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Real-Time Estimation of Tire Stiffness

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Sammanfattning

Ett däck är en nödvändig komponent på ett fordon. Olika däck har olika egenskaper, av vilka en är den longitudinella däckstyvheten. Däckets styvhet kan beskrivas genom att modellera däcket som små 'tråd'-komponenter. Dessa trådar kommer ha kontakt med marken och kommer att delas upp i en vidfästande del och en glidande del. Slippet är trådens rörelse i förhållande till marken. Krafterna som verkar på trådkomponenterna dividerat med slippet är definierat som däckstyvhet.

I denna rapport presenteras en algoritm som beräknar styvheten i realtid. Genom att använda olika algoritmer, som rekursiva minsta kvadratmetoden och minsta kvadratmetoden, testas om en god approximation av däckstyvheten kan uppnås.

Abstract

A tire is an essential part on a vehicle. Different tires have different properties, and one of them is the longitudinal stiffness of the tire. Tire stiffness can be explained by modelling the tire as small thread compounds. These small thread compounds will have contact with the surface and will contain one adhesion and one sliding region. The slip is the motion of the thread compounds relative to the surface. The forces that act on the thread compounds are divided by slip and this is defined as tire stiffness.

This thesis presents a method to estimate the tire stiffness in real-time. By using different algorithms, such as Recursive Least Squares and Least Mean Square, a good approximation of the tire stiffness can be achieved.

Acknowledgments

I would like to thank everyone at brake control group (REVB) and my supervisor at Scania, Sebastian Arcordh. I would also like to thank my supervisor at Linköping University, Kristoffer Ekberg, for proofreading and helping me improve this thesis. I would also like to thank my examiner Jan Åslund.

Södertälje, July 2016
Max Karjalainen

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Notations

Parameters and variables

Notation	Description
V	Speed [km/h]
t	Time [s]
u	Deflection [m]
Ω	Angular speed [RPM]
i	Slip [%]
a, x, r	Distances [m]
F	Force [N]
k	Ratios [1]
M	Momentum [Nm]
C	Tire stiffness [N/slip]

Abbreviations

Abbreviation	Description
CAN	Controller Area Network
ASR	'Antriebsschlupfregelung' or Traction Control (TC)
YC	Yaw Control
ROP	Roll-Over Protection
ABS	Anti-lock Braking System
HEX	Hexadecimal
RPS	Rapid Prototype System
CPU	Central Processing Unit
GPS	Global Positioning System
RLS	Recursive Least Square
LMS	Least Mean Square
RPM	Revolutions Per Minute
USB	Universal Serial Bus
SAE	Society of Automotive Engineers
VCI	Vehicle Communication Interface

1 Introduction

This thesis has been carried out at brake control group at Scania CV AB and is a cooperation between Linköping University and Scania. Scania is a truck and bus manufacturer and mainly located in Södertälje, Sweden. One of their core values is to deliver high quality products to their customers.

1.1 Background

Calculating tire stiffness in propulsion tires from the Controller Area Network Bus (CAN bus) in a vehicle can be done off-line. The problem is when the information of the tire stiffness is going to be used in a real-time application. For example, to modify the traction control parameters in order to get the most out of the tires, the tire stiffness has to be calculated continuously during operation and be available on the CAN bus.

1.2 Problem formulation

The outcome of this thesis is an algorithm which continuously calculates current tire stiffness during operation and distributes the information to the CAN bus, which distributes the information further to other systems in the vehicle.

The task is to investigate which parameters affect the tire stiffness of a truck and develop a method to continuously calculate tire stiffness, using available data from the sensors in the vehicle. The calculations should be made during vehicle operation so that the information can be used to adapt the behaviour of the vehicle, for example control target in anti-spin systems. Methods to calculate tire stiffness are already known and the vast part of this task consists of real-time calculation during vehicle operation. Calculations and implementations are going to be made in Matlab and Simulink. The code will be converted to C-code and tested on actual hardware.

For each longitudinal force that occurs, it is related for a different slip. The aim of this thesis is to create an efficient algorithm which calculates the best fitting linear curve of the tire stiffness. For low slip, the gradient increases linearly with increasing force. The balance between robustness and efficiency should be analyzed. Is it possible with good accuracy of the measured data, estimate the tire stiffness by also using low CPU-power?

1.3 Limitations

The limitations to achieve the result are that different trucks sometimes use different signals from the CAN bus. For example, one signal from one truck might not exist in another one. This may cause difficulties if the signal is essential for the tire stiffness calculation.

Other possible limitations is to handle delayed signals if some signals need to be calculated from other signals.

If the resolutions on the sensors are not sufficient, inaccurate calculations may be made.

1.4 Thesis outline

Chapter 1 A short introduction of the thesis is presented.

Chapter 2 Related work on the topic is presented.

Chapter 3 Vehicle modelling is presented.

Chapter 4 This chapter describes the approach.

Chapter 5 Results are presented.

Chapter 6 Conclusions and further work are discussed.

2

Related work

The articles that have been studied are mainly from SAE database and books, but also literature and documents from internal courses at Scania CV AB have been used. The literature which was chosen is mainly about the brush model for tires and different algorithms, such as recursive least squares, but also about how ABS and brakes work in general. These topics need to be studied further in order to get deeper knowledge of powertrain and tire modeling. The information about longitudinal tire stiffness is limited, but it can be derived if the road longitudinal force and slip are known.

2.1 Books

The books that have been studied is mainly to get deeper knowledge on how tire mechanics work, but also to get further ideas of different and interesting algorithms which can be implemented.

Breuer and Bill [4] describes how brake and ABS systems work and essential parts when modeling tire forces. They also describe how the contact surface changes during brake and load.

Since the braking forces have different behaviour during different road conditions, Day et al. [6] explains the difference on brake performance on different surfaces. Barton and Fieldhouse [2] also they explains brake performance, but also tire modeling with bristles and force distribution.

Wong [20] describes fundamental mechanics of tires, for example how rolling resistance and slip are calculated, but also how the braking force pressure is distributed over the tire.

G.Rill [7] explains in his textbook about vehicle dynamics and explains tire forces and momentum and how it is connected to tire stiffness. He also discuss different properties of tires, and also explains different forces of the tire, which may have to be taken into consideration. This textbook is useful to model and put up equations for tire dynamics.

2.2 Journals and papers

The journals contain mechanics of tires and how to calculate tire parameters. The journals also show the progress and results in research.

Sivaramakrishnan et al. [15] explains how tire design affects ABS systems and its stopping distance. In their research they tested tires with different stiffness in carcass and tread but also tread compound. Their research is based on linear parametrization to estimate the tire parameters on-line. The tire slip set point are achieved for the ABS-controller. With this result, a higher performance for a braking system can be achieved. Stellet et al. [18] also investigates how to maximize the vehicle safety in order to maximize the braking force but for electric vehicles. In their research, it is clear that the same theory can be applied for different propulsion.

Carlson and Gerdes [5] presents how to identify the longitudinal stiffness using sensors from GPS and ABS. They also present which parameters that affect the stiffness for low slip. They also conclude that inflation pressure, tread depth, normal load and temperature affect the tire stiffness. Miller et al. [12] answers the same question but uses different methods to achieve the answer. Their method is to use least-square to estimate the stiffness. An interesting point is that they do not use any filter for the speed of the vehicle except moving average. The moving average filter is only used to neglect outliers. Their research are based on post-processing of tire estimation, but they point out, if real-time estimation is being made, a higher update interval with no latency will be needed.

Ledesma [8] addresses different stiffness parameters in order to more accurate estimate the vehicle handling. He also shows that all three of the tire parameters are important when estimating the vehicle handling. In his paper he also put focus on truck handling which may be important in this thesis.

The paper by Bhoopalam et al. [3] investigate the friction between tire and ice. They also test the behaviour of tires on different surfaces. The outcome is a new design for wheels on trucks which drives on slippery surfaces. Their method is to model and simulate instead of running experimental tests in order to lower the cost.

The paper by Sorniotti and Velardocchia [16] explains how to permit real-time vehicle simulations. By using modeling they achieved a good fit of experimental data. Even if the modeling of the contact path may be unrealistic, they also show that a good fit can be achieved.

Miller et al. [12] presents how to generate a force-slip curve for the longitudinal stiffness and which algorithms that are used to identify the tire parameters. They also discuss different difficulties to estimate the tire parameters.

Svendenius and Wittenmark [19] present how to estimate the tire friction from simulation, and also how to improve the brush model. To do this, they have to study further about tire modeling, including the brush model, and friction estimation.

3 Modeling

The main part of this task is to create a model which calculates the tire stiffness in real-time. Mathematical modeling can be used to calculate the longitudinal force by using the brush model. The brush model is a simplified tire model which can be used to get an understanding of the longitudinal forces reacting on the contact patch of the tire and how slip is defined. The aim of this thesis is mainly focused on the longitudinal force of the tire. In order to calculate the tire stiffness, both momentum, force and slip have to be calculated. The longitudinal tire stiffness is the interesting one of this thesis.

3.1 Available signals

The inputs available from the CAN bus are found in table 3.1. To calculate the slip, the front tires are used as reference speed to compare with the rear wheels. By sending the speed of the propulsion tires and front wheel tires measurements to the CAN bus, it is possible to calculate the tire stiffness by dividing the longitudinal force by the longitudinal slip. The force is being plotted against slip and the resulting gradient is going to be estimated. The equations are explained in more detail in chapter 3.3 and 3.6.

Signal name	Explanation
t	Time vector
ABSActive	Indicates if ABS is active
ActualTransmissionOutputShaftTorque	Output momentum from transmission in Nm
FrontAxleLeftWheelSpeed FrontAxleRightWheelSpeed	The speed of the front wheels
RearAxleLeftWheelRotationalSpeed RearAxleRightWheelRotationalSpeed	The rotational speed of the rear wheels.
EngineSpeed	The speed of the engine in RPM
AxleWeight	The weight of indicated axle at certain time point
AxleLocation	Which axle it is measuring at the moment. The output is in HEX
ActualGearRatio	Gear ratio from the engine- to transmission shaft
ASRBrakeControlActive ASREngineControlActive	Indicates if ASR is active
YCBrakeControlActive YCEngineControlActive	Indicates if YC is active
ROPEngineControlActive ROPBrakeControlActive	Indicates if ROP is active
SteeringWheelAngle	Shows the steering wheel angle in radians
EngineAcceleration	Shows engine acceleration
AcceleratorPedalPosition	Shows in which position the accelerator has
BrakePedalPosition	Position of the brake pedal
SpeedDiff	Calculated speed difference between front- and rear wheels.

Table 3.1: *Table of useful signals from CAN bus*

The signals from the CAN bus in table 3.1 can be used by units in the truck to send messages to other components. Some of the signals, for example ABS, can set a flag, and when it is set, the algorithm can neglect the measured data in order to get more accurate measurements. The same can be applied for other signals. For example, when a certain threshold has been reached, or a flag been set, a system can stop collecting measurement data in order to neglect bad measurements. The brake and engine control works in parallell. For example, when the ROP-control needs to be activated, the engine control gets first activated and, if needed, also the brake control. Further discussion of which thresholds are being used can be found in chapter 4.3.

3.2 Vehicle modeling

According to Miller et al. [12], the longitudinal motion of a vehicle can be described as:

$$F_{xf} + F_{xr} - F_{rr} - F_d - mgsin\theta = ma_x \tag{3.1}$$

where F_{xf} is the driving, longitudinal force, F_{xr} is the braking, longitudinal force, F_{rr} the rolling resistance, F_d is the drag and θ is the grade angle. When driving at low speeds in no hills, the rolling resistance, drag force and grade can be neglected. From equation 3.1, following equation is obtained:

$$F_{xf} + F_{xr} = ma_x \tag{3.2}$$

Since the algorithm will be tested in high and low speeds, both equations 3.1 and 3.2 are interesting to compare.

3.3 Powertrain

If there is not any available sensors that measures tire forces, a powertrain has to be modeled in order to calculate the tire forces. The powertrain is an ideal model without any friction. Also, the power losses in the powertrain are neglected.

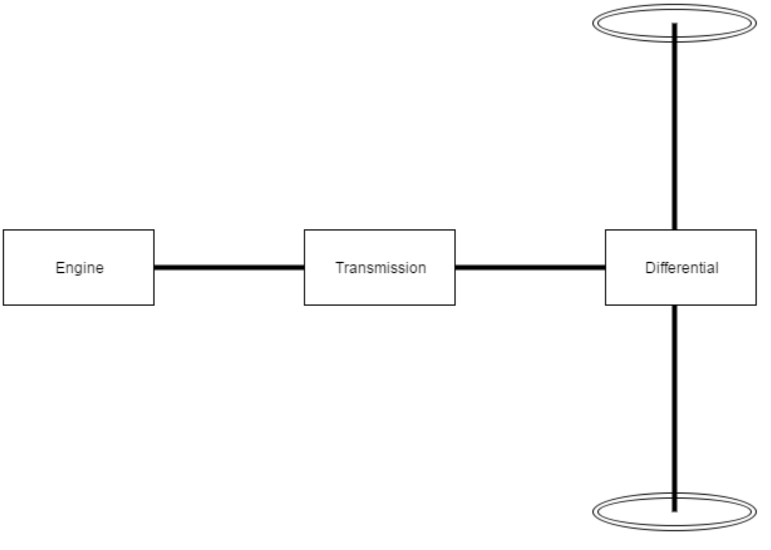

Figure 3.1: *Simplified powertrain of a vehicle with transmission and engine torque as input and tire force as output singals*

Figure 3.1 shows a simplified powertrain of a vehicle. The powertrain is using sensors measuring engine torque and transmission output torque as input. From the engine, the output speed is also being measured. Also, the gearing ratio can be calculated by taking dividing engine speed by transmission output shaft speed.

The same applies for the differential and the rotational speed of the wheels. The ratio for the differential can be calculated because the engine, transmission and wheel rotational speeds can be measured. Since the torque from engine and transmission are available, the forces applied on the wheel can be calculated.

3.3.1 Powertrain modeling

From the engine, the output shaft torque can be measured with a sensors. The same can also be measured from the transmission output shaft torque. The ratio between these two output torques are the gear ratio and changes depending on which gear that is selected. The differential in figure 3.1 has a fixed ratio. The differential constant can be obtained from an equation which is described by Longhurst [10]. The fixed constant can be written as $\frac{input}{output} = k$. From this fixed constant, the force applied to the tire can be calculated. It is also assumed that there is no loss of energy in the differential gear. But to calculate the differential constant, the wheel speed sensors and rotational wheel speed sensors can be used. This yields following equations.

$$\Omega_{engine} = k_{gear}\Omega_{transmission} \tag{3.3}$$

$$\Omega_{transmission} = k_{differential}\Omega_{tire} \tag{3.4}$$

In equations 3.3 and 3.4 the ratio between the different blocks, as in figure 3.1 can be seen. In equation 3.4 it is a fixed constant and is different from each truck.

In figure 3.1 and using the same analogy from equations 3.3 and 3.4, the ratio for the differential can be calculated with following formula:

$$k_{differential} = \frac{\Omega_{engine}}{k_{gear}\Omega_{tire}} \tag{3.5}$$

or using

$$k_{differential} = \frac{\Omega_{transmission}}{\Omega_{tire}} \tag{3.6}$$

Now when the ratio for the differential is known, it is possible to estimate the applied momentum on the tire.

3.3.2 Calculation of differential constant

The constant $k_{differential}$ can be obtained from a vehicle database, or calculated with equation 3.6 using the wheel speed rotational sensors and transmission output speed sensor in table 3.1 of the truck. Since the signal from the CAN bus is in RPM, it has to be rewritten with the same formula as in equation 3.14.

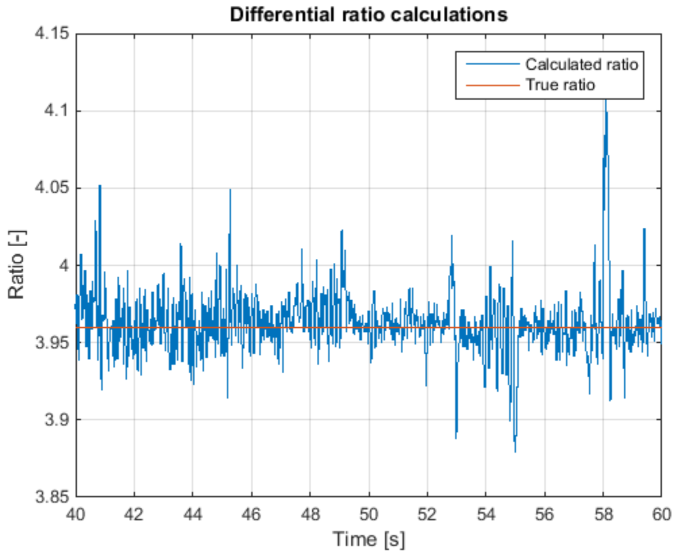

Figure 3.2: *Differential calculations during a test drive*

In figure 3.2 it is shown that the differential ratio constant can be calculated with a good accuracy but with a noisy signal.

3.4 Output torque

The output torque is the torque that acts on different components of the vehicle. The torque which acts on the tire, is called M_{tire}, can be calculated from the sensor using following formula:

$$M_{tire} = k_{differential} M_{transmission} \tag{3.7}$$

or

$$M_{tire} = k_{differential} k_{transmission} M_{engine} \tag{3.8}$$

if the delay is critical.

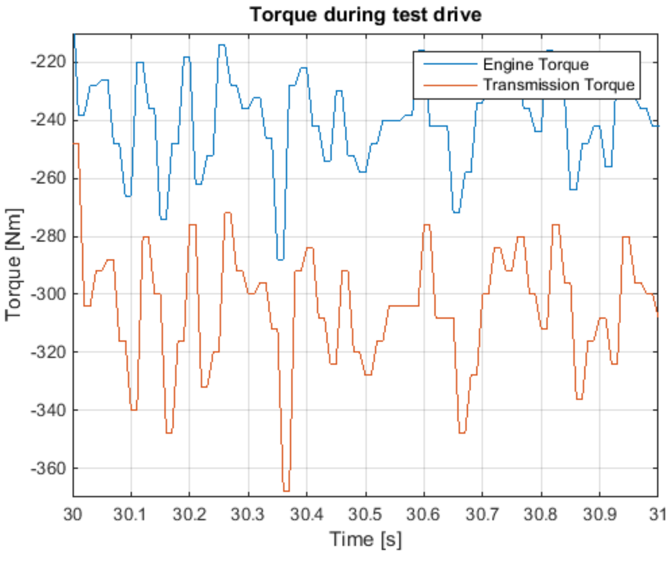

Figure 3.3: *Measured torque from transmission and engine during test drive*

From figure 3.3 it is clear that the measured transmission torque from the sensors are somewhat delayed compared to the engine torque.

3.5 Driving force

A driving force, performed during a test drive were plotted against time and can be shown in figure 3.4.

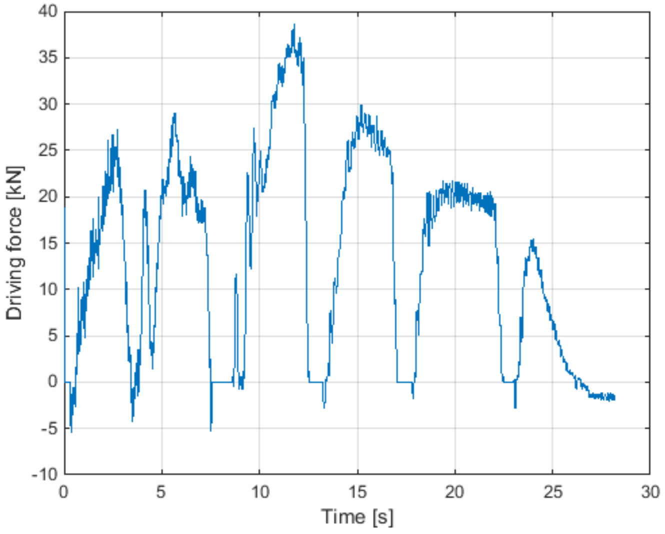

Figure 3.4: *Characteristic driving forces during a testdrive which shows the applied force on the tire*

Figure 3.4 shows the tire forces applied on the tire during a test drive. The tire torque is calculated as in following equation:

$$M_{transmission} * k_{differential} = M_{tire} \tag{3.9}$$

and the tire force is calculated as:

$$\frac{M_{transmission} * k_{differential}[Nm]}{r_{tire}[m]} = F_{tire}[N] \tag{3.10}$$

The output is taken from the transmission output torque and multiplied with the differential ratio and divided by tire radius. Hence, the driving force is obtained.

One interesting approach, which will not be used in this thesis, is to use the normalized force to plot the force-slip graph by using the axle weight sensors on the truck.

$$\mu = \frac{F_{tire}}{F_z} \tag{3.11}$$

In equation 3.11, F_{tire} is the longitudinal force and F_z is the vertical force.

3.6 Brush model

A tire can be modeled as small bristles that flexes in the longitudinal direction. When a force is applied on the tire, and the tire is rolling, the bristles starts to flex. This flexing is defined as slip. Here is also a slip point, s' introduced. The slip point is defined at the same distance as the center of rotation when the tire is rolling freely with the speed V_x.

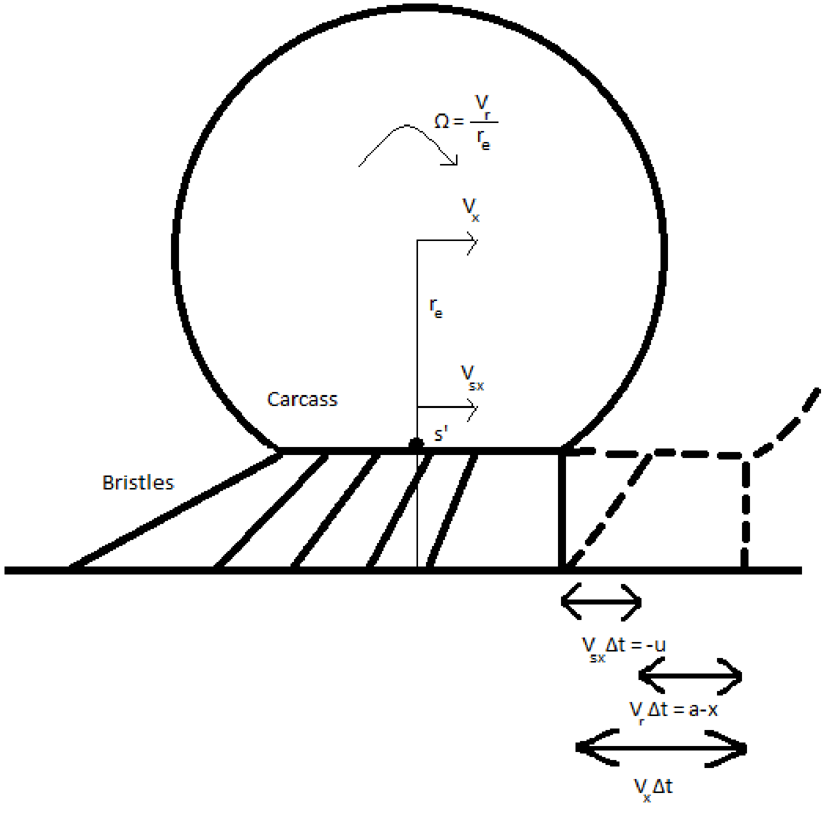

Figure 3.5: *Longitudinal brush model with applied forces on the bristles during rolling from a side-view with deflection u for one time step Δt*

Figure 3.5 based on Pacejka [13], shows a simple tire model according to the longitudinal brush model. The tire has an effective radius of r_e. A tire contains of a carcass and its bristles. The carcass is rigid and the bristles are elastic and deform when a force is applied on the bristles. The bristles are moving with the speed V_{sx}. The propulsion tire is moving with the speed V_r. The total travel distance of the vehicle during one time step Δt is $a - x + u$, where $a - x$ is the traveling distance of the propulsion tire, while u is the traveling distance while rolling freely. When the tire is rolling, the first bristle that has contact with the surface is perpendicular as seen in figure 3.5. During its contact with the surface, the deflection will increase. When the bristle is leftmost in figure 3.5, the maximum deflection is reached. The total force is the sum for the adhesion and sliding region. With the brush model, the slip can be defined and derived and found in subsection 3.6.1.

3.6.1 Longitudinal slip

The longitudinal slip the relative speed between the a free rolling tire and a propulsion tire. As seen in figure 3.5, a bristle is moving towards the left, has been deflected with the distance u. V_x is used as reference speed. From figure 3.5 and derivation from Pacejka [13], Δt can be expressed as $\frac{a-x}{V_x}$, and the following equation can be obtained.

$$u = -V_{sx}\frac{a-x}{V_x} \tag{3.12}$$

In equation 3.12, one can see that the deflection is dependent of the travelling speed of the vehicle and its slip-point. The deflection is u, the total travelling distance after a time step is $a-x$, V_{sx} is the travelling speed of the slip point. The speed of the slip point is the free rolling speed, V_x, minus the linear speed, V_r. Wong [20] explains this phenomena that the propulsion tire will travel shorter than a wheel in free rolling. The slip, defined from Sivaramakrishnan et al. [15] is the distance one bristle travels from its hibernation, can be written as:

$$i = \frac{V_x - r_e\Omega}{V_x} \tag{3.13}$$

Where i is the slip using the ratio $\frac{u}{a-x}$, V_x is the longitudinal speed of the vehicle, r_e the effective radius of the wheel and Ω the rotational speed of the propulsion tire. As in equation 3.12, the slip is defined the ratio between the deflection and the linear travel distance.

3.6.2 Tire radius of the propulsion tires

Since the there is no signal of the tire radius from the CAN bus, it has to be hard coded into the model or calculated during operation. During a test drive, different sensors has made the calculation possible. The wheel speed sensors are measuring the longitudinal speed on the front tires while the rotational wheel speed sensors are measuring the rotational wheel speed of the propulsion tires. By using the ratio between wheel speed and rotational wheel speed sensors it is possible to calculate the radius. The wheel speed sensors are measuring the speed in km/h and the rotational wheel speed in RPM. By converting from km/h to RPMand using the radius r in millimeters, one can use following formula:

$$v = 2\pi r * \text{RPM}\frac{36}{10000}[km/h] \tag{3.14}$$

and can be solved for r and simplified:

$$r = \frac{25000v}{3\pi}[mm] \tag{3.15}$$

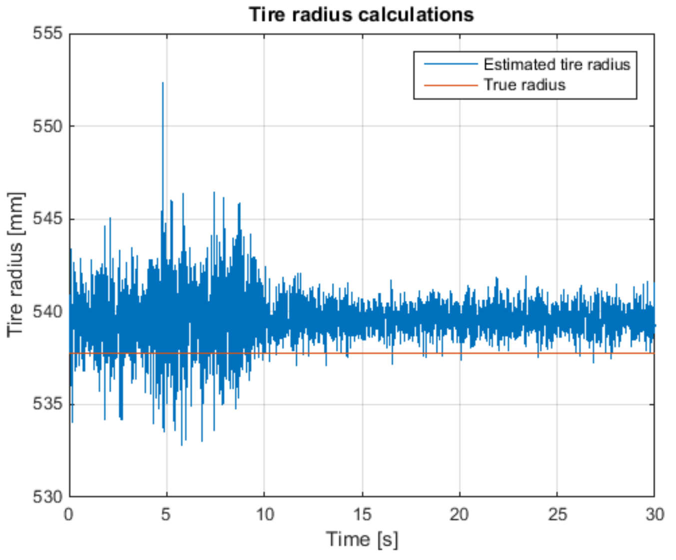

Figure 3.6: *Calculated versus true value, based on specifications, of radius of the propulsion tires during a testdrive using equation 3.15*

As shown in figure 3.6 it is possible to calculate the tire radius using wheel speed sensors and rotational wheel speed sensors, as them found in table 3.1 with a good accuracy.

3.6.3 Lateral slip

The lateral slip is also considered when modeling a tire according to the brush model, but this slip is not taken into consideration in this thesis.

3.7 Longitudinal tire stiffness

Now when the driving force and slip is defined it is possible to plot the force against slip as in figure 3.7.

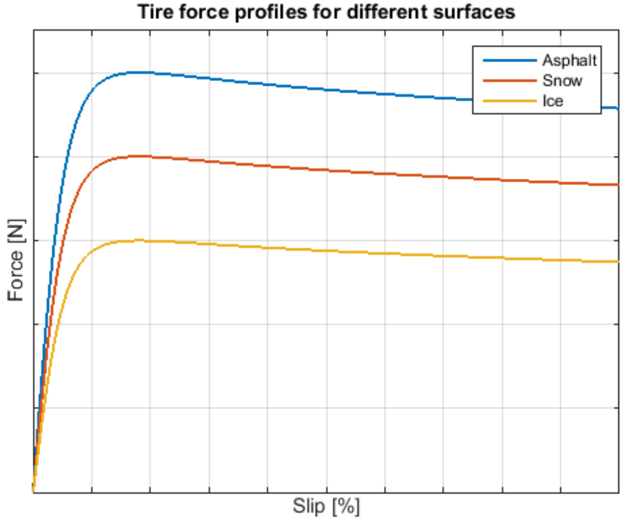

Figure 3.7: *Force slip ratio on different surfaces*

Figure 3.7, shows a characteristic behaviour of longitudinal force at certain slip for different tires according to Singh and Taheri [14]. For low slip the slope in figure 3.7 is linear. By assuming that the tire stiffness is linear, it can be calculated. By sing equation 3.7 and 3.13 to compare the relationship between them, it can be written as:

$$F_{tire} = i\hat{C} + \hat{b} \tag{3.16}$$

In equation 3.16 the offset variable $\hat{b}$ is assumed to be zero. It yields the following equation for the tire stiffness parameter:

$$\frac{F_{tire}}{i} = \hat{C} \tag{3.17}$$

Equation 3.17 shows the formula to calculate the longitudinal tire stiffness.

3.7.1 Applications

The tire stiffness is going to be calculated on different types and conditions of the road, for example wet and dry. Also it will also be tested on different types of tires. Even if the tire is worn out, the software will take it into consideration. Since the properties of the tires are same, even for different road conditions, the gradient of normalized force-slip ratio will stay constant. The only difference is that the maximum traction force before sliding occurs is decreasing. When the tire stiffness is estimated, it is possible to increase the traction control limit and therefor use the maximum capacity of the tire.

3.8 Semi-empirical tire models

Instead of only using plain mathematical and theoretical models it is also interesting to use semi-empirical tire models to investigate the tire parameters. By using semi empirical formulas, both mathematical formulas and experimental values are combined.

3.8.1 The Magic Formula tire model

According to Pacejka [13] a semi-empirical tire model, called the Magic Formula, is modeled from a physical and empirical perspective and is widely used today for tire modeling. The equation can be written as:

$$y = Dsin[CarctanBx - E(Bx - arctanBx)] \tag{3.18}$$

Where B is the stiffness factor, C the shape factor, D peak value and E curvature factor.

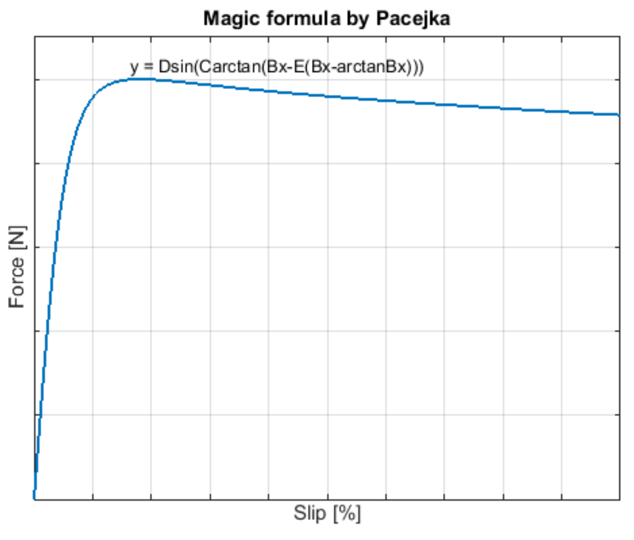

Figure 3.8: *Magic Formula by Pacejka which shows the tire force and slip ratio*

Figure 3.8, described by Pacejka [13], shows a curve, where the parameters have been identified. By creating the tire deformation and measure the resulting tire forces, it is possible to identify the parameters.

4

Approach

In this chapter, the approaches are being explained to show how the the tire stiffness estimation problem is being solved and which hardware and software are being used.

4.1 Algorithms

The different algorithms which are being implemented and tested are both off-line and real-time methods. The least mean squares can be used for off-line processing of data. With off-line processing of data it can be compared to real-time methods such as recursive least squares RLS and Kalman filter. The parameters which has to be estimated is written in the form:

$$y = \hat{a}x + \hat{b} \tag{4.1}$$

where y is the measured force, F_x and x the calculated slip, i. In equation 4.1, $\hat{a}$ is estimated using different algorithms such as recursive least squares. $\hat{b}$ is the offset, which theoretically should be equal to zero.

4.1.1 Least Mean Squares, LMS

The least mean squares (LMS) method minimizes the mean error. After data is collected, the minimized error can be calculated.

$$\min \sum \left\| y - (\hat{a}x + \hat{b}) \right\|^2 \tag{4.2}$$

In equation 4.2 the data has to be collected into a vector and calculated using all sample data. After the data has been collected, $\hat{x}$ can be estimated. This algorithm is best used for off-line calculations and can be used to be compared with the real-time processing.

4.1.2 Recursive Least Squares, RLS

The (RLS) is useful when using real-time parametrization since it uses low amount of memory. The RLS only need the previous state and the current state in order to estimate the parameters, that is, the signal will be processed as it become available. Also, it is necessary to complete the processing within one sample interval. This is stated by Ljung [9]. Stackexchange [17] explains easy step by step explanation of the algorithm. Instead of batch calculation, which least mean squares uses, the algorithm can calculate only by using the new sample update. The algorithm to calculate mean values, described by Stackexchange [17] can be explained as:

Algorithm 1 Recursive mean value

$A = \frac{x_1+x_2+\cdots+x_N}{N}$
procedure CALCULATE MEAN VALUE RECURSIVELY
    $A \leftarrow$ *Read last mean value*
    $A \leftarrow A + \frac{1}{N+1}(A - \textit{new last mean value})$
save and repeat procedure:

As in algorithm 1, the mean estimation can be calculated recursively. The disadvantage using this method is that it first has to collect samples in order to make an estimation. To calculate the tire stiffness recursively the following algorithm from Bar-Shalom et al. [1] is better suitable:

Algorithm 2 Recursive least squares

$\hat{x}(k) \leftarrow$ *Init state*
$P(k) \leftarrow$ *Init covariance*
procedure LOOP
    $S(k+1) = H(k+1)P(k)H(k+1)' + R(k+1)$
    $W(k+1) = P(k)H(k+1)'S(k+1)^{-1}$
    $P(k+1) = P(k) - W(k+1)S(k+1)W(k+1)'$
    $\hat{x}(k+1) = \hat{x}(k) + W(k+1)[z(k+1) - H(k+1)\hat{x}(k)]$
end procedure

In algorithm 2 the recursive least squares which is implemented is explained. The two first steps is to initialize the state and covariance matrix. S is denoting the covariance of the residual, H the calculated slip, R as design parameters, W as parameter update gain, P as recursion of the covariance and $\hat{x}$ as the new state estimate.

4.1.3 Kalman filter

The Kalman filter is very useful when it comes to real-time calculation. With the same reasons as for RLS, the Kalman filter uses a low amount of memory. The

Kalman filter also handles noisy measurements. The Kalman filter will not be implemented in this thesis.

4.1.4 Moving average

A moving average filter will be tested and used to filter outliers. The moving average uses a series of data and then calculates the average of these data points. It can also be seen as a low pass filter in signal processing. The moving average is useful to calculate different constants, like differential constant and tire radius, which can be noisy without using moving average filter and can give quite inaccurate value due to the outliers. According to Mathworks [11] a moving average filter, with an appropriate window size, can be expressed with following equation:

$$y(n) = \frac{1}{windowSize}(x(n) + x(n-1) + \cdots + x(n-(windowSize-1))) \tag{4.3}$$

An application of using a moving average filter is shown in following figure:

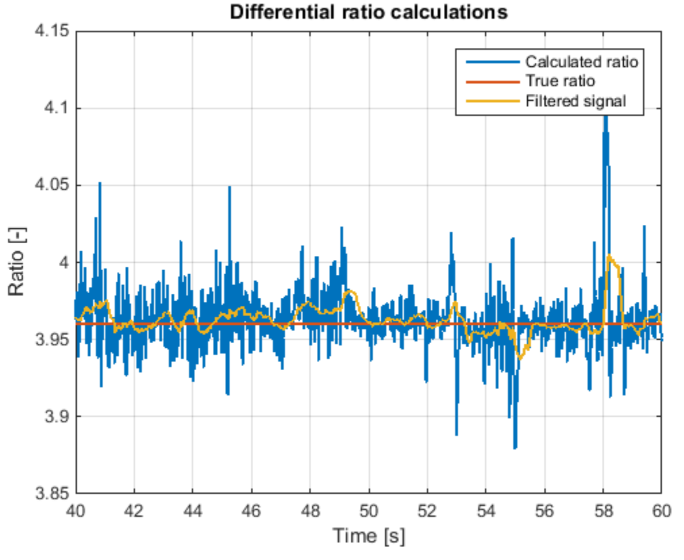

Figure 4.1: *Moving average filter on differential calculation*

In figure 4.1 the result of a low pass filter with window size 50 samples is presented. It shows that it is feasible to use a filter to get a more accurate value of a noisy signal.

4.1.5 Curve fitting

The curve fitting toolbox in Matlab will also be tested to find the best fitting curve to the set of data points collected. This is more appropriate for off-line calculation, but can be used in order to compare to the least squares methods. The curve fitting toolbox in Matlab will calculate a regression line and filter out outliers.

4.2 Experimental setup

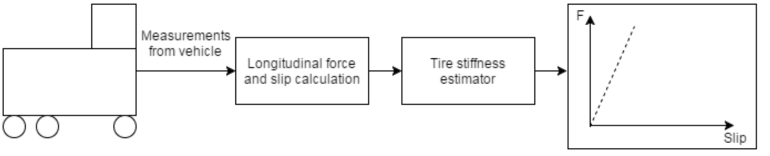

Figure 4.2: *Procedure of the experimental setup*

Figure 4.2 shows how the method is going to proceed. The signals from the vehicle are wheel speed, rotational wheel speed and transmission output momentum sensors. These signals will be used to calculate the slip and tire forces. The second block will estimate the longitudinal tire stiffness. While the truck is driving, the CAN bus will calculate the slip and tire force and then send signals from the vehicle to the estimators.

4.2.1 Data retrieval

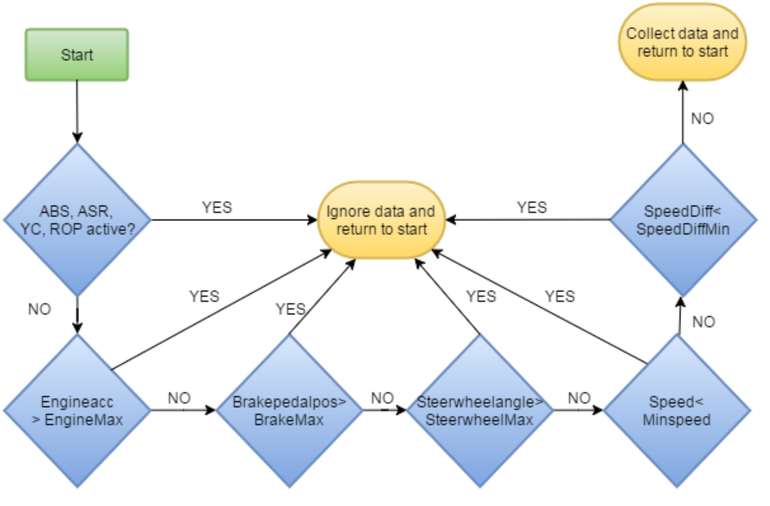

Figure 4.3: *Flowchart of an algorithm for choosing datapoints*

Figure 4.3 shows a flowchart of the data retrieval from the CAN bus. The first block with ABS, ASR, YC and ROP will set a flag, while the others are measurements. For each time sample, the algorithm will estimate the stiffness from the available data and then send it to CAN. When any of the flags or measurements shown in 4.3 is triggered, the data is being ignored since the data is unreliable. The thresholds for these flags are discussed in chapter 4.3.

4.2.2 Software

The software being used is Matlab and Simulink to create a model which can estimate the tire stiffness in real-time. The model was then exported to C-code through Rapid-prototyping (RPS). The complied software is used to flash the RPS in figure 4.4 using the VCI in figure 4.6. To plot the results in realtime, the software Vector CANAlyzer is being used. CANAlyzer can also be used to test the model, using user input, instead of testing directly on a truck.

4.2.3 Hardware

The hardware being used are trucks with sensors which are mentioned in chapter 3.1.

Figure 4.4: *RPS hardware*

Figure 4.4 shows the RPS hardware which will be used in the truck. This is connected to 24 volt power source with a power switch and one CAN bus is connected to the CAN case. This RPS flashed from a model made in Matlab Simulink.

Figure 4.5: *CAN case*

The CAN case in figure 4.5 is used as a data logger to and from the RPS and is connected with USB to the workstation. The CAN case is used to recieve and transmit signals to the RPS as in figure 4.4. The signals can be analyzed at the workstation. The CAN case can also be used to simulate signals before testing it on actual hardware.

Figure 4.6: *VCI flashing tool*

Figure 4.6 showing the tool which is used to flash the C007 RPS hardware. The generated C-code from Simulink is used to flash the RPS and to do this, this VCI in figure 4.6 is used.

4.3 Thresholds

Possible obstacles have to be taken into consideration. For example, when the truck is turning, the right and left of the front wheel rolls in different speed. However, an appropriate threshold for speed difference has to be set. If left tire is spinning much faster than the right wheel, the actual speed will not correspond to the reference speed. Also, when the truck is braking or the traction control is active, the software should not make any calculations because the estimation may be mislead due to false reference speed. When traction control is activated, one wheel will spin while the other remains still. With false reference speed the estimated data will not be accurate. Also one critical obstacle is when sliding occurs. Sliding occurs when tire force decreases at a higher slip. For dry road with high adhesion the longitudinal force is higher before instability occurs than a road with less adhesion, ice and gravel for example. At which threshold should the traction control be set, in order not make the truck slide?

Signal name	**Value**
SteeringWheelAngle	max(0.2) rad
EngineAcceleration	max(1000) rpm/s
BrakePedalPosition	max(0) %
MinSpeed	min(10) km/h
SpeedDiff	min(1) km/h

Table 4.1: *Table of thresholds for the RLS algorithm*

In table 4.1 the values of the thresholds will be tested on the actual system. For example, the steering wheel angle needs to be low so that the right and left front wheel tires speeds not differs from each other. Also the reason why a minimum speed is important is because in equation 3.13, one can see that the equation diverges for speeds close to zero. The algorithm which uses the thresholds in table 4.1, can be found in figure 4.3. The same applies for tire stiffness calculation, if the slip is close to zero, the tire stiffness calculation will diverge.

5 Results

In following chapter the results are presented. The real-time calculations are compared to off-line calculations of the same test drive. The retrieved data is from a truck, driving on Scanias test track. The test plan for driving the truck can be found in Appendix A.

5.1 Real-time processing of data

The real-time processing will later be compared with the off-line method. Real-time processing are made in real-time and presented in following sub sections.

5.1.1 Real-time data without implemented threshold set

In following subsection, four different tests are presented and compared.

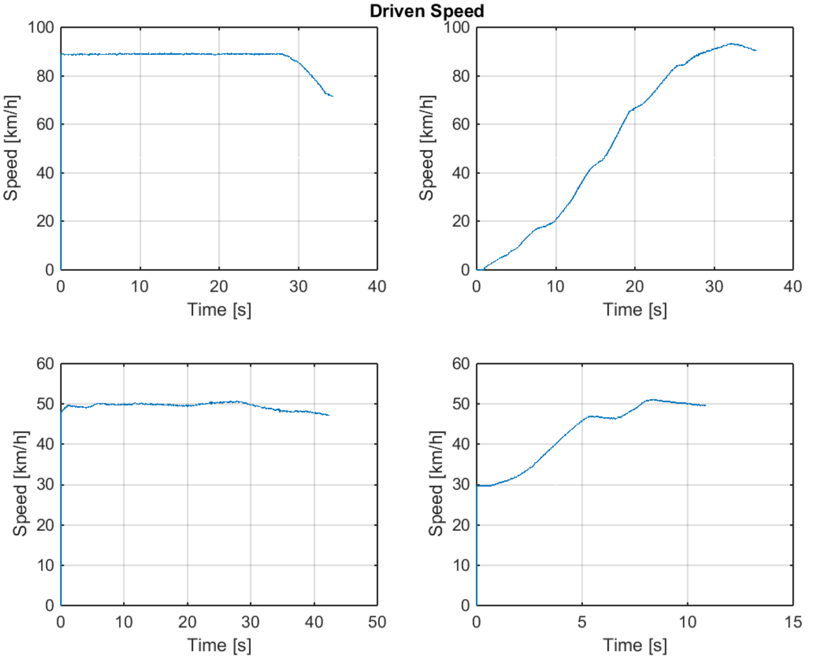

Figure 5.1: Truck speed for four different test drives according to appendix A

As shown in figure 5.1, the tests show which kind of speed the tests were conducted at. In the upper left, the truck were driving at constant 90 km/h. The upper right the truck were accelerating to 90 km/h. The lower left the truck were driving 50 km/h and the last figure the truck were accelerating from 30 km/h to 50 km/h. These results is compared in order to see which calculations could give the best estimation.

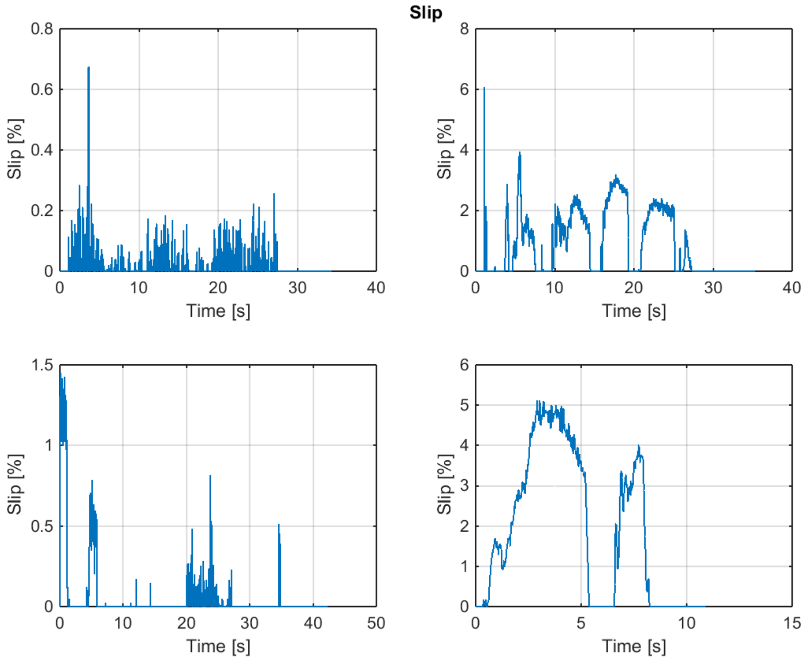

Figure 5.2: *Truck slip for four different test drives*

In figure 5.2 the slip were plotted during driving, in the same order as in figure 5.1. The plots are in driving at the same speed as in figure 5.1. As seen in these pictures the slip never gets higher than 6 %.

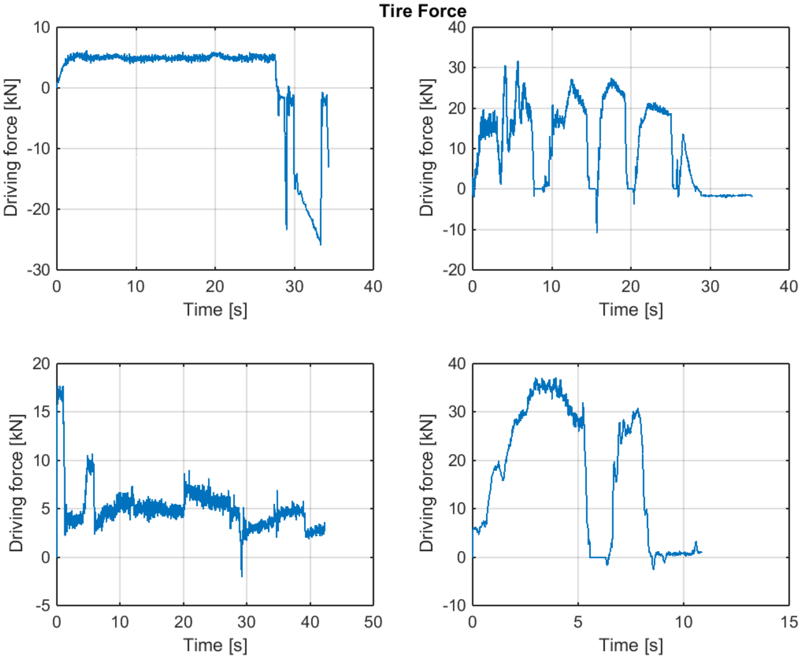

Figure 5.3: *Truck driving force for four different test drives*

Also in this figure, 5.3, the driving force, which is found in equation 3.10, is plotted during the different driving as in figure 5.1. The maximum driving force reaches almost 40 kN and occurs during acceleration.

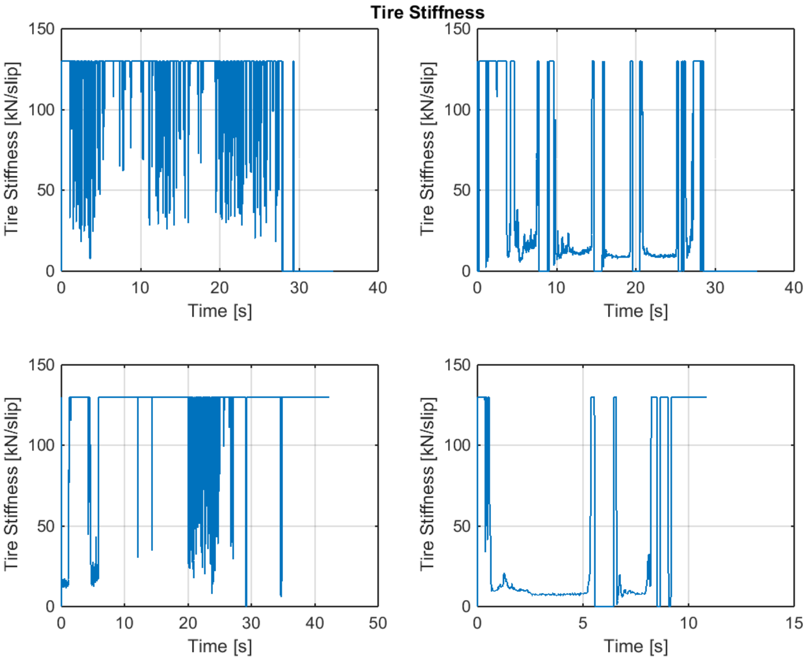

Figure 5.4: Tire stiffness for four different test drives

In figure 5.4 the stiffness are calculated during driving as in figure 5.1. In these figures it is difficult to see the stiffness directly since the signals are getting saturated due to the low slip, which equals a tire stiffness which goes to infinity. But when the signal is not getting saturated, the tire stiffness is approximately around 9 kN/slip.

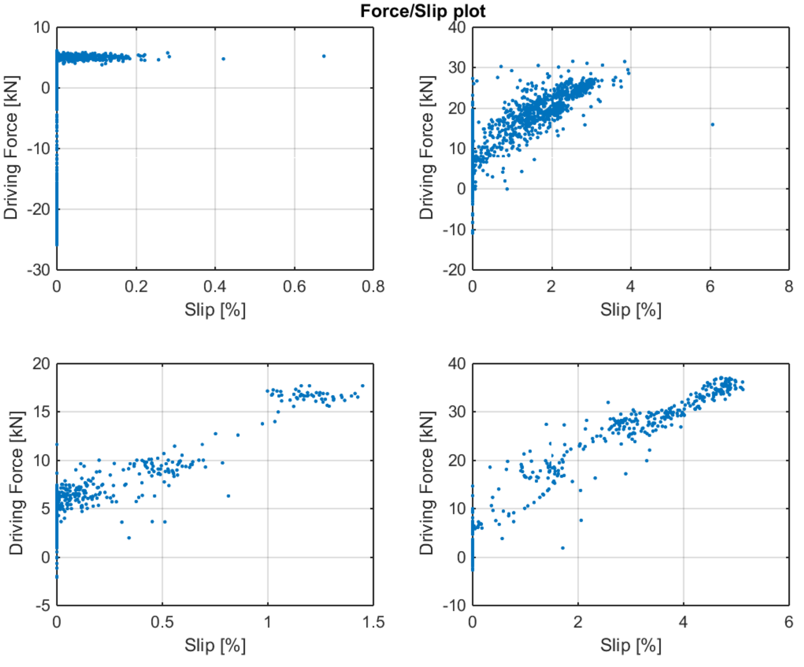

Figure 5.5: Force slip ratio for four different test drives

In figure 5.5 the force/slip ratios are presented for different driving on the test track. Also it is possible to see that the upper right picture gives the best results because when the truck is accelerating, it exerts forces on the tire at the same time the truck is driving at a high speed. When the truck is driving at a constant speed, the tire forces are not that high and therefore not showing a variety of slip, which makes it more difficult to estimate the stiffness. It is shown in the upper left picture. The same yields for the lower left picture when driving in 50 km/h. As accelerating from 30 km/h to 50 km/h also does not exerts tire forces as much as accelerating to 90 km/h and therefore does not generate too much slip on the tires. Therefore accelerating from 0 km/h to 90 km/h gives the best results.

5.2 Recursive least squares estimation, RLS

The least squares are solved recursively and the convergence are shown in following subsection.

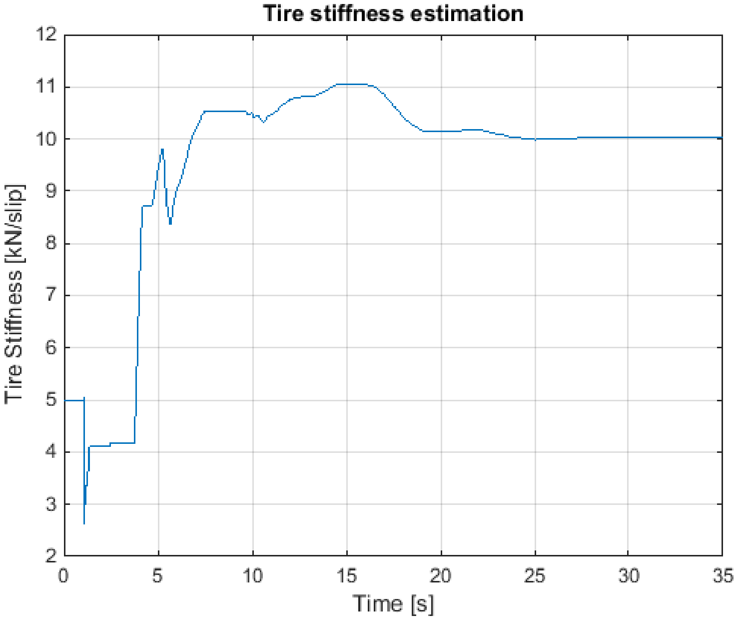

Figure 5.6: *Tire stiffness estimation using RLS*

In figure 5.6 the recursive least squares algorithm is implemented. Here one can see that the algorithm converges within 20 seconds during the testdrive in appendix A.3. The initial covariance matrix were set to 100 and the initial state guess were set to 5 kN/slip.

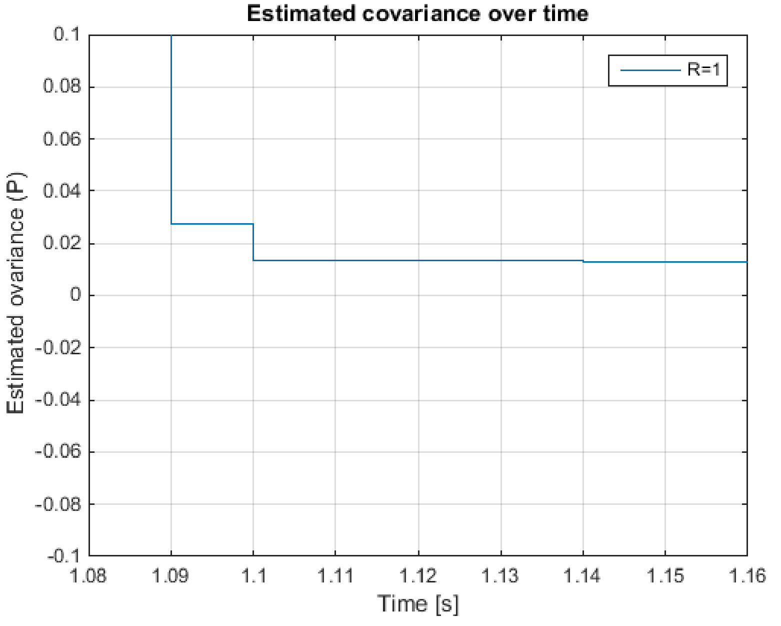

Figure 5.7: *Estimated covariance during real-time estimation*

In figure 5.7 shows the estimated covariance. It starts with an initial guess of 100, since the algorithm does not know anything of the tire stiffness yet, and then converges very fast to about 0.0001 as the algorithm gets more data. After it has reached a low value, the estimated stiffness will not change too rapidly.

5.2.1 Different covariances

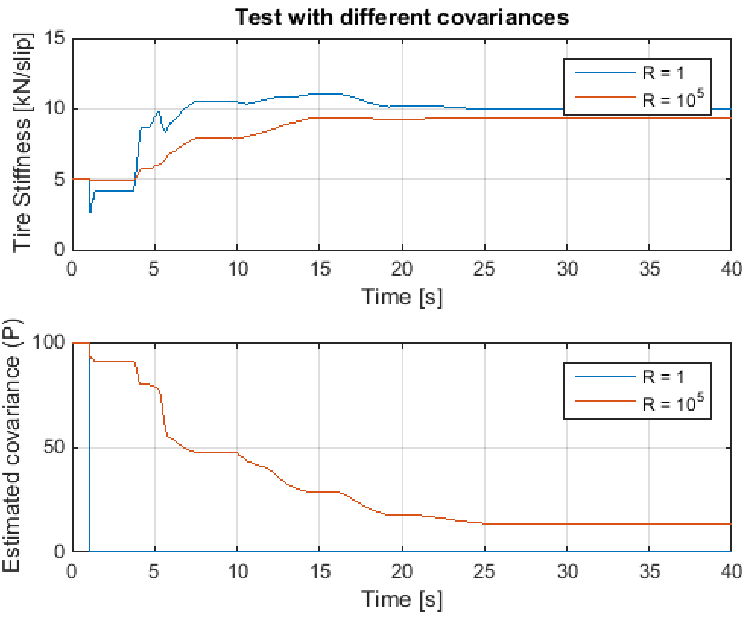

Figure 5.8: *Results of covariance matrix P, by changing the matrix R*

By changing the covariance matrix R, different results can be achieved which can be found in figure 5.8. If the covariance gets higher, the algorithm will not be sensitive to changes, but will converge slower. But if the covariance gets smaller, the algorithm will be sensitive to changes.

5.2.2 Residuals

In order to see the difference between the observation and the predicted value the residual, $z(k+1) - H(k+1)\hat{x}(k)$, can be analyzed. If the difference between the observation and the predicted value is zero, predicted value will be equal to the observed value. During the test drive, the residual during this test drive can be found in figure 5.9.

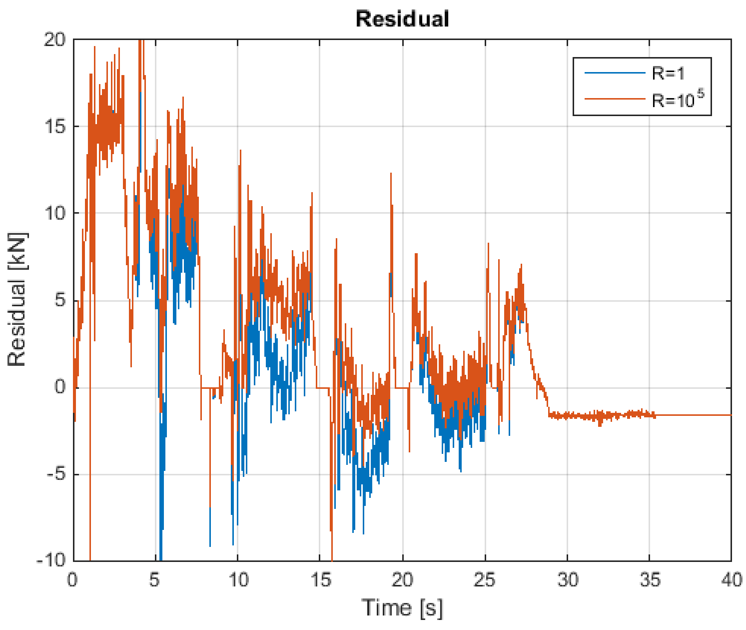

Figure 5.9: *Difference between predicted and estimated tire stiffness*

As seen in figure 5.9, the difference between the predicted value and estimated value converges close to zero.

5.3 Off-line processing of data

The following section, results from post-processing the data is presented. The offline calculations is important to get a approximate value of the tire stiffness. Then it is easier to compare it with real-time calculations and to see if it is probable.

5.3.1 Off-line calculations without threshold activated

The first test is to only calculate the tire stiffness from all input-data without taking thresholds from table 4.1 into consideration. Figure 5.10 and 5.11 are taken during acceleration from 0 km/h to 90 km/h since the real-time measurements showed the best results.

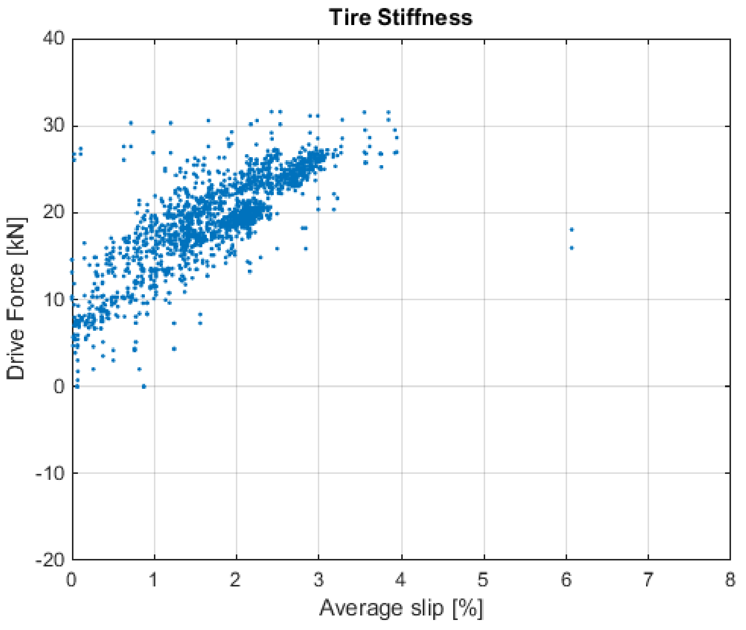

Figure 5.10: *Off-line force slip ratio during driving according to appendix A.3*

In figure 5.10 the resolution is quite bad and has many outliers. It is still possible to estimate the tire stiffness by looking at the gradient from a least squares minimization.

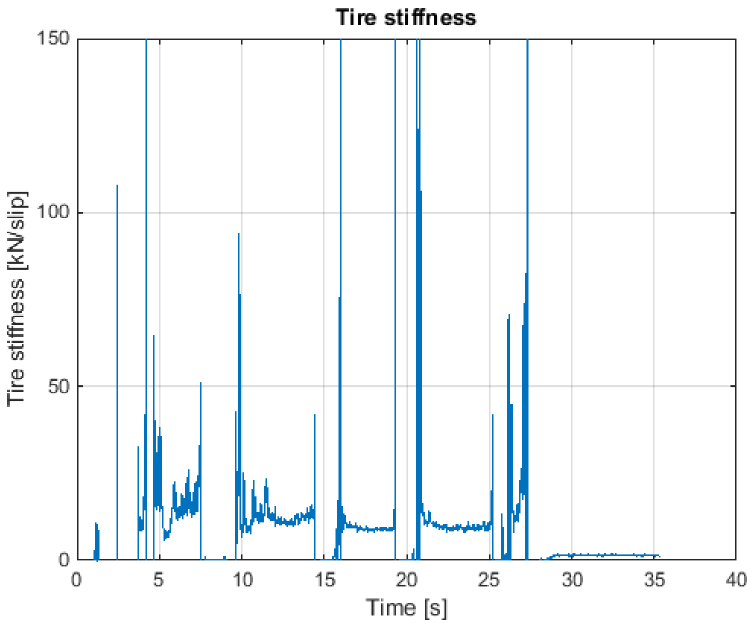

Figure 5.11: *Off-line tire stiffness calculation*

In figure 5.11 one can also see that the values are getting saturated quite often and therefore it may be difficult to get a good estimation.

5.3.2 Activating threshold

The algorithm that sort out unwanted values are implemented for off-line comparison. The thresholds can be found in table 4.1. The advantage with offline calculations is that it is possible to set a certain threshold and run the script again and iterate until a good results is shown, without making new test runs.

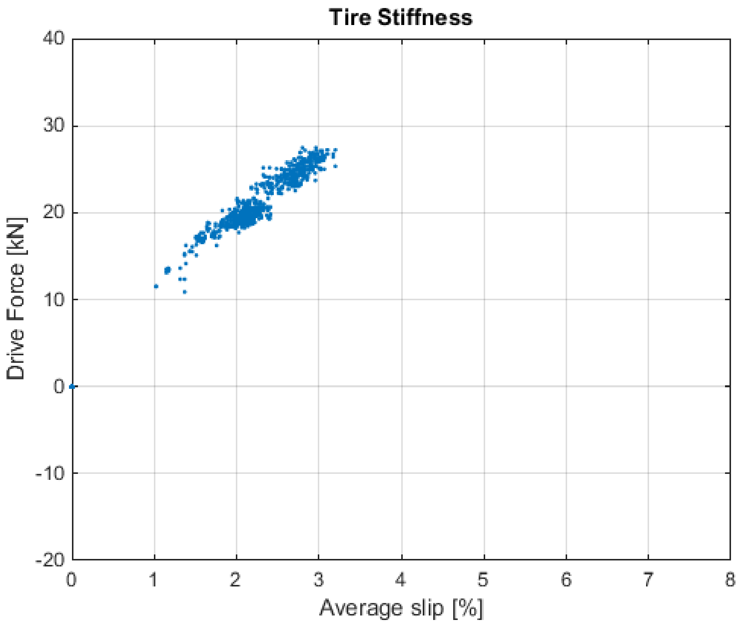

Figure 5.12: *Off-line force slip ratio*

In figure 5.12 by using the thresholds it is possible to see that the resolution is better and more accurate, determine the gradient in figure 5.12 since the number of outliers are less.

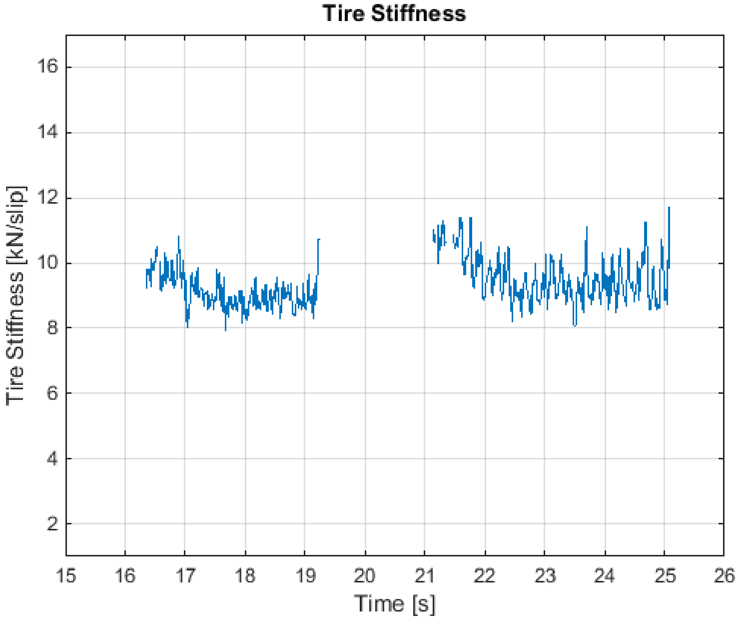

Figure 5.13: *Off-line tire stiffness calculation*

Since the tire stiffness is calculated with $N/slip$, the calculations are made in real-time. With the offline calculations it is possible to see that the stiffness are kept at a constant value.

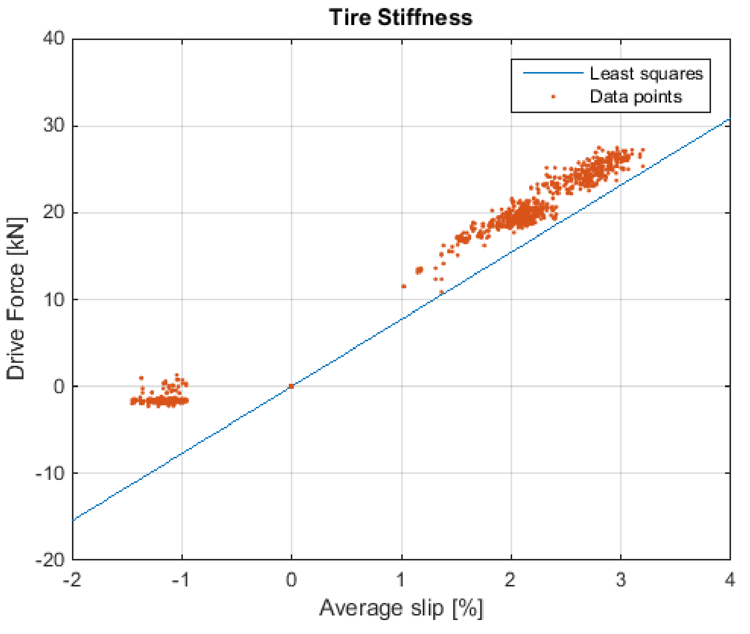

Figure 5.14: *Off-line tire stiffness calculation using LMS*

In figure 5.14 the slope coefficient is 7.7203 kN/slip and the offset 1.6245 kN. But only the gradient has been plotted in this figure. The offset does not have to be taken into consideration since only the gradient is important. So in this figure, one can see that the tire stiffness is 7.7203 kN/slip.

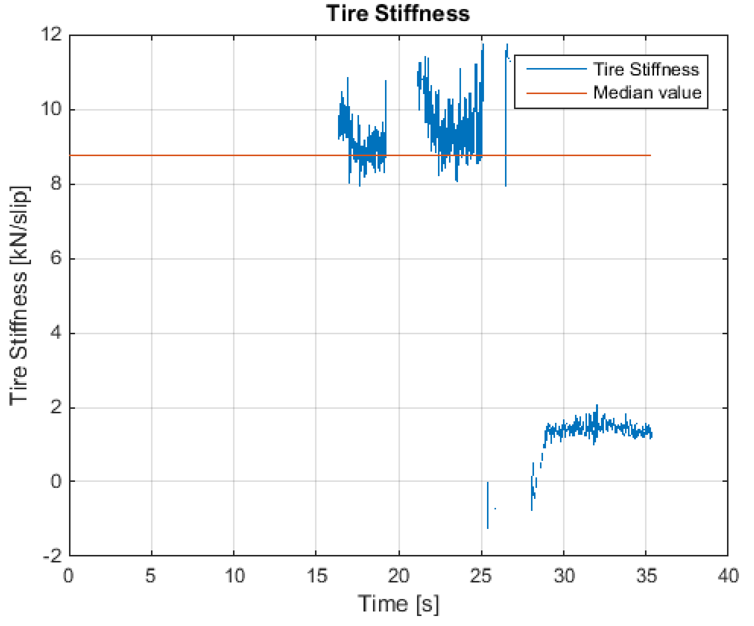

Figure 5.15: *Off-line tire stiffness calculation using median value*

In figure 5.15 the median value is 8.7666 kN/slip. But since the stiffness in figure 5.14 was calculated to 7.7203 kN/slip, the offset plays an important role. So by taking the driving force and divide it by slip and calculated directly, it will itself have an offset. So these results are not as accurate as the tire stiffness calculations as in figure 5.14. It is also important to note that during the end of the testdrive, the truck were slowing down and therefore showed a deviant value.

6
Conclusions

In this chapter the results, further work and improvements are discussed. Following conclusion can be made.

- RLS shows a good approximation of the tire stiffness
- The truck has to accelerate all the time in order to estimate the tire stiffness
- The parameters of the RLS may be tuned for different applications
- More accurate sensors can decrease the offset
- The calculated stiffness could be more reasonable if a reference tire has been used as well

6.1 Discussion

The results show a quite good accuracy of the tire stiffness using a recursive least squares estimation. By activating the thresholds and run an offline calculation, as shown in figure 5.14, a stiffness of 7.7203 kN/slip, with a offset of 1.6245 kN could be achieved. During real-time calculation, assuming the offset is zero, a stiffness of around 10 kN/slip could be achieved after 35 seconds of driving. This is shown in figure 5.6. By looking at the current tire stiffness from figure 5.11 using the algorithm it is possible to see that the mean stiffness is kept around 9.5 kN/slip. By taking the offset into consideration the results could be much better.

The results could be more accurate if a reference value could be used. If only one test were conducted, it would be more difficult to determine if the result were satisfying or not. With a reference value, a threshold could be set. If the tire stiffness is estimated within this interval, it would be easier to get a better result.

6.2 Further work and improvements

In this thesis the focus has been on the longitudinal stiffness. A broader approach can for example be about cornering stiffness, and combined stiffness. With further research on this topic, it may be possible to improve the braking performance even further, and not only when the truck is moving in its longitudinal direction.

By calculating the longitudinal stiffness, a higher braking performance can be achieved. Since the maximum slip can be estimated, it is possible to achieve maximum braking performance before the truck starts to slide. With the estimation, the maximum drive- and braking force can easier be estimated. The suggested further work is to see how this algorithm can increase braking performance.

One possible approach to find the maximum drive and braking force is to estimate the parameters using the Magic Formula by Pacejka [13].

Also, one other interesting topic of investigation can be improved vehicle handling. With estimated tire stiffness, it may be used to improve the vehicle handling no matter on which surface the vehicle is driving.

Further improvements on the software can be automatic calculations of the differential ratio and tire radius. If it is calculated during driving, it is not needed to hardcode these values into Matlab Simulink. Then it is possible to calculate the tire stiffness on each type of truck without making any modifications in the software.

Since the estimated variable $\hat{b}$ were set to 0, a better result could be achieved if this offset parameter were estimated as well. It would require more computational power to estimate this parameter as well, but it would give a more accurate result.

Also, different algorithms such as recursive maximum likelihood estimation could also be used to compare different real-time algorithms to estimate the tire stiffness.

Appendix

A

Testplan for driving

The tests were conducted with a truck at Scania on their test track in Södertälje, Sweden. The tested truck tire has a circumference of 3.018 meters and a differential with a ratio of 3.42. The truck were loaded with 7 tons extra weight on the axle.

A.1 First driving test

Following driving instructions were followed during the first test drive:

Testnumber	Instructions
1	Accelerate to 30 km/h
2	Driving in 30 km/h
3	Accelerate from 30 km/h to 50 km/h
4	Driving in 50 km/h
5	Accelerate to 90 km/h
6	Driving in 90 km/h
7	Driving to and from test track

A.2 Second driving test

After post processing the experiments in Matlab, the four tests which could give the best and most accurate results were presented in this thesis.

Testnumber	Instructions
1	Driving in 90 km/h
2	Accelerate to 90 km/h
3	Driving in 50 km/h
4	Accelerate from 30km/h to 50 km/h

A.3 Third driving test

The following table shows the testdrive which gave the best estimation of the tire stiffness while driving.

Testnumber	Instructions
1	Accelerate to 90 km/h

B

Testdrive with other trucks

Other testdrives were also conducted in order to compare the results.

B.1 "Berlin"

"Berlin" is a gas operated truck with a circumference of 3.018 meters and a differential constant of 3.42. The test can be found in figure B.1.

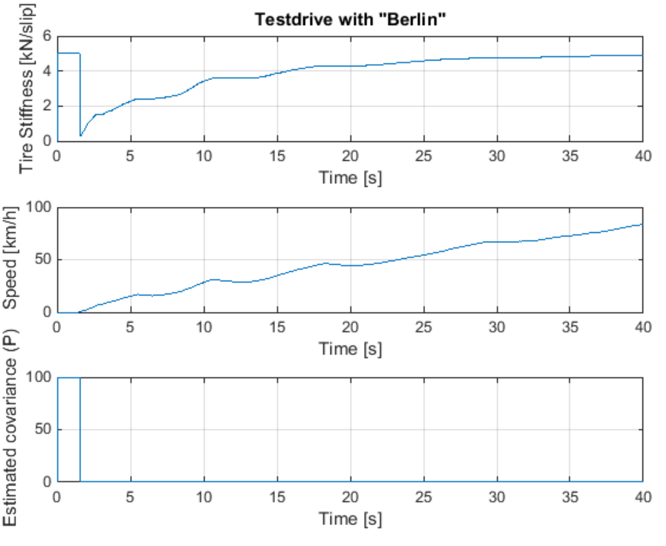

Figure B.1: *Testdrive with "Berlin" using winter tires*

B.2 "Drabant" plus trailer

"Drabant" is the main truck used in this thesis, but the truck were also tested with a connected trailer.

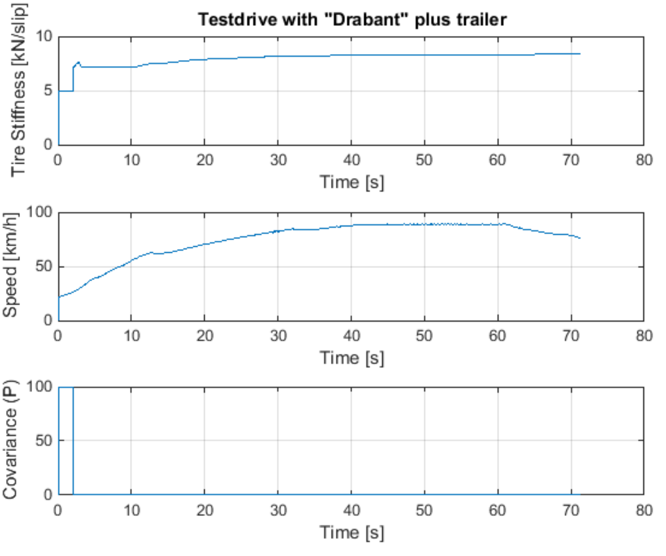

Figure B.2: *Testdrive with "Drabant" plus trailer*

As shown in figure B.2 and using a full trailer connected, the tire stiffness remains almost the same as without.

Bibliography

[1] Yaakov Bar-Shalom, X. Rong Li, and Thiagalingam Kirubarajan. *Estimation with Applications to Tracking and Navigation*. Wiley-Interscience, second edition, 2004. Cited on page 20.

[2] David Barton and John Fieldhouse. *Braking 2006*. University of Leeds and authors, first edition, 2006. Cited on page 3.

[3] Anudeep K. Bhoopalam, Corina Sandu, and Saied Taheri. Tire traction of commercial vehicles on icy roads. *SAE International*, 2014. doi: 10.4271/2014-01-2292. Cited on page 4.

[4] Bert Breuer and Karlheinz H. Bill. *Bremsenhandbuch*. Vieweg and Teubner Verlag, second edition, 2004. Cited on page 3.

[5] Christopher R. Carlson and J. Christian Gerdes. Nonlinear estimation of longitudinal tire slip under several driving conditions. *IEEE*, 2003. URL `http://www-cdr.stanford.edu/dynamic/WheelSlip/CarlsonGerdesACC2003.pdf`. Cited on page 4.

[6] A J Day, J Klaps, and C F Ross. *Braking of Road Vehicles*. Inprint and Design Ltd, first edition, 2012. Cited on page 3.

[7] G.Rill. *Fahrzeugdynamik*. Technische Hochschule Regensburg, Elektroakustik-Labor, 2001. URL `http://www.autogumi.com/FDV_Skript.pdf`. Cited on page 4.

[8] Ragnar Ledesma. The effect of tire stiffness parameters on medium-duty truck handling. *SAE International*, 2000. Cited on page 4.

[9] Lennart Ljung. *System Identification, Theory for the User*. Prentice-Hall Inc, first edition, 1999. Cited on page 20.

[10] Christopher J Longhurst. *THE TRANSMISSION BIBLE*. Chris Longhurst, 2016. URL `http://www.carbibles.com/transmission_bible.html`. Cited on page 10.

[11] Mathworks. *1-D digital filter*. 2016. URL http://se.mathworks.com/help/matlab/ref/filter.html. Cited on page 21.

[12] Shannon L. Miller, Brett Youngberg, Alex Millie, Patrick Schweizer, and J. Christian Gerdes. Calculating longitudinal wheel slip and tire parameters using gps velocity. *IEEE*, 2001. URL http://www-cdr.stanford.edu/dynamic/WheelSlip/SlmillerGerdesACC.pdf. Cited on pages 4, 5, and 9.

[13] Hans B. Pacejka. *Tire and Vehicle Dynamics*. Elsevier Ltd, third edition, 2012. Cited on pages 14, 15, 18, and 44.

[14] Kanwar Bharat Singh and Saied Taheri. Estimation of tire–road friction coefficient and its application in chassis control systems. *Taylor and Francis*, 2014. URL http://dx.doi.org/10.1080/21642583.2014.985804. Cited on page 17.

[15] Srikanth Sivaramakrishnan, Kanwar Bharat Singh, and Peter Lee. Experimental investigation of the influence of tire design parameters on anti-lock braking system (abs) performance. *SAE International*, 2015. doi: 10.4271/2015-01-1511. Cited on pages 4 and 15.

[16] Aldo Sorniotti and Mauro Velardocchia. Enhanced tire brush model for vehicle dynamics simulation. *SAE International*, 2008. Cited on page 5.

[17] Stackexchange. *Simple example of recursive least squares (RLS)*. 2014. URL http://math.stackexchange.com/questions/631498/simple-example-of-recursive-least-squares-rls. Cited on page 20.

[18] Jan Erik Stellet, Martin Giessler, Frank Gauterin, and Fernando Puente Leon. *Model-based Traction Control for Electric Vehicles*. 2014. URL https://www.fast.kit.edu/download/DownloadsFahrzeugtechnik/140331_Model-based_Traction_Control_for_Electric_Vehicles.pdf. Cited on page 4.

[19] Jacob Svendenius and Björn Wittenmark. *Review of Wheel Modeling and Friction Estimation*. 2003. URL http://www.control.lth.se/documents/2003/tfrt7607.pdf. Cited on page 5.

[20] J.Y. Wong. *Theory of Ground Vehicles*. Hoboken, N.J. : Wiley, c2008, 2008. Cited on pages 3 and 15.