Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Faster Locking Differential Through Active Brake-Control

Examensarbete utfört i reglerteknik
vid Tekniska högskolan vid Linköpings universitet
av

Joakim Hallqvist

LiTH-ISY-EX–14/4809–SE

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Linköpings universitet
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Snabbare differental spärrar med hjälp av färdbroms

Faster Locking Differential Through Active Brake-Control

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Sammanfattning
Abstract

When a vehicle with wheels aligned in pairs turn, the wheel traveling around the outside of the curve has to roll farther than the wheel on the inside. This means that some sort of device must must be used to allow the drive wheels to rotate at different speeds to prevent wear on the tires. This is usually a mechanical device where the input rotation controls the sum of the two output rotations, this is known as a differential. This solution however has some shortcomings, the biggest one is that the total amount of force that can be transferred between the tires and the road surface is limited by the tire with the least traction. In slippery conditions this can be a big problem since it only takes one wheel to lose traction in order to prevent the vehicle from accelerating. In this thesis a locking differential is used to overcome this shortcoming, this gives the driver the option to lock the shafts of the driving wheels together. This is done by pushing two cogwheels, one attached to each shaft, together. The aim of this thesis is to shorten the lock- and unlock-time of the locking differential by aligning the cogwheels using the service brakes and available sensors. The results were evaluated by implementing the software in a truck and doing test runs on Scanias test track. These tests showed that the system greatly improved both lock- and unlock-times but at cost of lower driver comfort. With additional work with some fine tuning of the system, the overall performance could probably be increased even more.

Nyckelord
Keywords

Differential, Differential-lock, brake pressure control

Abstract

When a vehicle with wheels aligned in pairs turn, the wheel traveling around the outside of the curve has to roll farther than the wheel on the inside. This means that some sort of device must must be used to allow the drive wheels to rotate at different speeds to prevent wear on the tires. This is usually a mechanical device where the input rotation controls the sum of the two output rotations, this is known as a differential. This solution however has some shortcomings, the biggest one is that the total amount of force that can be transferred between the tires and the road surface is limited by the tire with the least traction. In slippery conditions this can be a big problem since it only takes one wheel to lose traction in order to prevent the vehicle from accelerating. In this thesis a locking differential is used to overcome this shortcoming, this gives the driver the option to lock the shafts of the driving wheels together. This is done by pushing two cogwheels, one attached to each shaft, together. The aim of this thesis is to shorten the lock- and unlock-time of the locking differential by aligning the cogwheels using the service brakes and available sensors. The results were evaluated by implementing the software in a truck and doing test runs on Scanias test track. These tests showed that the system greatly improved both lock- and unlock-times but at cost of lower driver comfort. With additional work with some fine tuning of the system, the overall performance could probably be increased even more.

Contents

Notation

Abbreviation	Meaning
i_{wheel}	Slip on a single wheel [%]
i_{right}	Slip on right wheel [%]
i_{left}	Slip on left wheel [%]
i_{desired}	Desired slip on a single wheel [%]
$i_{\text{braked wheel}}$	Slip on the braked wheel [%]
$i_{\text{other wheel}}$	Slip on the non braked wheel [%]
ω_{wheel}	Speed of a single wheel [rotations/s]
ω_{vehicle}	Average rotation speed of non driving wheels [rotations/s]
$\Delta\omega$	Difference in rotation speed [rotations/s]
$\Delta\omega_{\text{desired}}$	Desired difference in rotation speed [rotations/s]
ω_{right}	Rotation speed of right wheel [rotations/s]
ω_{left}	Rotation speed of left wheel [rotations/s]
p_{brake}	Brake pressure [bar]
C_{i}	The coefficient for converting slip to force on the road suffice [N/slip]
K_{brake}	The coefficient for converting brake pressure to wheel torque [Nm/bar]
r	Radius of the wheel [m]
R	Speed of the right wheel [km/h]
L	Speed of the leftwheel [km/h]
T_{max}	Upper threshold for wheel speed difference [rotations/s]
T_{min}	Lower threshold for wheel speed difference [rotations/s]
S_{min}	Minimum speed threshold for attempted brake [km/h]

1 Introduction

When a vehicle with wheels aligned in pairs is turning, the wheel traveling around the outside of the curve has to roll farther than the wheel on the inside. This means that the driving wheels have to turn at different speeds but the engine only has one angular velocity as output. In almost all vehicles this is solved by using a differential. A differential is a device, usually employing gears, that connects three shafts, one input and two outputs. This connection is made in such a way that the rotation and torque of the input shaft is transfered to the two output shafts [8]. The transfer of angular velocity is such that $z = ax + by$ where z is the angular velocity of the shaft connecting the gearbox to the differential, x and y are angular velocities of the shafts that connect the differential to the drive wheels. a and b are constants describing the gearing of the differential, in this case study as in most cases a is equal to b. This allows the two driving wheels to rotate at different speeds but the sum of the two rotations is decided by the rotation speed given by the engine. At the same time, the torque generated by the engine is equally distributed between the two wheels. In some cases, this even distribution of torque is undesirable. These cases may include driving in bumpy or slippery terrain in which one wheel may lose traction [10]. The total torque that can be generated is normally limited by the engine but also by the maximum force that can be generated between the tire and the road. Since the torque is evenly distributed between the two wheels the result of one wheel losing traction will be that the total amount of torque to the drive wheels will be reduced. This is a big problem when e.g. starting in an uphill where one wheel may lose traction. As mentioned above, reduced traction on one wheel will reduce the total amount of torque that can be transferred to the road. This means that even if the other wheel has good traction the reduced torque applied to that wheel may not be enough to get the vehicle moving [1]. To aid in cases like this where one wheel may lose traction there are several different techniques used by car manufactures. These techniques can be dived into two main groups, limited slip diffentials and locking differentials.

1.1 Limited Slip Differential

A limited slip differential contains a gear train just like an open differential but also contains some sort of mechanism to apply internal torque to the differential. This allows the limited slip differential to control how closely the drive wheels are coupled to each other. The amount of limiting torque provided by these mechanisms varies by design. Some traditional limited slip differential include viscous-type that uses friction in a high viscosity liquid to reduce the speed difference between the drive wheels. Another example is clutch-type differential that can be either speed-or torque-sensitive and uses clutches on each axle to control the slip [2]. Traction control systems (TCS) is an alternative to the traditional limited differential. Where other systems uses mechanically modified differentials this system instead uses the cars sensors and algorithms to control possible slip. This can be done either by braking the wheel that is slipping or reducing the throttle if the vehicle uses drive-by-wire throttle [3].

1.2 Locking Differential

The locking differential works by forcing the two drive axis together so they rotate at the same speed. The locking mechanism can either use pneumatics, cables or electromagnets to force the cogwheels together. The advantage with locking the differential is that the total torque will be limited by the sum of the traction available at each drive wheel. The disadvantage of this type of differential is that it has to be unlocked when turning to prevent wear on the tires and not to affect controllability. Sometimes there can be problems with getting the two axles to lock or unlock [2]. This will be discussed later in the thesis.

2

Description Of The Problem

This chapter contains a short summary of the problems that this thesis is supposed to solve.

2.1 Problems When Locking The Differential

In this study a locking differential will be used and the main goal is to speed up the engaging and disengaging of the locking mechanism. The locking differential used in this study works by having a pair of cogwheels connected to each of the wheel axis, see figure 2.1. These cogwheels can then be forced together using a cylinder powered by pressurized air and thus locking the two axles together. There are a few problems with this method, if the cogs do not line up when they are pushed together the axles will not lock and if there are no difference in rotational speed the cogs will never line up. This is usually a problem when approaching e.g. a hill in a straight line. In this case it is desierd to lock the differential before reaching the hill. Another problem is if the difference in rotational speed between the two wheels are too great when the lock is engaged, then the cogs or other parts may get damaged. This usually happens when one wheel suddenly loses traction, e.g. on surfaces with low friction.

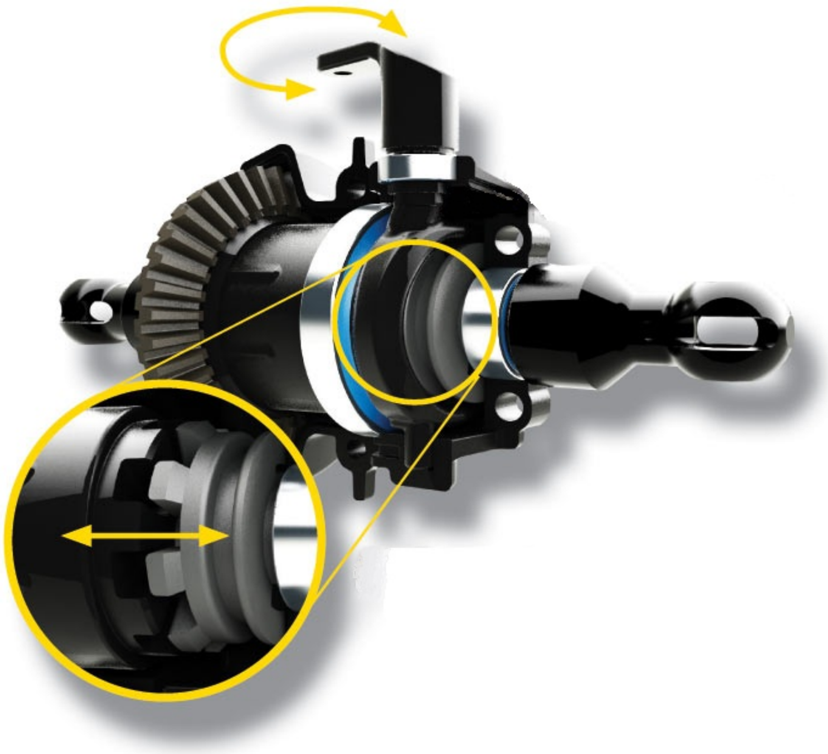

Figure 2.1: Example of a locking differential, this differential comes from a smaller truck than the ones used in this thesis. This means that the size of the differental and the number of cogs are different

2.2 Problems When Unlocking The Differential

When unlocking the differential, the air in the cylinder is released and a spring pushes the the cogwheels apart. The problem in this case occurs when a momentum is being applied between the two cogwheels due to winding of the drive shafts. This is usually a result of turning with the differential locked. In these cases, the spring responsible for separating the cogwheels simply do not have enough force to push them apart and is thus unable to lock the differential. This can be problematic while trying to disengage the differential before or during a turn, or other times when a quick unlock is required. This thesis is supposed to investigate solutions for the above described problems.

3

Experimental Platform

This chapter contains an examination of the platform used in this thesis.

3.1 Software

The lock system were designed in MATLAB, SIMULINK and through Rapid-prototyping converted to C-code to and tested.

3.2 Hardware

To evaluate the performance of the lock, a couple of 2x4 Scania trucks were used, 2x4 meaning a four wheeled tuck with two drive wheels. These have been modified to allow for testing of new software. All trucks used had the same type of differential-locking-mechanism as described in Section 2.1. The trucks were equipped with a number of sensors and the important ones for this thesis is described in Section 3.3. The testing of the lock system was then performed on the Scania test track.

3.3 Signals And Sensors

This section contains a summary of what sensors and signals were used, problems with different signals and sensors and what needs to be improved in order for this concept to make it into production trucks.

3.3.1 Wheel Speed

The wheel speed is measured by attaching a cogwheel to the wheel axis, a sensor will then measure the current induced by the cogs of the cogwheel as they pass by the sensor. This will result in a sine-wave type signal and by identifying the frequency of the sine-wave and knowing the number of cogs on the cogwheel the rotational speed of the axis can be measured [9]. The control system developed in the research for this thesis uses rotational speeds of the wheels as input. However, the rotational speed is not made available on the CAN-bus. The signal is instead converted to give the wheels speed relative to the road using the radius of the wheel. The wheel radius used in the calculation is adaptive and is calculated through comparing the speed difference between all wheels. This is done in order to compensate for use of different tires, tire pressures or tire compression caused by varying load on the axis. But this calculated wheel radius is not made available on the bus which means that there is no way to get the actual rotation speed of the axis. In the test runs performed during this study, the calculated wheel radii were retrieved from the truck memory and preprogrammed in to the control algorithm.

3.3.2 Differential Lock Sensor

The sensor that measure if the two cogwheels in the differential locking device have locked together is a simple sensor that is only activated when the cogs are completely pushed together. This can be a problem since it may give false information about if the differential is locked or not. E.g. if the cogwheels have locked together half way through an unlocking, the sensor will read that the differential is unlocked and the control system will not aid in achieving a actual unlocking of the differential. Replacing the simple sensor with a new sensor that can measure the relative position of the cogwheel would result in a better working control system.

The frequency of which the differential lock sensor data is sent over the bus is 2 Hz. This is far too low for the control system developed in this thesis partly because this will result in that the system will order the wheels to brake for unnecessary long time, but mainly because the system will not be able to tell at what point there is no axle torsion, see Figure 3.1 on the facing page. The first plot shows the wheel speeds of the two driving wheels, the second plot shows the lock request-signal, the registered lock by the sensor and the lock-signal sent on the bus. The third plot shows the applied brake pressure on the driving wheels. The fourth plot shows the relative rotation between the drive wheels. The relative rotation is calculated by integrating the difference in wheel speeds. The fifth plot shows the difference in wheels peeds between the two driving wheels. All plots show a scenario where the truck is turning slightly to the left, pressure is then applied to the left brake to increase the speed difference between the two wheels. From the plots it is clear that the relative rotation shown in the fourth plot would not be correctly reset if the lock signal shown on the bus would have been used. However it is also clear that the relative speed difference starts to decrease at around 484.8 s without any decrease in brake pressure and this is before the sensor detects that the differential is locked. This suggests that that the differential actually locks earlier than the sensor can detect. This is because the cogs are locked together but not completely pressed together so the sensor do not register a lock. This could cause the system to order braking on the wrong wheel when trying to unlock the differential since it might draw the wrong conclusion regarding the winding of the wheel axles and thus brake the wrong wheel. The reason why the difference in rotational speed dips below zero is because there are still a brake pressure on the wheel and this causes a wind up in the opposite direction.

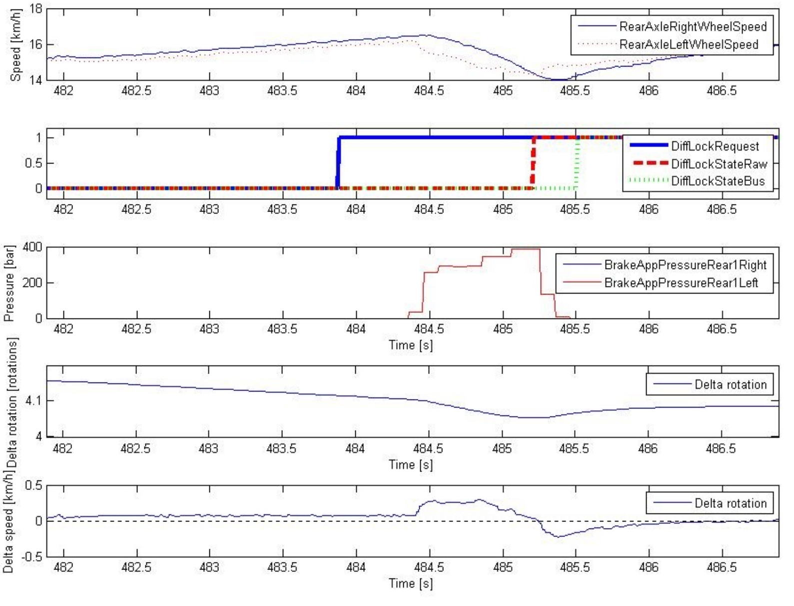

Figure 3.1: *This plot shows the delay in the lock-sensor data sent on the bus and how this could effect the measurement of the axle torsion. The plot contains the wheels speeds, lock request, actual lock signal from sensor, lock signal sent on bus, brake pressure, relative rotation between the drive wheels and the difference in wheel speed between the two wheels.*

4

Approach

This chapter contains the approach that was taken in order to solve the problem presented in Chapter 2.

4.1 Concept

The main idea in order to solve the problems described above is to use the service brakes of the vehicle to turn the differential into desirable positions. The goal is to speed up the locking/unlocking time as much as possible while trying to minimize driver discomfort. There are several variables to consider when designing the control system, first it is desired to minimize the stress on the different parts of the vehicle e.g. tires, drive shaft, engine or the lock mechanism itself. Secondly, the braking should be done in such a way that the drivers comfort and vehicle control remains as high as possible.

4.2 Locking The Differential

When trying to engage the differential lock there are a few scenarios to consider, as mentioned in 2.1. The basic concept that will be used for getting the cog-wheels to lock can be seen in figure 4.1. The Figure represents the case with one pair of drive wheels, named Rear axle 1. Note that the actuating of the differential lock is performed by a separate system and is always activated by a lock request unless the difference in wheel speed exceeds 0.7 rotations/s. Originally two thresholds for the speed difference between the drive wheels were to be used, one maximum threshold that if exceeded may damage the locking mechanism and one minimum that will not result in a fast enough lock. Some initial tests were performed based on this idea but newer Scania trucks will use more robust differential locking devices that can handle locking at greater speed difference, so focus were switched to only solve the problem where the speed difference is too low. In this scenario, where the speed difference is too low, the logical thing to do is to increase the speed difference. This is accomplished by braking the wheel with the lowest rotational speed. If there is no speed difference between a pair of drive wheels one wheel will be chosen according to the following reasoning. If there are only one pair of driving wheels one brake will be chosen arbitrary. However if there are additional pairs of drive wheels the braking of these pairs will be made in such a way that they brake on the opposite side of the vehicle compared to the previous wheel pair. Braking like this should result in the least decrease in driver control but due to vehicle maintenances there were no opportunity to test this. If the vehicle speed is below 5 km/h no locking attempts will be performed since they would result in to high brake pressures.

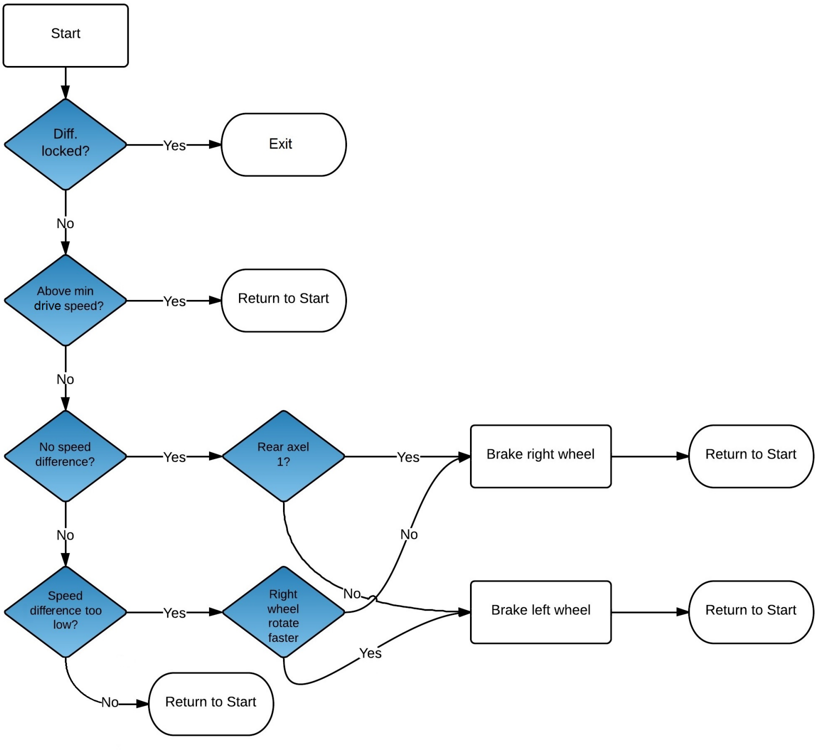

Figure 4.1: Flowshart for locking the differential

4.3 Unlocking The Differential

As the differential gets locked the system will start to integrate the differences in rotational speeds between the two axles due to slip in the locking mechanism and flexibility in the axles and tires. This measurement will then be used to calculate in which direction torque is being applied on the locking mechanism. The system will then brake the wheel on the correct side in order to cancel that torque, see Figure 4.2 for a flowchart of this process.

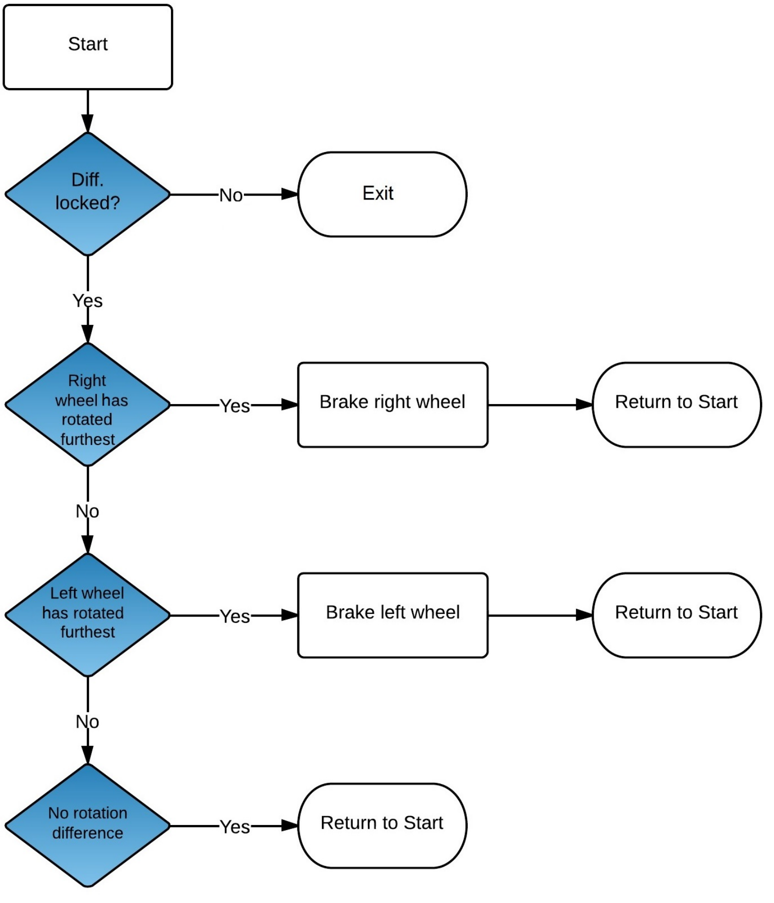

Figure 4.2: *Flowshart for unlocking the differential.*

4.4 Brake control

This section explains how the brake pressure is calculated.

4.4.1 Locking The Differential

The goal when calculating the brake pressure is to apply enough pressure to achieve/reduce slip but at the same time minimize the negative influence on driver comfort. Several methods of what initial pressure to use and how to possibly vary it over time were investigated. First preset values were fed to the brake control to test the overall concept of which wheel to brake. These tests also gave a broad sense of what pressure intervals were reasonable in order to get the desired effect. After this, different time-varying pressures were used to see how that might effect the wheel slip. During these tests, the wheel speed difference were measured to determine at what speed the differential is most likely to lock without taking damage. The manufacturer of the differential lock have prevented locking at a speed difference above 0.7 rotations per second so any speed below this was considered safe. The results from these tests can be seen in Figure 4.3.

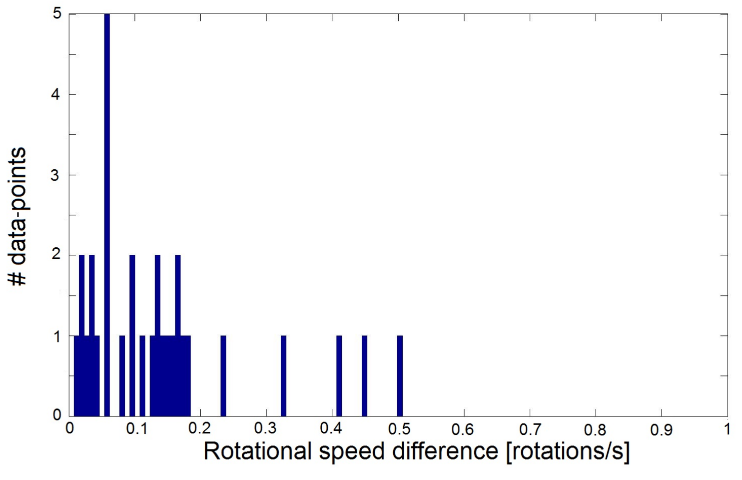

Figure 4.3: *Distribution of rotational speed differences when locking occurred. In this plot some data-points at higher rotation speed differences have been removed.*

In this figure, locks that occur at higher speed differences have been discarded and are not shown in the plot. This can be done since the goal is to achieve fast locks with as little negative effect on driver comfort as possible. Meaning that it's preferable to have low rotational speed differences if the lock time still is sufficiently low. Locks at speed differences below 0.02 rotations/s mainly occurs when the cogwheels of the locking mechanism is already aligned and are not interesting for this thesis. From this data the reference signal for the brake pressure control system were chosen to 0.1 rotations/s and the minimum threshold, mentioned in section 4.2 on page 11, were chosen to 0.05 rotations/s. The reference signal was chosen so that the wheel speed difference was to travel through an interval where the majority of the locks occurred. From this argument, a higher reference value might have been better but that would've also caused higher brake pressures, so a more conservative approach was chosen. The same goes for the minimum threshold that also was chosen conservatively in order to reduce brake pressure since there still were several locks occurring between 0.05 an 0.1 rotations/s.

After these initial tests had been carried out, a new brake model were designed that uses the slip on each wheel along with the vehicles brake-factor and the wheel-stiffness to calculate the brake pressure. In this case, the brake-factor is a coefficient that is used to transfer applied brake pressure to torque on the wheels and is specified for all Scania trucks. The wheel-stiffness is a coefficient that correlates to how much the tires slip as a result of the engine applying torque to them, see Section 4.5 on page 18. The slip is calculated using Equation 4.1 where ω_{wheel} is the speed of the slipping wheel and the slip is given in percentage.

$$i_{wheel} = 100 * \frac{\omega_{vehicle} - \omega_{wheel}}{\omega_{vehicle}} \text{ [\%]}. \tag{4.1}$$

The difference in rotation speed is calculated using 4.2.

$$\Delta\omega = \omega_{right} - \omega_{left} \text{ [rotations/s]}. \tag{4.2}$$

By inserting 4.1 into 4.2 and replacing $\Delta\omega$ with the desired rotation speed difference Equation 4.3 is obtained.

$$\Delta\omega_{desiredrotation} = (i_{right} + i_{left}) * \omega_{vehicle} \text{ [rotations/s]}. \tag{4.3}$$

Through the flowcharts 4.1 and 4.2 we know which wheel we want to brake and can now calculate the desired slip on the braked wheel, 4.4. The ± sign are dependent on which wheel is being braked.

$$i_{brakedwheel} = \pm \frac{\Delta\omega_{\text{desired rotation}}}{\omega_{vehicle}} + i_{otherwheel} \text{ [\%]}. \tag{4.4}$$

In order to transfer the calculated slip in to brake pressure, three constants are required, Brake-factor K_{brake} [Nm/bar], Wheel-stiffness C_i [N/slip] and Wheel radius r $[m]$ This will finally result in 4.5. The division by zero, when $\omega_{vehicle}$ is zero, is no problem since no braking will be performed at speeds below 5 km/h, see Section 4.2 on page 11.

$$P_{brake} = \frac{r * C_i}{K_{brake}} \left(\frac{\Delta\omega_{\text{desired rotation}}}{\omega_{vehicle}} + i_{\text{other wheel}} \right) \text{ [bar]}. \tag{4.5}$$

As mentioned, the brake factor is well defined for all Scania Trucks and can be set before the test starts. The wheel-stiffness on the other hand is dependent on several factors like temperature, tires and especially load. Since the load can vary a lot, the wheel-stiffness will be calculated and updated continuously from data collected during driving, see Section 4.5 on page 18.

Locking Control Loop

The brake pressure is controlled through the vehicles CAN-bus (controller area network-bus) [7] and the feedback from the sensors were also sent through the CAN-bus. Due to this the control loop has to be able to handle the data-delay caused by the bus. Because of this delay in combination with a relative long delay in regulating brake pressure, the fear was that a regular PID-regulator would require a large K_p to give a short rise-time and that this large K_p would result in oscillations and/or overshoot. In addition to this the relationship between the force transfered to a wheel and the slip of that wheel is nonlinear at stronger forces [4], see Figure 4.6 on page 19. Because of this, Equation 4.5 on the preceding page was used to calculate what brake pressure that theoretically should give the correct slip. There are several other attempts at creating better slip control systems [5], [6], but since designing the brake pressure regulator was only one part of this thesis there were no time to explore this further. This value was then directly sent to the bus without any feedback-loop. However, there was still a need to compensate for inaccuracy in the theoretical brake pressure value so an I-regulator was implemented, see Figure 4.4. There is also a constant added to the applied brake pressure in addition to the the calculated theoretical correct pressure. This is because the brakes themselves require a certain pressure before they start to brake. This results in an open-loop regulator that uses a theoretically correct value and an I-regulator that is added to compensate for errors in the calculated value. In Figure 4.4 the reference signal is the desired slip and the $\frac{r*C}{k_{brake}}$ is the coefficient calculated in 4.5 on the previous page. See Figure 4.4 for a schematic over the brake pressure controller.

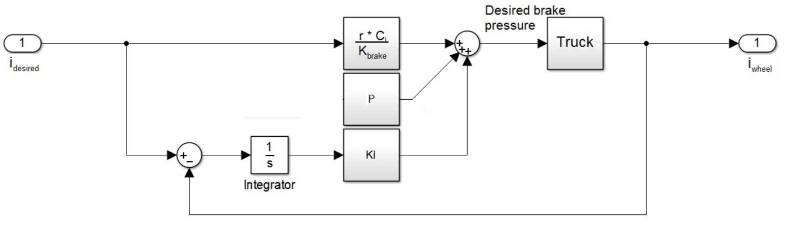

Figure 4.4: *Concept of the locking control loop, the actual control was made in MatLab, Stateflow.*

4.4.2 Unocking Control Loop

As explained in Chapter 2.2, the problem with unlocking the differential is that there might be a momentum between the cogwheels that locks the two drive shafts together. This is caused by the winding of the axles that is a result of turning while the differential is locked. As described in Section 3.3.2, the orientation and degree of winding of the axles will be calculated by integrating the wheel speed difference after a lock has occurred. Using this calculation as reference, the system will try to unwind the axles and thus allow the cogwheels to separate. In order to give the cogwheels the best opportunity to separate, the system will aim to turn the axles past the point of no wind-up of the axles and then gradually reducing the brake pressure. This is done in order to give the cogwheels two chances of separating and to compensate for measurement errors in the winding of the axles. The brake pressure control loop during the unwinding part of the control can be seen in Figure 4.5 on the next page. In this figure the reference signal is the desired winding of the axles, usually 0.02 revolutions past the point of no wind-up. The difference between the reference and the actual winding of the axles is then integrated and fed to the control system. In addition to this input the control system also gets two extra inputs. A constant pressure that is used to overcome the initial pressure needed to activate the brakes and to compensate for the slow feedback over the bus and thus resulting in a faster initial braking. The second extra input is a feed forward signal from the steering wheel angle. This is done since the act of turning will result in a wind up of the axles and thus requiring more brake pressure. A major task for the control algorithm is to identify situations where no braking is required despite there being a wind-up of the axles. These can be categorized into two categories, one for cases where the axles will unwind themselves and one for cases where the effort to unwind the axles would result in too high brake pressures that might severely effect the stability of the truck. In order to identify these cases the system will use three measurement signals, the steering wheel angle, the axle torsion, and the vehicle speed. In the first category, there are turns in a direction that will unwind the axles without any assistants from the brake system, this can be identified by comparing the axle torsion and the steering wheel angle. If for example, the steering wheel angle shows that the vehicle are turning to the right and the axle torsion shows that the right wheel has rotated furthest, the axle will unwind itself. In the second category are sharp turns that would require really high brake pressures to overcome and would result in severe instability of the truck, this can also be identified by looking on the steering angle and see if the absolute value is getting too large. In this category is also the case were the vehicle speed is to low.

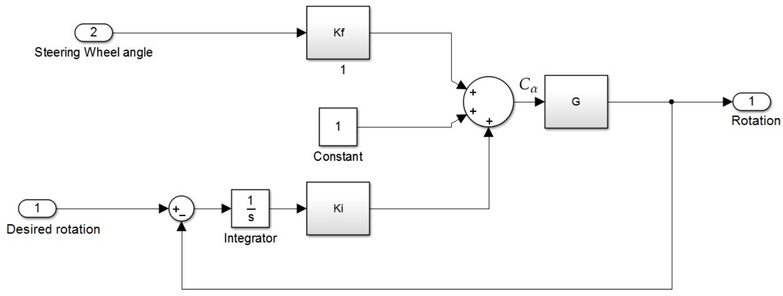

Figure 4.5: *Concept of the unlocking control loop, the actual control was made in MatLab, Stateflow. The input, Desired rotation, is the desired winding of the axles, C_α is the applied brake pressure and the output is the current winding of the axles.*

4.5 Calculating Wheel-Stiffness

The wheel-stiffness, in this case, is a measure of how much the drive wheels slip relative to torque applied on them by the engine. This is not a linear process since at large enough torque depending on tire, road conditions and so on, the force between the tires and the road surface will completely overcome the static friction. Due to the gape between static and kinetic friction coefficients, the process becomes hard to predict close to or above the threshold of static friction, see Figure 4.6 on the facing page. In Figure 4.6 on the next page the data is collected from a test run with a series of accelerations, data collected during cornering and braking have been removed to better show the linearity at lower engine powers. This test run was done on asphalt but for surfaces with lower friction both the point of non linearity and the overall look of the non linearity may be completely different.

The goal of the stiffness calculation is to continuously identify the slope coefficient of the linear part as seen in Figure 4.6 on the facing page. To do this, drive wheel slip and engine force are periodically sampled and stored in five different vectors of length 40 elements. Which vectors the data was placed in depend on the current engine force, there were five intervals 0–5 [kN], 5–10 [kN], 10–15 [kN], 15–25 [kN] and 25–40 [kN]. The current slip of the drive wheels are stored in corresponding vectors. As the vector gets filled, the oldest data will be removed to give room for new data. Periodically, a mean value vill be calculated for each vector and a least square fit will be calculated on these values to get the slope coefficient, see Figure 4.7 on page 20. Note that the data in Figure 4.6 on the facing page and Figure 4.7 on page 20 were collected during different test runs. The data in Figure 4.6 on the facing page were collected during a long run

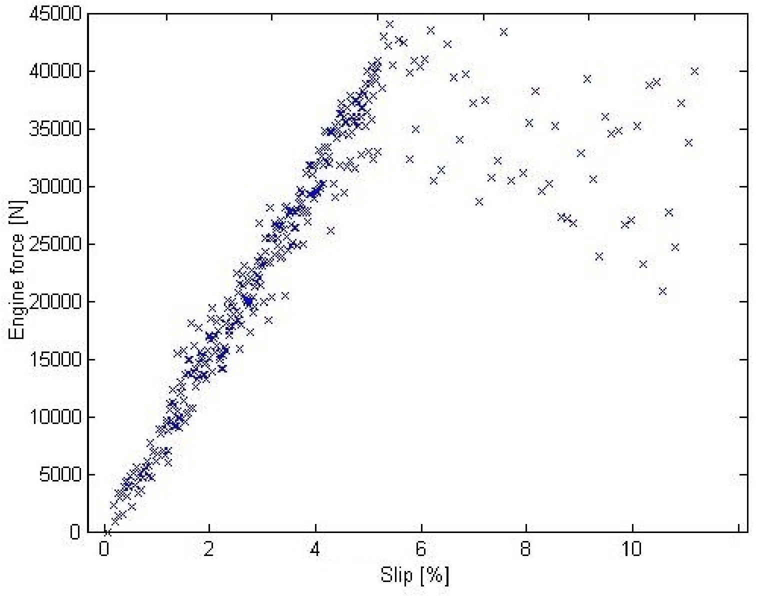

Figure 4.6: *This plot shows the correlation between wheel slip and engine force. The data were collected during a test run.*

on a freeway while the data in Figure 4.7 on the next page were collected during a fairly short run on the Scania test truck that, as mentioned, contains a lot of turns during which no wheel-stiffness data can be collected due to the difference in wheel speeds between the right and left side. This is why Figure 4.7 on the following page not appears to be as liner as Figure 4.6.

The value derived from these tests have been confirmed to be accurate within 1 % through off-line calculations with more data points.

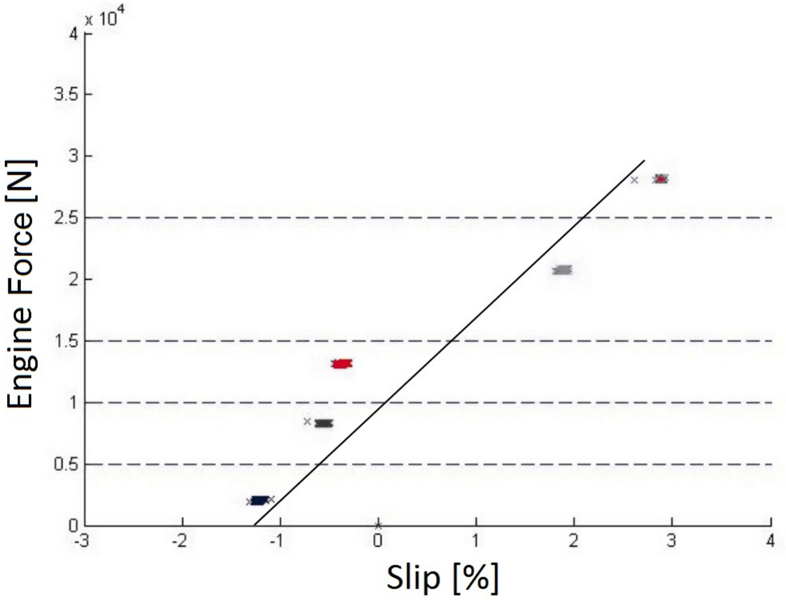

Figure 4.7: *This plot shows the mean values of each vector and how they change during a test run. Due to a offsets in the data used to calculate these data points, the line is moved slightly to the left, but since it's the slop of the line that is interesting this does not effect the results.*

5

Results

The performance of the differential locking control system will be evaluated in this chapter and will mainly be based on the minimization of lock/unlock-time. A second and probably equally important parameter is how the system is perceived by the driver, this includes driver controllability and overall comfort. This is harder to quantify and to do a fair comparison between different approaches. Some drivers might prioritize a faster lock/unlock and be more forgiving to the fact that they have to compensate for potential veer of the truck whilst other drivers might priorities differently. It is also hard to see how these prioritize might change over time when drivers get more used to the system.

According to the drivers of one of Scanias test trucks that were loaned out to a trucking company, the uncertainty of when the differential would lock made many drivers hesitate to use the differential lock. So a more aggressive approach i.e. higher brake pressures, might be preferable.

5.1 Evaluation

When it comes to locking the differential there are several ways to evaluate the performance of the control system. The main one is as mentioned in the beginning of this chapter the lock-time but this chapter will also contain evaluations of the control loop and how well it performs as intended.

5.1.1 Lock-Time Evaluation

In order to evaluate the performance of the lock-system, some reference data from test runs without the system activated were collected. The lock times, i.e. the time between a requested lock and a registered lock, can be seen in table 5.1.

This table shows some fast locks where the cogs are in favorable positions but over all few locks occurs within 10 s and some locks occurs over a minute after the lock request have been given. These data were collected on the Scania test track which contains different types of corners, road surfaces, inclines and straits. Lock requests were then given randomly during two laps.

Lock time [s]
18.7
9.9
10.8
5.0
18.7
80.3
18.7
0.4
17.1
80.1
Mean Value:
26
Standard deviation:
29.2517

Table 5.1: *Time between requested lock and registered lock [s].*

With the lock-system enabled, the lock-times clearly decreases, see Table 5.2 on the facing page, but as previously mentioned it is important to see at what cost. The easiest way to measure how much the system interferes with the performance of the vehicle is to measure the maximum amount of brake pressure applied during each lock. This can be seen in table 5.2. During this test run, the system parameters where set quite aggressively which means that the system was to prioritize fast locks over low brake pressures. This was the technique preferred by the test driver since he felt that it was easier to compensate a sudden jerk than a slower more constant pull over a longer period of time. With consideration to that the drivers of the test truck were hesitant to use the differential lock due to the inconsistency in lock-time, as mentioned in the beginning of this chapter, these settings should be preferred since they give a consistent lock time that rarely exceeds 2 s. To get a sense of what these brake pressures means, the maximum brake pressure that can be applied is 1000 kPa. In Table 5.2, the maximum applied brake pressure is 495 kPa which is a very noticeable braking but can be compensated quite easily by a prepared driver and the decrease in speed was only 2 km/h during a 1.83 s braking.

In order to activate the differential lock, a knob is turned into different positions depending on which differential to lock. The differential lock system in this thesis was designed to be activated separately from this knob, see Figure 5.1, by a button next to it. This means that the driver can choose to use the system or not which allows for more aggressive braking since the driver is more prepared to

Lock time [s]	Left pressure [kPa]	Right pressure [kPa]	Decrease in speed [km/h]	Initial speed [km/h]
1.0400	0	440	2.5586	20.7617
1.4300	300	0	1.7520	24.9883
1.6300	0	210	1.9277	35.8730
0.1400	0	0	-0.0527	35.3535
1.2400	0	260	1.4375	30.6016
2.3400	300	0	2.6406	30.3105
1.5400	0	340	1.1367	20.0059
0.3400	0	105	0.5371	24.8945
0.4400	0	200	0.8828	25.3008
1.5400	0	405	0.2969	18.0625
0.6300	0	0	0.0918	11.8262
0.8300	0	370	1.8086	25.1777
1.9300	315	0	0.3223	24.6563
1.1300	340	0	1.3398	19.0938
0.1300	0	0	0.0195	14.8105
2.0300	0	330	-2.2207	24.2598
1.3300	0	240	-0.4023	24.8301
0.6300	0	0	0.6719	17.1719
0.6300	495	0	2.0527	30.0742
1.2300	400	0	-0.1445	18.1211
0.9300	450	0	2.5605	16.0449
1.1300	0	0	-0.9844	22.5195
1.1300	0	0	-0.2930	24.7422
0.4300	0	0	-0.3457	26.0352
1.1300	0	180	0.0996	23.7930
1.8300	0	0	-1.1914	25.6699
0.3300	0	0	-0.0469	29.4648
0.6300	0	0	-0.0234	23.4629
1.6300	0	190	2.1230	41.2324
0.8300	0	235	1.6934	39.0488
1.6300	220	0	3.3359	37.6855
0.4300	0	175	0.3809	34.3223
1.8300	0	350	3.9395	24.0469
1.2300	0	325	2.0215	24.3730
0.4300	0	215	0.4453	24.8320
2.0300	350	0	1.1582	17.4648
0.1400	0	0	-0.0840	24.9453
Mean:				
1.0784	352.2222*	267.0588*	1.2951**	26.1483**
Standard deviation:				
0.6067	84.1914*	88.6013*	1.2968**	6.9044**

Table 5.2: *Time between requested lock and registered lock [s]. *The values were only calculated when pressure were being applied on the right respectively left brake. **The values were only calculated when pressure were being applied on the right or left brake.*

compensate for the braking.

Figure 5.1: *Differential lock control.*

To sum up, the performance of the lock-system greatly reduces lock-times and is fairly consistent, rarely exceeding 2 s. There is a decrease in vehicle speed as a result of the braking which sometimes is as high as 4 km/h, unfortunately this can't simply be compensated by giving more power to the engine as this would counteract the locking of the axles. Overall, the system works well with a relative short and consistent lock-time and a not to severe effect on driver controllability.

5.1.2 Unlock-Time Evaluation

The evaluation off the unlock-system will be covered in this section and will be done in the same fashion as for the lock-system. When it comes to unlocking, the main reason that the differential lock do not disengage is that there is a momentum between the cogwheels as a result of a torsion of the axles which in turn is a result of the turning of the vehicle. This torsion will, as mentioned in Section 4.3, be counteracted by braking the wheel that has rotated the furthest. But if the vehicle is turning sharply when the unlock request is given, the brake pressure required to overcome that torque will be too great and will also cause the vehicle to increase its turn radius which might be dangerous on narrow roads. Since the system will not engage if the steering wheel angle is too great, it will cause the unlock times to be less predictable.

As an initial comparison, as in the case of the lock-system, some test runs were performed with the system disengaged. The result of this can be seen in Table 5.3.

Lock time
0.5
8.6
11.4
8.6
14.7
17.5
6.0
17.1
23.1
0.9
11.1
Mean Value:
10.9
Standard deviation:
6.9879

Table 5.3: *Time between unrequested lock and registrated unlock [s].*

After this, some new test runs were made with the unlock-system activated. These results can be seen in Table 5.4. Note that during these test runs, the between the locking of the differential and an unlock request time were varied to see how well the wind-up of the axles could be measured.

From these results it is clear that if the winding of the axles is correctly calculated, which were the case in all locks above, the system achieves a fairly fast unlocking and that the unlock time variations is mostly related to steering wheel angle since all brakes above 500 kPa occurs at steering angles above 580 degrees, see Figure 5.2. If the wind-up is calculated to be in the wrong direction, the system will brake the wrong wheel and not achieve an unlocking. However, since the system only has access to the wheel speeds that have been calculated using the adaptive wheel radius, see Section 3.3, there is a slight measurement error that will be amplified through the integration and the system will measure a wind up of the axles that is not present. This may cause the system to either brake the wrong wheel or brake the correct wheel but not for a long enough period of time. To avoid this, some extra functions will have to be implemented that can detect inconsistency from the different sensors. One such function might reset the wind up of the axles if the steering angle is close to zero for an extended period of time. This can be done since the torsion in a winded axle will counteract the wind-up of the axle. This means that if no extra force is applied to either wheel, i.e. the truck is driving straight, the axle will unwind itself. If this function should make it in to production trucks, the bus protocol should probably have to be changed in order to give the system access to the wheel rotation speed to prevent faulty wheel radius calculation to play any part. For more possible improvements, see Chapter 7.

Unlock time [s]	Left pressure [kPa]	Right pressure [kPa]	Decrees in speed [km/h]	Steering wheel angle [degrees]	Time locked [s]
0.4400	130	0	-0.5957	-8.9511	0
5.9300	275	35	10.4863	11.7515	8.5700
0.1400	0	0	-0.1348	-3.0201	39.8600
0.5400	100	0	0.1328	-2.6844	4.4600
0.1400	0	0	-0.0371	-2.4606	33.3600
5.8400	160	50	9.5469	94.2260	9.1600
0.4300	125	0	-0.2793	-4.2511	35.0700
0.1300	0	0	-0.0508	-2.7963	5.3700
2.1300	140	0	0.2539	-6.4892	24.8700
7.2400	970	0	10.8809	- 582.2446	19.2600
25.630	965	0	5.6836	-625.4403	22.8700
0.9300	105	0	-0.4609	0.2252	10.0700
15.730	205	0	7.6113	-1.3415	23.7700
31.630	910	985	7.0234	623.8763	21.3700
7.9300	565	550	14.9883	642.0050	21.5700
0.4300	105	0	-0.2930	-2.5725	20.5700
5.9300	215	0	-0.0742	101.8356	19.5700
2.5300	200	0	-0.1055	-23.4989	3.4700
4.8300	245	0	2.3105	9.9610	73.1800
1.8300	0	150	0.2930	106.4238	7.6700
2.2300	250	0	2.9277	-39.1657	5.7700
4.0300	645	855	19.2227	695.1603	5.4700
0.9300	225	0	1.7129	-91.7614	22.0700
1.8300	0	90	-0.4512	110.3405	11.6700
4.8300	205	0	5.0078	-41.9633	5.1700
4.0300	300	165	10.4902	254.4752	5.4700
1.2300	55	85	0.3164	2.5752	24.2700
0.1300	0	0	-0.0586	-1.5653	3.8700
1.0300	100	0	0.5625	-15.1059	5.9700
11.630	275	0	15.8457	103.1785	7.8700
16.230	165	0	1.9141	1.2323	28.2700
0.0300	0	0	-0.0566	-3.2439	9.4700
0.4300	75	0	0.0391	-0.7820	5.5700
0.4300	150	0	-0.0391	-1.1177	27.0700
Mean:					
5.8766	295.1613*	308.0000*	4.2372**	33.1372	16.9647
Standard deviation:					
7.5527	269.0926*	355.4512*	5.4145**	238.6986	13.8363

Table 5.4: *Time between requested unlock and registered unlock [s]. *The values were only calculated when pressure was being applied on the right and left brake, respectively. **The values were only calculated when pressure was being applied on the right or left brake.*

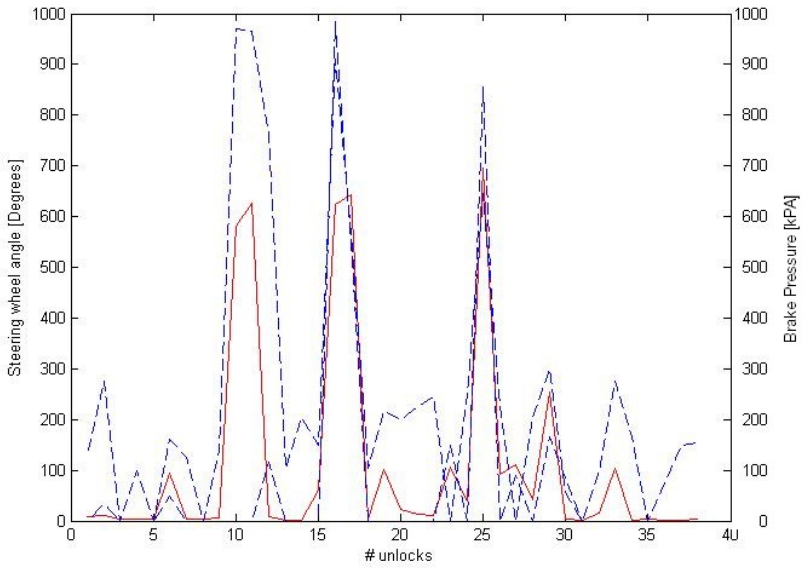

Figure 5.2: *The solid line shows the stering wheel angle and the dashed lines shows the brake pressure.*

So to sum up, the unlock function works fairly well if the torsion of the axles is correctly calculated but is not consistent enough and need some more work before it could be implemented in production trucks.

5.1.3 Brake Pressure Control-Loop Evaluation

In order to evaluate the brake pressure control-loop, some tests were performed to see how well the system followed the reference signal. In this test, a lock request was given which orders the system to achieve a rotational speed difference of 0.1 rotations/s. The test were performed when the truck was driving in a straight line, which means that there were no initial speed difference between the too wheels. The result of this test can be seen in Figure 5.3. These teste iluminates the delay caused by the bus and especially the brake-system. The slow response time of the system is clear from this figure with a 10% to 90% rise-time of 0.4 s and a 0% to 90% rise-time of 0.8 s. The system tends to oscillate once it reaches the reference signal level as a result of the slow sample rate. Despite this oscillation, the system stays above 80% of the reference signal which works well enough for this application.

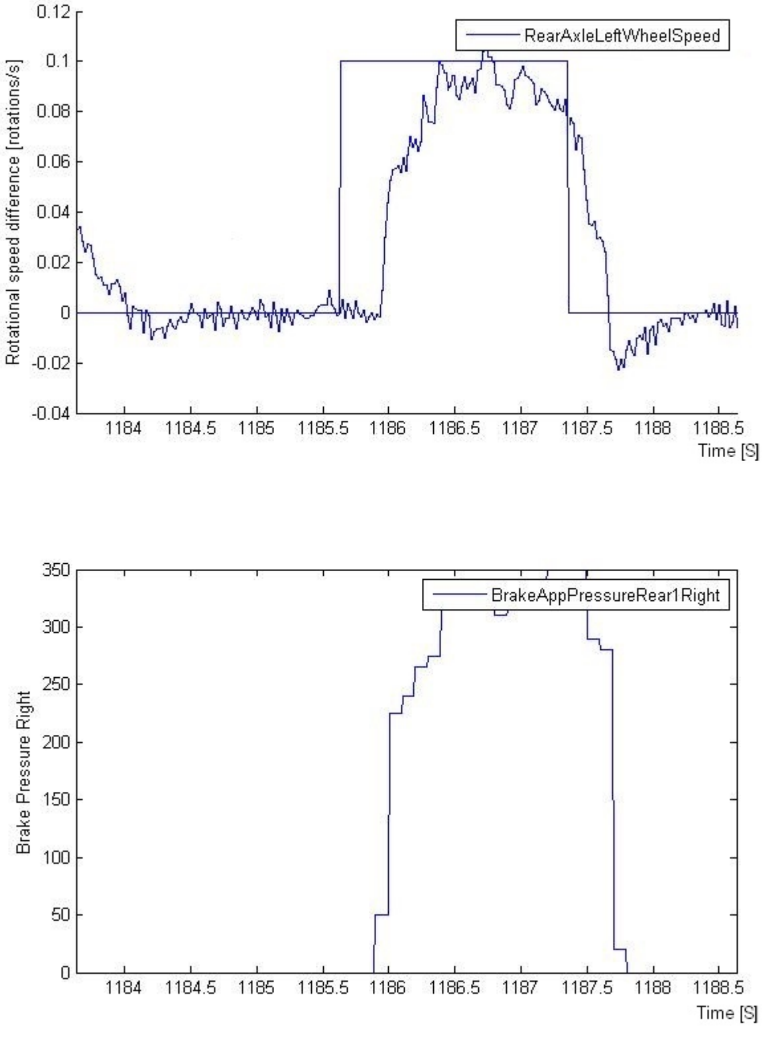

Figure 5.3: *The top graph shows how the rotation speed difference of the wheel follows the reference signal. The bottom graph shows the applied brake pressure.*

6

Relation to other work

Lots of work have been done in the field of traction control, most modern cars have some sort of active traction control, see 1.1 on page 4.

In the case of traction control through the differential, most work are focused on limited slip differentials or self-locking differentials but these are mainly used in smaller vehicles.

There are alternatives to the type of differential lock used in this thesis, where friction plates is used instead of gears, see [11]. This has the advantage of not having to to line up the cogs inorder to lock/unlock the differential.

Other truck manufacturers that uses locking differentials have similar systems to the one developed in this thesis, for example Volvo trucks have a system called DLS, Diff Lock Sync, that synchronize the wheels before the differential lock is activated, see [12].

However, no research have been published regarding using the vehicle brakes to aid in the unlocking of the differential, which makes it hard to compare the results from this thesis.

7 Conclusions/Future work

This chapter will cover a conclusion as well as potential improvements on the system and potential other system designs that could be tested.

7.1 Conclusion

The main goal of this thesis was to evaluate if the service brakes on a vehicle can be used to achieve faster locks/unlocks of a differential lock system. An important aspect to evaluate was how the use of the service brakes would effect the vehicles driving performance.

From the data collected in this thesis it is clear that the concept works with decreased lock and unlock times, there are however some things to consider. How much the applied brake pressure effects the drivers control over the vehicle is, as mentioned in Chapter 5, hard to quantify. In order to properly evaluate this, there needs to be a bigger survey with more test pilots to get a broader sense, how the drivers prioritize comfort over fast locks. Note that lower brake pressures do not necessarily means better driver comfort. From such a survey there might be possible to create a couple of preset modes for the locking system, where the driver can choose how aggressively they want to brake. So to sum up, the concept seems to work but some more research needs to be done in order to know how best to implement the feature in to production trucks. The performance of the system might also be improved by improving the brake pressure controller.

7.2 Future Work

As mentioned in 5.1.2 and in 3.3, one of the main problems is that the wheel rotation speed is not available through the bus and this should be a big improvement if the bus protocol could be changed. This would especially help with the unlocking, since it is very sensitive to measurement errors of wheels rotation speed.

Also mentioned in 3.3, the sensor measuring if the differential is locked some times gives false readings and do not show the differential to be locked if the differential is actually locked but the cogwheels have not been completely pushed together. This is a bigger problem since it requires a new sensor, that can measure the position of the cogwheels relative to each other, to be installed. With this improvement, the system would always know if the differential actually was locked or not. An other alternative, that does not require new hardware, is to look at how the wheel speeds change in relationship to each other if the speed difference decreases without a decrease in brake pressure, then it might be best to assume that the cogs have fitted together.

As mentioned in the beginning of this chapter, the unlock system is quite sensitive to measurement errors in the relative rotation speed of the drive wheels. Also, as mentioned in Section 5.1.2 there need to be some sort of function that compensates for these measurement errors and don't allow the integration to drift. Considering these problems, there might be necessary to investigate other approaches. One idea would be to only use the calculated wind-up of the axles to perform an initial guess of which wheel to brake. After this initial brake has been performed, the relative wheel speeds would be measured as well as the relative rotation. The maximum torsion, of the axles could be known through tests on each truck. So if the relative change in wheel speed started to drastically decrease, without any change in brake pressure, before the axles torsion would have reached half of the maximum torsion the system would know that the axles would have started to get winded-up in the other direction. This means that the system had braked the wrong wheel and could start braking the other. This solution would be more robust towards measurement errors but can not identify when the axles are in an unwinded state. The approach might be used as a backup for the system developed in this thesis and step in when it detects that the wrong wheel has been braked.

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