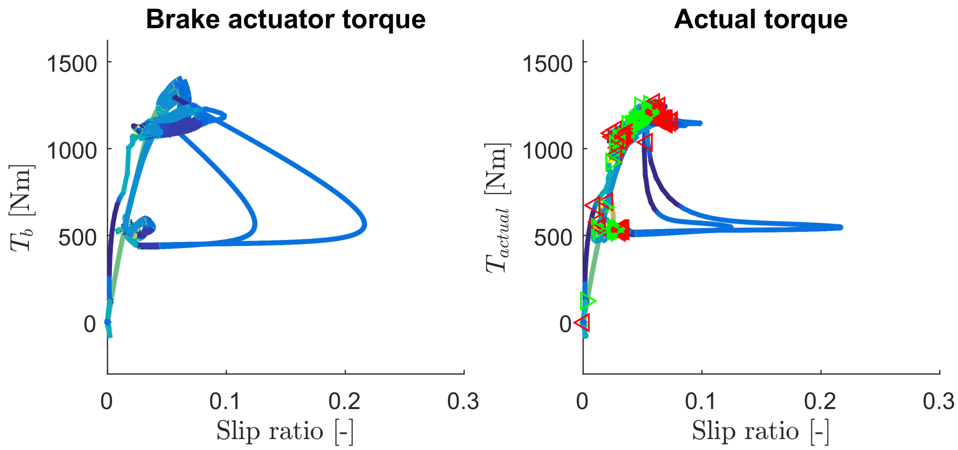

Figure 4.5: Slip vs torque Front left, multiple changes in friction

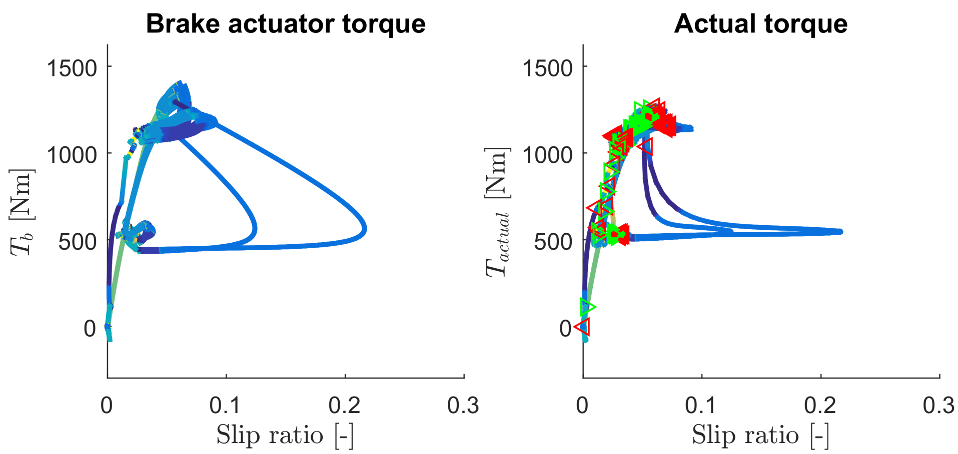

Figure 4.6: Slip vs torque Front right, multiple changes in friction

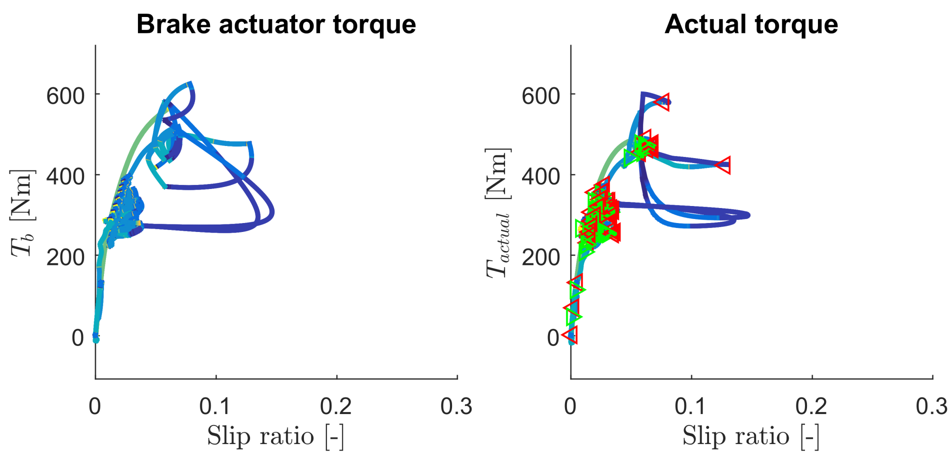

Figure 4.7: Slip vs torque Rear left, multiple changes in friction

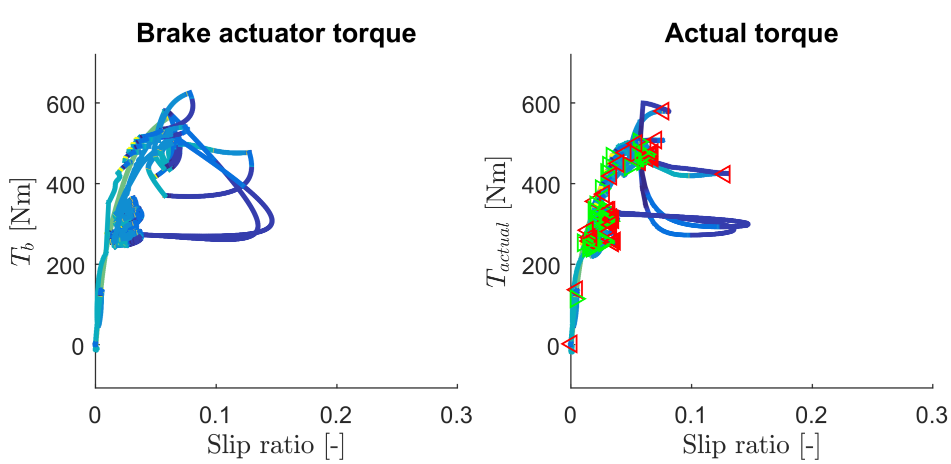

Figure 4.8: Slip vs torque Rear right, multiple changes in friction

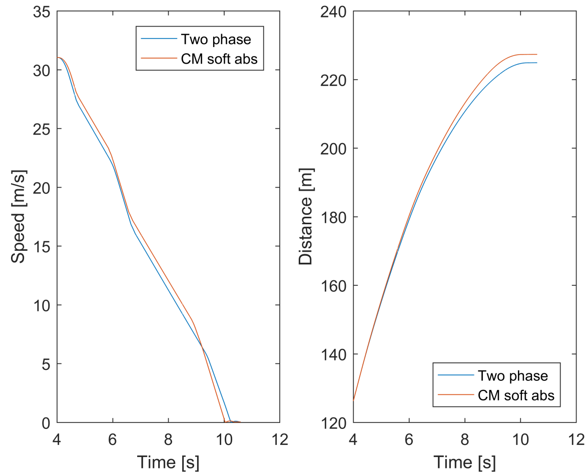

Figure 4.9: Comparison of speed and distance between two-phase abs and soft abs

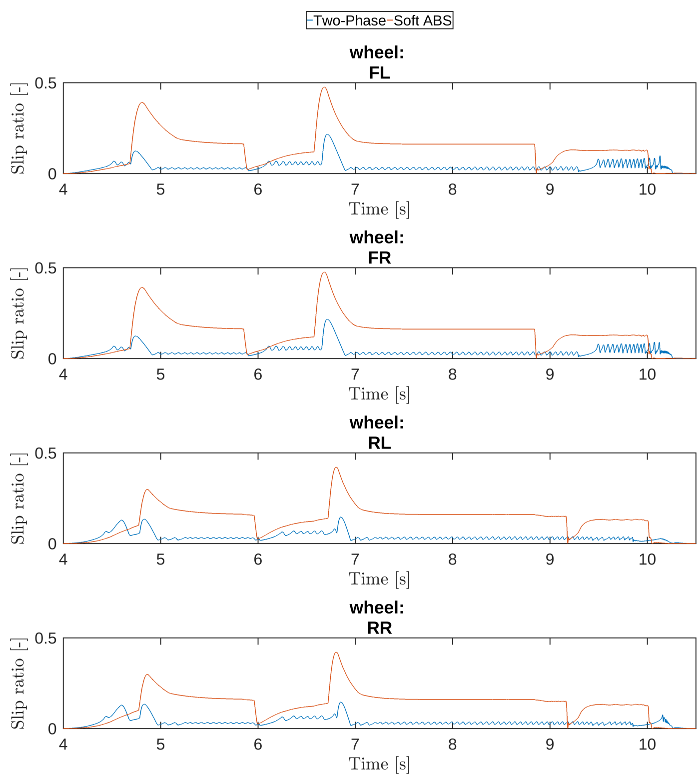

Figure 4.10: Comparing slip with Soft ABS versus Two Phase

4.3.2 Split mu

In the following figures the results for the integration with the ESC, for a split-mu case are given. Each figure represents a wheel. In the first four figures of this section the torques are plotted against the time, in the

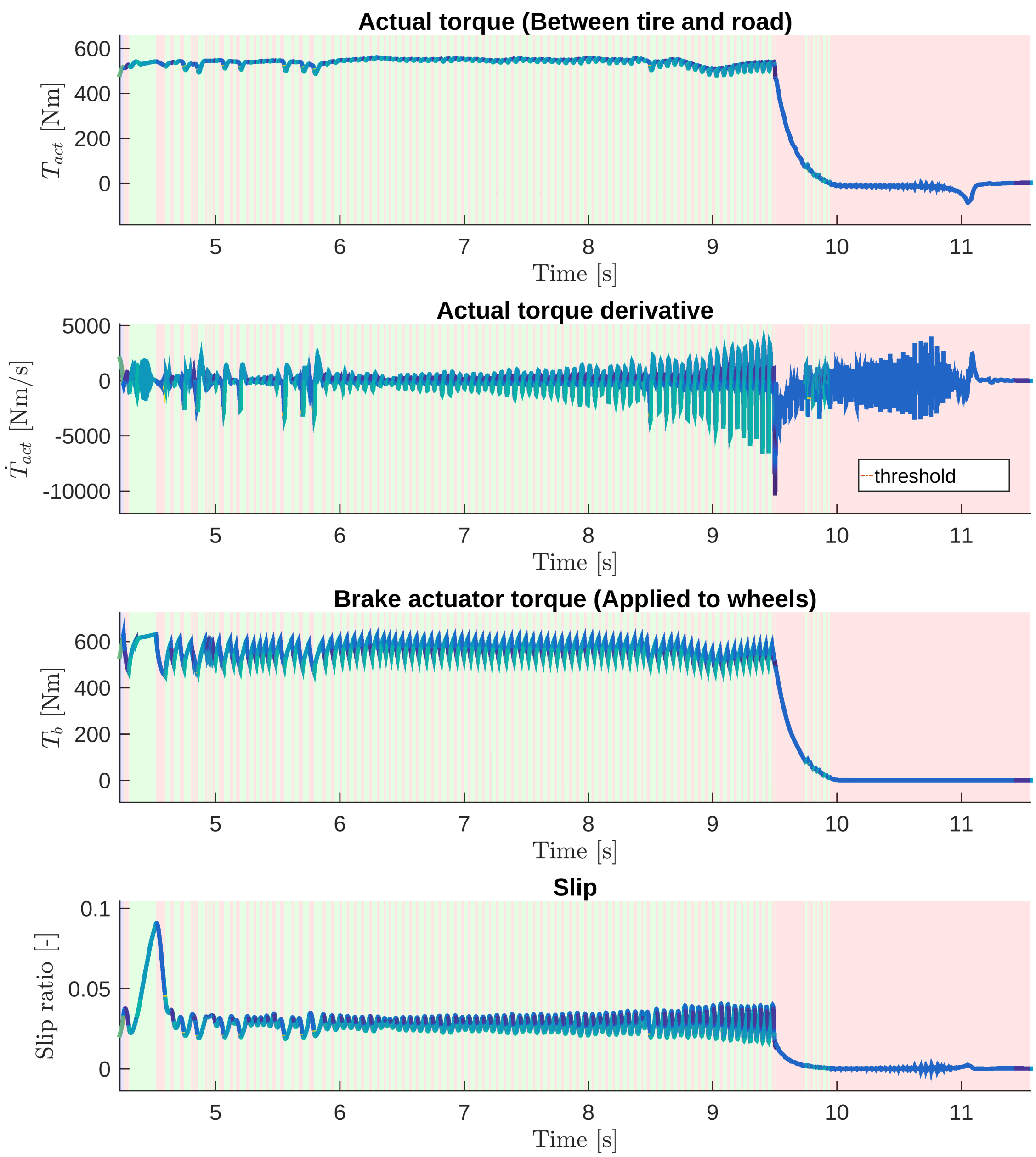

Figure 4.11: Torque and slip vs time, Front left

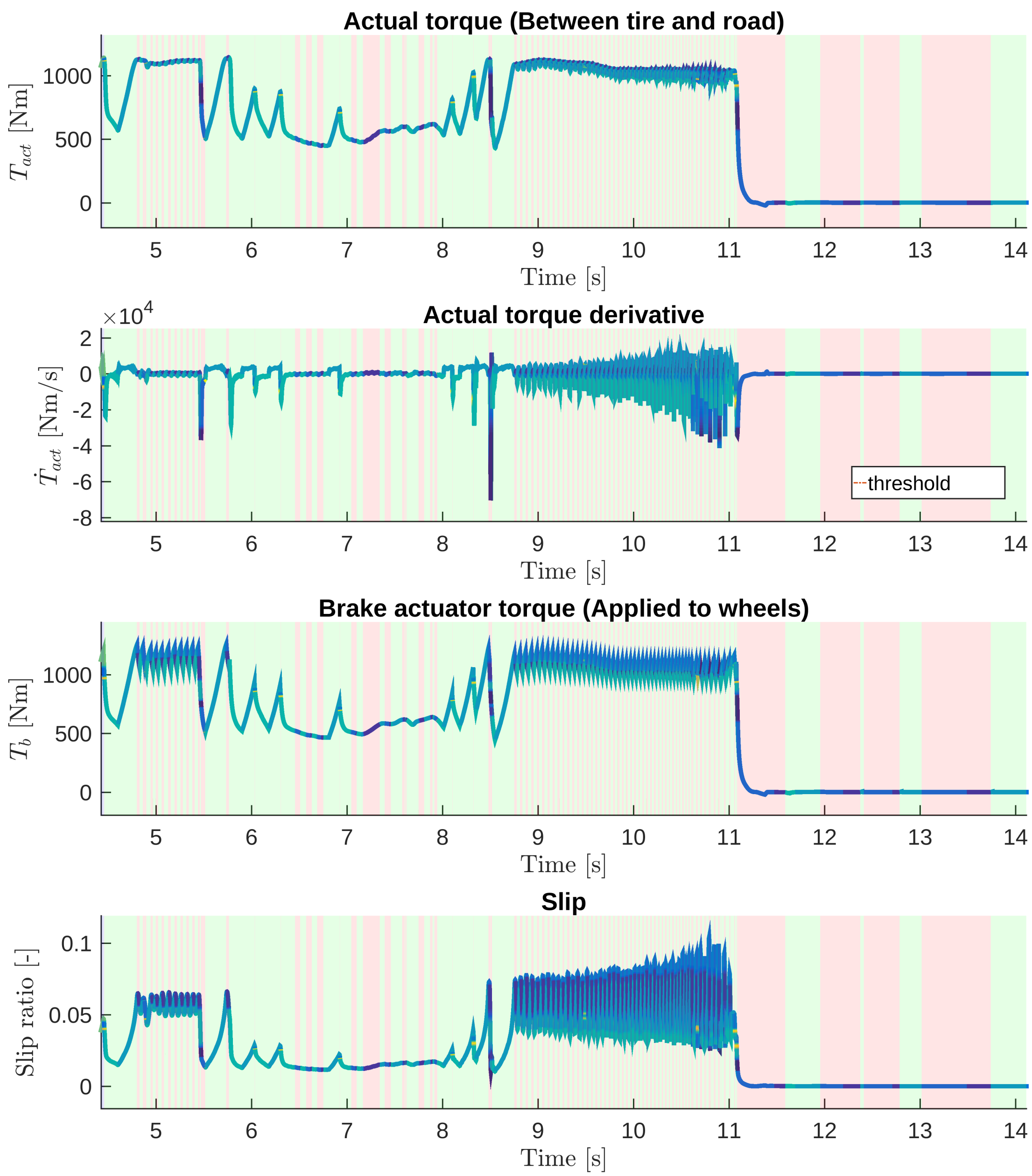

Figure 4.12: Torque and slip vs time, Front right wheel

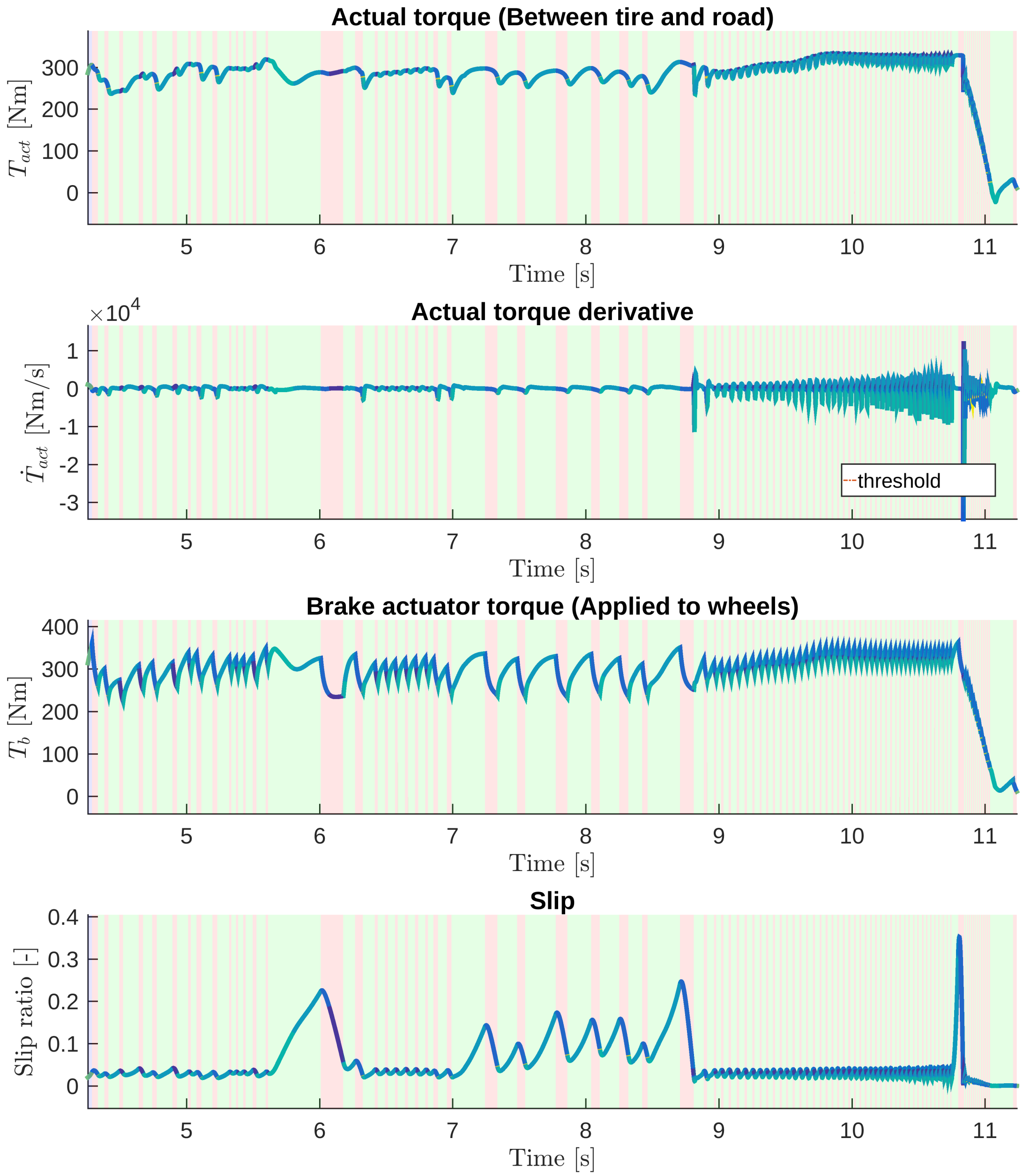

Figure 4.13: Torque and slip vs time, Rear left wheel

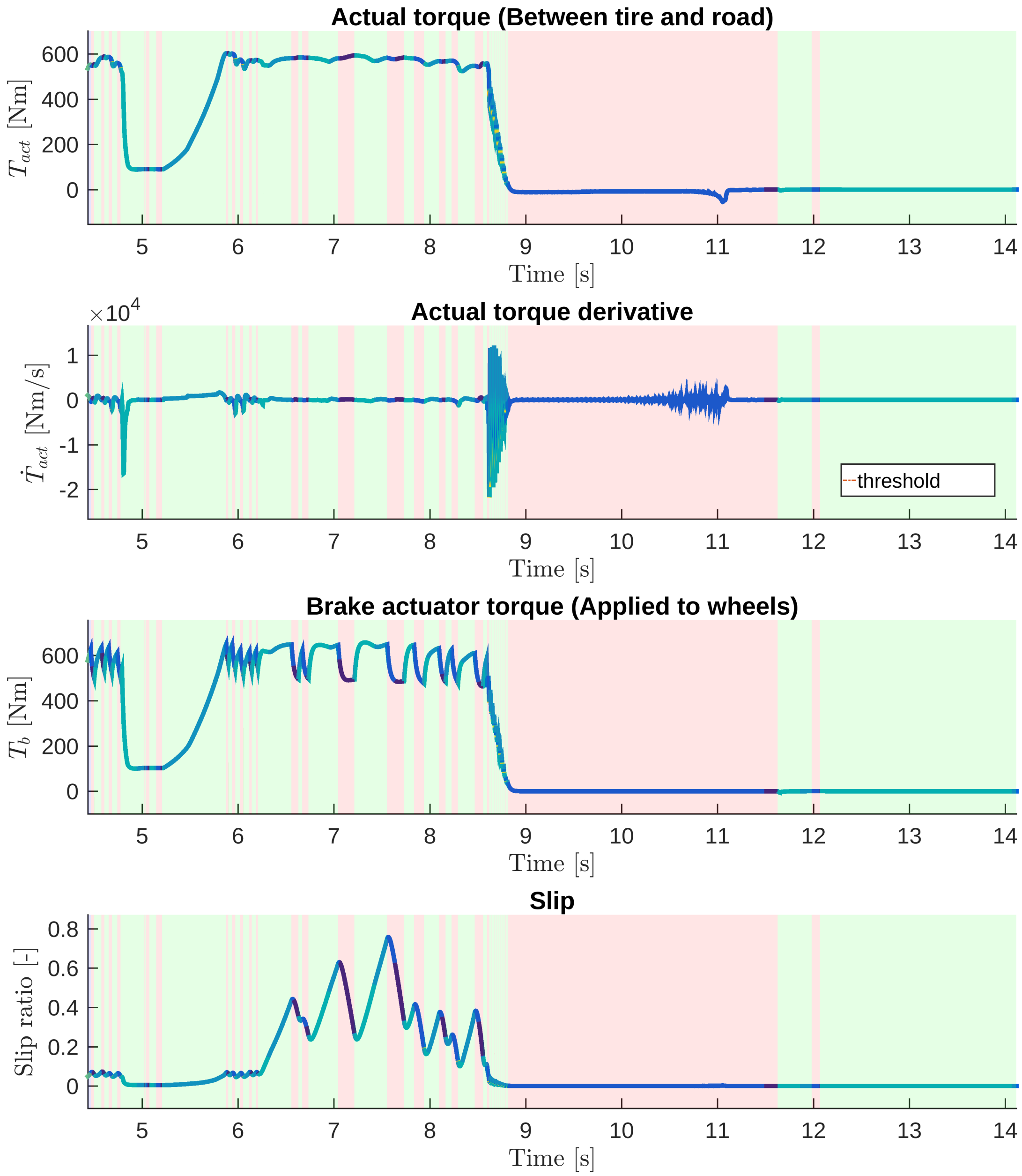

Figure 4.14: Torque and slip vs time, Rear right wheel

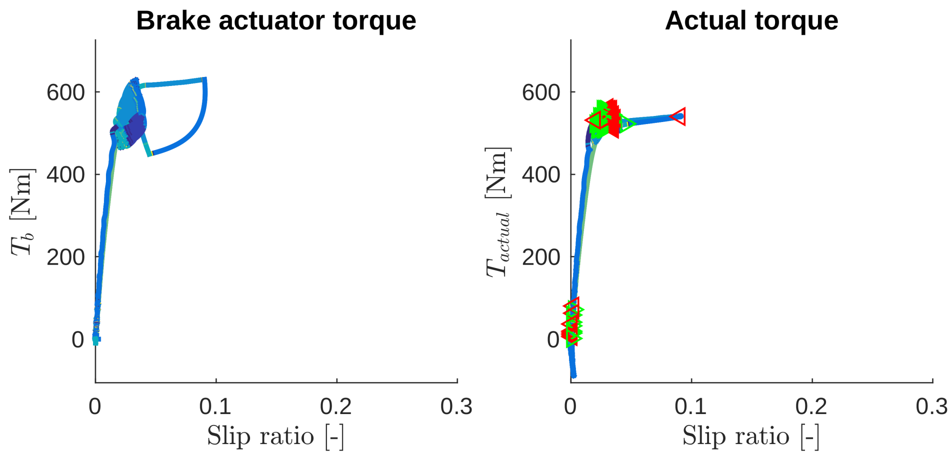

Figure 4.15: Slip vs torque Front left wheel, multiple changes in friction

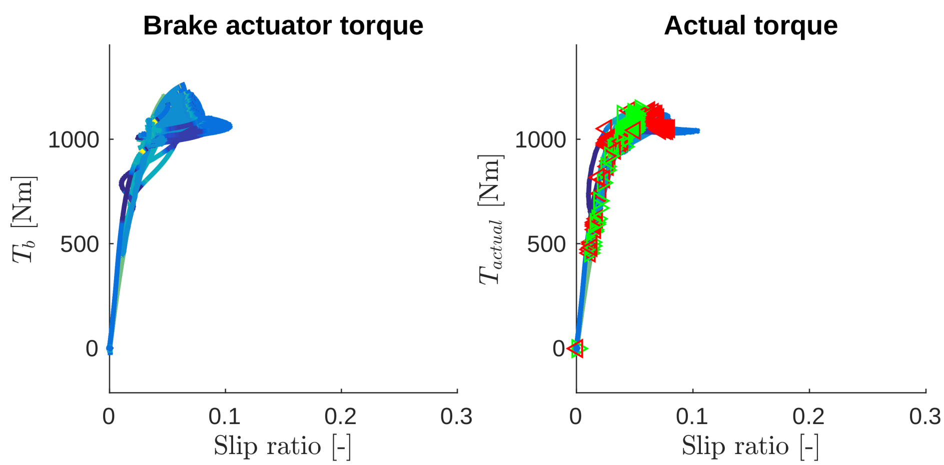

Figure 4.16: Slip vs torque Front right wheel, multiple changes in friction

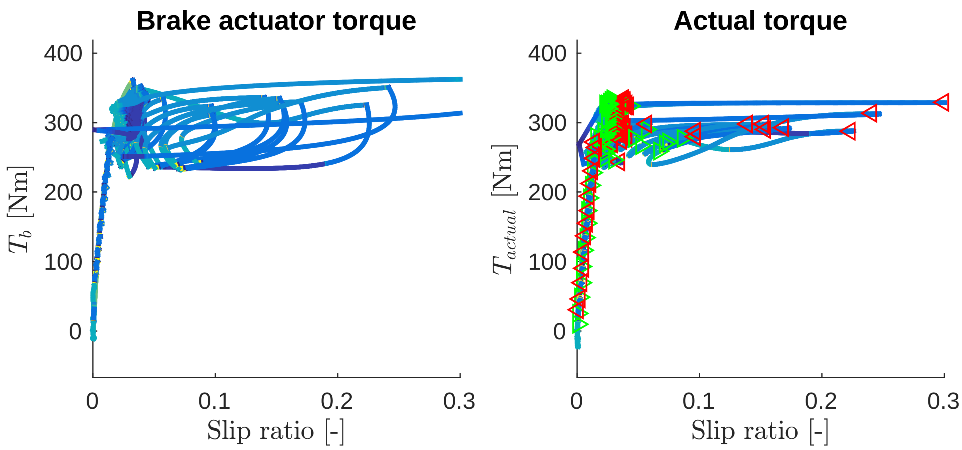

Figure 4.17: Slip vs torque Rear left wheel, multiple changes in friction

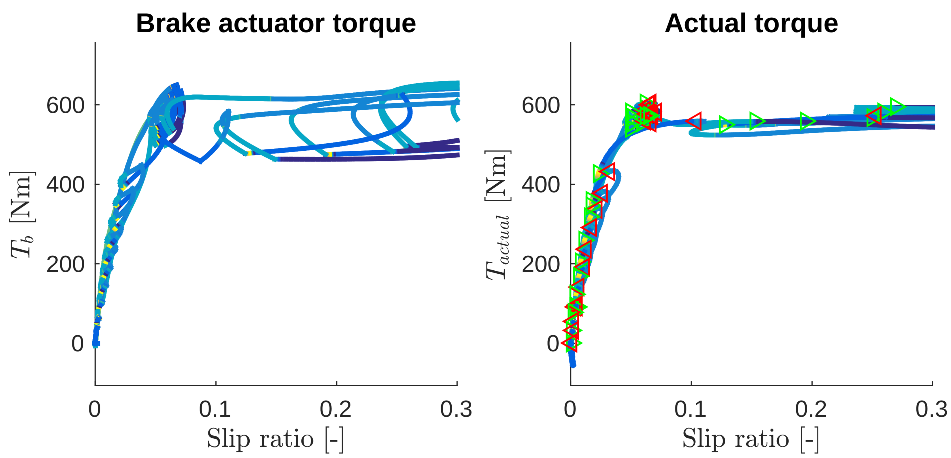

Figure 4.18: Slip vs torque Rear right wheel, multiple changes in friction

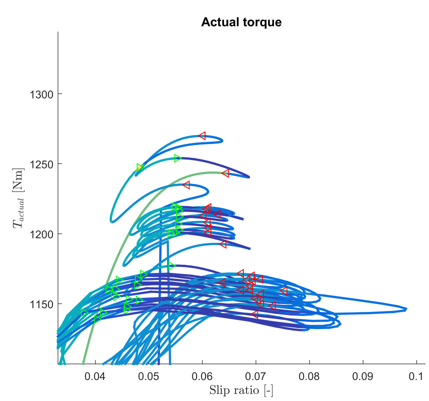

Figure 4.19: The slip versus the actual torque detailed

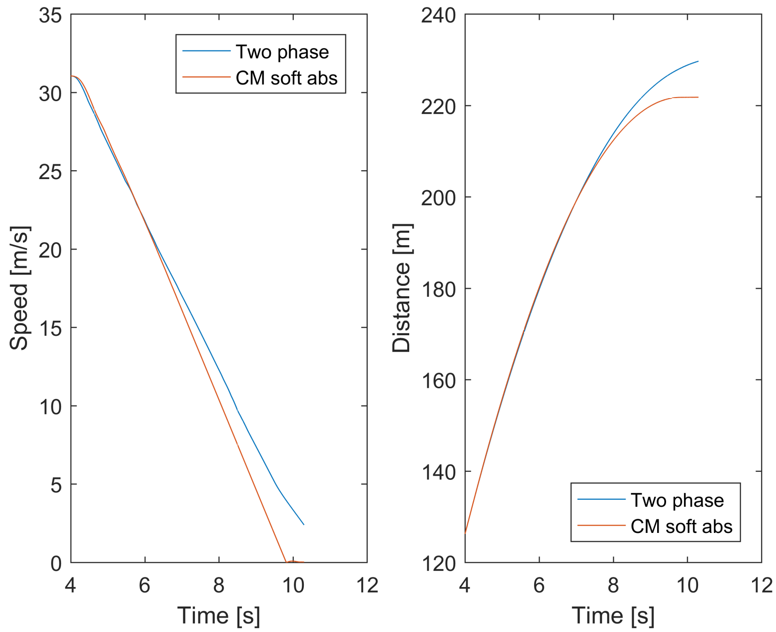

Figure 4.20: The two phase algorithm compared with Soft ABS for the split-mu test

4.4 Conclusion and discussion

In general it can be said that the results show that the algorithm is able to keep the wheels from lock up, even when the friction of the road surface suddenly changes in figure 4.1 it can be seen that around 6 [s] and 9.3 [s] the friction increases for a short moment. It can also be seen that the slip is increasing the most when the friction of the road surface drops suddenly, this is at 6.8 [s]. The algorithm could be improved by tuning the fast decrease parameter, which can be found in the simulink model. A fast decrease event is recognised by looking at the foo numbers the event start at $foo == 1$ and end at $foo == 3$.

In the figures 4.5 until 4.4 it can be seen that there are red triangles at the left side of the optimal slipping point, indicating a false detection of a decrease phase. This false detection is part of the strategy and necessary for the algorithm to work with different road conditions. Furthermore it can be seen that the slip remains stable, so it can be said that the false phase detection is successfully recognised by the algorithm.

In figure 4.19 fluctuations in the slip-torque curve are visible, the explanation for this is that the normal force in a full car is changing due to the movement of the body of the car caused by the spring damper systems. This results in fluctuations of the friction force between the tire and the road and therefore in fluctuations in the actual torque. It can be seen that the algorithm is capable of dealing with this disturbance. To make the algorithm more robust, these disturbances could be measured with an intelligent bearing [9].

Because the wheels are connected to each other by the vehicle itself, the braking effort of one wheel affects the torque measurements of the other wheels. From figures 4.1 until 4.4 it can be concluded that this is not a problem for a road where the friction changes in the same way for the wheels on the left and on the right, as the slip graph is reasonably the same for all four wheels.

From the comparison with the Soft ABS in figure 4.9 it can be seen that the braking distance with the Two Phase controller is 98.65 [m] and with the Soft ABS 101.08 [m]. Therefore it can be concluded that the Two Phase controller does a good job in maintaining the optimal slipping ratio. When comparing the slip ratio of the Two Phase controller with those obtained by using the Soft ABS shown in figure 4.10 it can be seen right away that average slip ratio of the Two Phase controller is significantly lower than that of the Soft ABS, furthermore the slip of the Soft ABS is more smooth. So clearly the Two Phase controller is operating at a different optimal slipping point than the Soft ABS. The Two Phase algorithm searches for the first optimum in the torque, it could be that the algorithm is operating at a suboptimal slipping point. In this case different tuning parameters in the initial phase can be introduced to skip this suboptimal slipping point.

It has to be said that the brake actuator model used with the Two Phase algorithm is different than the one used with the Soft ABS, therefore increasing and decreasing the braking torque might be slightly different depending on which controller is used, this means that one of the controllers could be in advantage for getting to the optimal braking torque. So for a good one to one comparison of the braking distance the same actuator model should be used instead. The comparison of the slip however is still a valid comparison.

The ESC is not tuned for the selected car, which is one of the causes that the slip of the rear right wheel is exceeding a reasonable limit as it gets nearly in lock up. However when the ESC is not enabled the wheels of the vehicle will immediately lock up and the vehicle starts to spin, with the ESC enabled the yaw angle of the car remains between reasonable limits during the brake event. The latter can not be concluded from the results in this report but this insight can be obtained by watching the animations from the simulations.

The result of the slip mu test in figure 4.14 show that the right rear wheel has a difficulties to increase braking again at 8.7 [s]. At this point in time the friction of the road has suddenly increased, but the ESC it not allowing the increasing, as soon as the ESC action stops the wrong phase is selected by the algorithm and is not able to get out of it leading to no braking at all.

The algorithm can be improved by making the phase go into increase or even initial phase when the ESC action stops, in this way braking is ensured. The algorithm will still go into decrease phase when the calculated torque from the ABS is lower than the torque which is adjusted by the ESC, and therefore the latter will not contradict the strategy of always going into decrease phase.

5 Conclusion

The main question of this research was whether it is feasible to use only torque measurements for the application of the ABS controller, as this enables the possibility to always brake at maximum torque without the need of parameters which describe the road condition that are usually obtained by expensive sensors. Furthermore braking based on torques brings the control of braking and accelerating closer together, which improves the application of torque vectoring. It can be concluded from the results and discussion that it is fairly feasible to use only the torque to control the slipping of the wheels.

The following benefits can be concluded.

- Maintaining maximal grip on different road surfaces, even when the road changes during a brake event.
- No need for expensive sensors, since only a measurement or a estimation of the torque is needed.
- ABS using only torque measurements is highly feasible and even capable of decreasing the braking distance, because the braking is more at the optimal slipping point.
- The algorithm is able to deal with different friction surfaces.
- Integration with ESC is possible, but (or and) there is room for improvement.

6 Recommendations

The two-phase algorithm can be more reliable by tuning the thresholds which affect the sensitivity of the phase decision making. Also the addition of an intelligent load sensor bearing to measure the down-force in each wheel can contribute to a better algorithm. Besides recommendations for the algorithm itself further improvement of the model for the EM [10] might lead to better tuning possibilities. Furthermore the tuning parameters could be calibrated automatically with an iterative algorithm, in this way the two-phase algorithm can be integrated more easily in a new vehicle. Because each wheel operates individually integration of the two-phase controller with ESC is highly recommended.

The measurement of the torque is assumed to be infinite good, in reality a filter e.g. Kalman or a low pass filter should be used to have a smooth torque curve leading to an useful derivative. This will add some delay and to be able to maintain a good performance may need a high precision measurement system and computational power for the filter to process this data.

7 Appendices

```
function [ state, foo, increase_check, forced_dec, forced_inc, case_A, Topt]= fcn(threshold1, threshold2, Tcurrent,
      Tdcurrent, current_state, increase_check_prev  , forced_dec, forced_inc, case_A, foo_prev, Topt)
switch current_state
    case 1 % Decrease state
        if Tdcurrent > threshold2   % big road surface change more grip
            state = 2; % goto increase; stay in decrease very robust, can be changed to state 2 for better performance
            foo = 15;
            increase_check = 0;
            case_A = 0;
        elseif Tdcurrent < -threshold2  % big road surface change less grip
            state = 1; % stay in decrease
            foo = 1;
            increase_check = 0;
        elseif Tdcurrent > 0 && (foo_prev==5 || foo_prev==1) % check for case A or B or F
            state = 1; % stay in decrease
            increase_check = 0;
            foo = 12;
            forced_dec = 0;
            case_A = 1; % decrease grip before optimum slip of new surface
            Topt = Tcurrent; % store optimal torque, for bail out purpose
        elseif Tdcurrent > 0 && case_A == 0% check for increasing, slip towards optimal
            state = 1; % stay in decrease
            increase_check = 1;
            foo = 2;
            forced_dec = 0;
            Topt = 0; % reset Topt
        elseif Tdcurrent < -threshold1 && increase_check_prev == 1 % detection of decrease after torque has increased
            state = 2; % goto increase
            foo = 3;
            increase_check = 0; % reset forced decrease
            case_A = 0;
        elseif Tdcurrent < 0 && case_A == 1 % Check for decrease, end of case_A
            state = 1; % stay in decrease
            foo = 17;
            increase_check = increase_check_prev;
            case_A = 0;
        elseif Topt-Tcurrent > threshold1+10 % No optimal slippoint here, try increasing
            state = 2; % goto increase
            foo = 18;
            increase_check = 0;
            Topt = 0;
        else % keep decreasing until Tcurrent starts to decrease again after torque has increased
            state = 1; % stay in decrease
            foo = 4;
            increase_check = increase_check_prev;
        end
    case 2 % Increase state
        if Tdcurrent > threshold2   % big road surface change more grip
            state = 2; % stay in increase
            foo = 13;
            increase_check = 0;
        elseif Tdcurrent < -threshold2 % big road surface change less grip
            state = 1; % change to decrease state, to be safe
            foo = 5;
            Topt = 0;
            increase_check = 0;
        elseif Tdcurrent > 0 && foo_prev==15 % detecting case D or E
            state = 1; % goto decrease, safety for case E, store optimal torque for case D
            increase_check = 1;
            foo = 14;
            forced_inc = 0;      % reset forced increase
            %case_D = 1;
            Topt = Tcurrent; % store optimal torque, for bail out purpose
```

```
        elseif  Tdcurrent > 0% check for increasing
            state = 2; % stay in increase
            increase_check = 1;
            foo = 6;
            forced_inc = 0;      % reset forced increase
        elseif  Tdcurrent < -threshold1 && increase_check_prev == 1;% detection of decrease after torque has increased, optimal slip ratio reached
            state = 1; % goto decrease
            foo = 7;
            increase_check = 0;
            Topt = Tcurrent; % store optimal torque, for bail out purpose
        else % keep increasing until Tcurrent starts to decrease again after torque has increased
            state = 2; % stay in increase
            foo = 8;
            increase_check = increase_check_prev;
        end
    case 3 % Initial state
        if Tdcurrent > threshold2 || Tdcurrent < -threshold2 % big road surface change
            state = 2; % goto increase
            foo = 9;
            increase_check = 0;
        elseif  Tdcurrent < -threshold1 % optimal slip ratio reached
            increase_check = 0;
            state = 1; % goto decrease
            foo = 10;
        else
            state = 3; % stay in initial
            foo = 11;
            increase_check = 1;
        end
    otherwise % impossible state
        foo = 0;
        state = current_state;
        increase_check = increase_check_prev;
end
```

Listing 1: Implementation of the two-phase algorithm in Matlab

7.1 About NEVS

National Electric Vehicle Sweden (NEVS) is a Swedish electric vehicle manufacturer founded in 2012 by the Chinese-Swedish entrepreneur Kai Johan Jiang. NEVS has acquired the assets of the Saab Automobile company and has around 900 employees in Trollättan. Trollättan is located in the southwest of Sweden at the south of the biggest lake of the European Union, Vänern.

7.1.1 A word from NEVS [4]

Our vision
We were founded in 2012 with the determination to create change for those around us and for coming generations. Our vision of shaping mobility for a more sustainable future is our north star, guiding everything we do. We don't believe that you need to compromise quality, safety, performance or comfort to do good. By challenging conventions, we design premium electric vehicles and mobility experiences that are simple, engaging and distinctive, but that also shape a brighter, cleaner future for all. We aim to give people who are curious and passionate about the world a way to express themselves – and invite them to take part in shaping the future of mobility.

Our future
We design and produce premium electric vehicles – no combustion powertrains or hybrids. We see this as only one aspect of the mobility experiences that will shape life for generations to come. Electrification, connected vehicles, changing ownership models, and autonomous driving are just some of the important trends that are transforming the industry. Our start-up mentality, coupled with our rich history, knowledge and competence in auto-making gives us a unique edge. That means we can hit the ground running focusing solely on what we believe is the future: electric vehicles and sustainable mobility experiences. To bolster our innovation, we're establishing a production joint venture and an R&D joint venture in Tianjin Binhai High-Tech zone, and opening a brand experience center in Beijing.

Our legacy
We are a new company, but we see our future as an extension of our past. Since 1947, Saab cars have revolutionized the industry by rethinking the status quo. We build on our strong heritage, and, like Saab cars, we will continue to be innovative and daring. Our desire to challenge conventional thinking – whether a big idea or a small improvement – continues to inspire us. From openness in collaboration, quality in design and innovation in ergonomics, our Swedish heritage and culture continues to be a foundation for everything we do.

7.2 Reflection

At the start of my internship three subjects are investigated with some literature study. All three subjects involve improvement of active stability control. One of the subjects which is not mentioned in the report was about surrounding perception, which is about detecting objects and road markings or signs to get a good understanding how autonomous driving actually works. The other two were the identification of the EM and the synthesis of the two-phase algorithm. It was very useful to investigate these subjects on beforehand to get a broader understanding of the global subject, active stability control.

At my first day I had a meeting with my supervisor to discuss the subject of my internship, he told me about the project which was currently going on and the possibilities for me to contribute on that. The next day I was assigned to a desk so I could start with a bit of a literature study to find out what I wanted to do and what was possible during the limited time I had. One week later, after some meetings and small presentations of what I thought I should contribute I got a clear picture of what my work was going to look like. I started with the first subject which was the identification of the Electric Machine as discussed in the introduction, and here I needed to cooperate with the people in the test rig to find out to which frequency the signals could communicate and if this could be improved if necessary, unfortunately the frequency was not high enough and improving this would take too much time.

During my work I did al the work by myself, there were of course meetings to discuss the progress, but the I did't work in a team or such. During these meetings I presented my work and the feedback was always positive I was never forced into a certain direction in which things should go, therefore I was able to look with an open minded mind to the problem.

Besides the work on my own, researching the best way for the system identification, I was attending some of the meetings to get a broader picture of what all the other people where doing. During lunch time I joined my colleagues which was at least once a week outside the company somewhere in the city, which is a good way to clear your mind of the work. The lunchtimes were also a good moment to get to know the colleges better, which was quite interesting because I learned about the existence of working philosophies like scrum, agile, matrix and xp which are things I never learned in this way at the University.

Furthermore there where symposiums in which other companies come to advertise their product, one of the presenting companies was a inwheel motor manufacturer, so they where making wheels with the motor inside the wheel. We talked about the idea of using the electric motor for ABS braking, they were interested and because we had some factors that limit the identification they were willing to perform some experiments. So I prepared an experiment which they could test on their setup as can be read in appendix 7.3, but it turned out that they had the same sort of limitations as we did.

Therefore I decided to start with the second subject which was the development of a two phase braking algorithm for ABS purpose. The development of the two phase controller was a iterative proses, in the report it might seem that I researched everything and than came with a complete solution at once, this is far form how it went in reality. I started with creating a simple algorithm which was only able to deal with a road surface which has a constant friction. To add the functionality to deal with different surface frictions, I used the same algorithm to see when it did go wrong and than applied a solution to it. After testing the new algorithm it sometimes worked well and sometimes it did not. At this point I came up with the different cases to change from one friction curve to another, which are depicted in figure 3.4. This allowed me to test the algorithm for each case and to make sure that the solution in one case did not affect the way how the algorithm should act in all other cases. So I learned that sometimes you need to do some trial and error in order to get a full understanding of a fairly abstract thing like a control design.

Almost at the end of the internship I got a little bit bored by all the theoretical work on the computer, but luckily I was working at a car company which has cars and a test track, it was nice to see the product made by NEVS. I did't contribute to that, be I can imagine that if I did it would feel amazing. I now know that I want to point the direction of my career into a function in which I can do at least sometimes something practical as well, such as testing and validation, or working with physical objects for redesigning.

7.3 Ident documentation

Documentation for the input signals

For the purpose of designing a controller it is desired to find a model that provides a relation between the requested torque input of the inverter and the delivered torque output of the electric motor. The goal is to have a representation of the systems dynamic behaviour at different speeds, this will be obtained by applying the same input signal at a speed of choice, e.g. $0, 200, 400, 600, 800, 1000, 1200, 1400$ and 1600 [RPM].

When considering a system set-up which contains an electric motor connected to a dyno, the torque will be measured at a regulated speed. As the dyno has a response settling-time of 5 [ms], the input signal should not exceed frequencies above 200 [Hz]. Furthermore because it is only possible to determine the systems frequency response up to the Nyquist frequency, the model could in theory be an accurate representation until 100 [Hz]. For the measurements it is important to have a sample frequency that is at least 10 times higher than the sample frequency of the input signal, i.e. 2 [KHz], more samples will not harm.

I have made two types of input signals, the signals are based on either a multi-sine or a pseudo random binary signal (PRBS). The multi-sine approach will probably benefit from a better response from the dyno, while the PRBS signal contains far more frequencies leading to a better identification, however the dyno might have some trouble to keep the speed at a constant level, leading to inaccurate torque measurements.

The signals have the following characteristics: a maximum amplitude of 1000 [Nm], the amount of samples $N = 4095$ and the sample time $ts = 0.005$ [s]. It would also be interesting to have a result from an experiment with a small excitation amplitude, e.g. 15 [Nm], to see if this has a positive effect on the torque measurement. Furthermore results from several experiments with only a positive torque would be interesting to have. For this the signals can be easily modified by either scaling the signals, or by adding the value of the maximum amplitude to each value of the signal.

The multi-sine signal consist of 40 frequencies, which are listed in table 1. For a preview, the first second of the signals is depicted in figure 1, the total duration of the signals is 20.47 [s]. The complete signals can be found in the files 'sine.txt' and 'prbs.txt' which contain a time column and a list of values representing the torques for each sample.

#	[Hz]	#	[Hz]	#	[Hz]	#	[Hz]
1	0.04884	11	25.44567	21	51.28205	31	77.11844
2	2.58852	12	28.03419	22	53.87057	32	79.65812
3	5.12821	13	30.62271	23	56.45910	33	82.19780
4	7.66789	14	33.21123	24	59.04762	34	84.73748
5	10.20757	15	35.79976	25	61.63614	35	87.27717
6	12.74725	16	38.38828	26	64.22466	36	89.81685
7	15.28694	17	40.97680	27	66.81319	37	92.35653
8	17.82662	18	43.56532	28	69.40171	38	94.89621
9	20.36630	19	46.15385	29	71.99023	39	97.43590
10	22.90598	20	48.74237	30	74.57875	40	99.97558

Table 1: Frequencies of the multi-sine signal

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