Experiments on the flat plank tyre tester

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Experiments on the Flat plank tyre tester

Abstract

In the summer of 2003 a tyre measuring machine, the flat plank tyre tester, has been moved from Delft University of Technology to the TU/e. To learn how to operate the machine and check whether it has sustained no damage during transport, relaxation length and longitudinal stiffness measurements already carried out with the flat-plank tyre tester in Delft, are repeated at the TU/e and compared with the results from the measurements carried out in Delft.

After the machine has turned out to be fine, some other types of measurements are carried out and the results are analysed to check whether they show the expected behaviour.

Finally recommendations are made for improving the machine.

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Chapter 1 Introduction

During the summer of 2003 a tyre measuring machine, the so-called Flat Plank Tyre Tester has been moved from the Delft University of Technology to the TU/e. Because there is very little to no knowledge of the operation of the machine at the TU/e, the first step that has to be taken is to get acquainted to the machine.

These are the subjects of this traineeship:

1) *Learn how to operate the machine and make a manual for this.*
2) *Check whether the measurements, with a tyre that has already been tested in Delft and will undergo the same tests in Eindhoven, are good.*

Because it is desirable that other people are able to operate the machine without elaborate explanation, an operating manual has been written [Lit 4]. In this manual it is explained how the machine operates and what procedures should be used for several different types of measurements.

This report focuses mainly on how the measurements are processed. First of all, in chapter 2, there is a short description of the machine. Furthermore this chapter describes how the measured forces are transformed to the forces at the axle centre and contact patch.

Next, in chapter 3, the data processing of the different types of measurements is treated.

In chapter 4 the measurements carried out at the TU/e are compared to those carried out at Delft. After this some other types of measurements are carried out, the results of these measurements are also treated in this chapter.

Finally some recommendations for further testing and improvement of the machine are made.

Chapter 2 Description of the flat plank tyre tester

§ 2.1 Parts of the flat plank tyre tester

The flat plank is a machine to measure tyre characteristics at a low speed.

The machine is composed of a main frame, flat steel track, measuring hub, turn table, axle height and lateral position adjust mechanism, brake, camber mechanism, trigger unit and driving motor with reduction gear box. The machine has the following dimensions:

Length: 15 m, wide: 2 m and height: 2m.
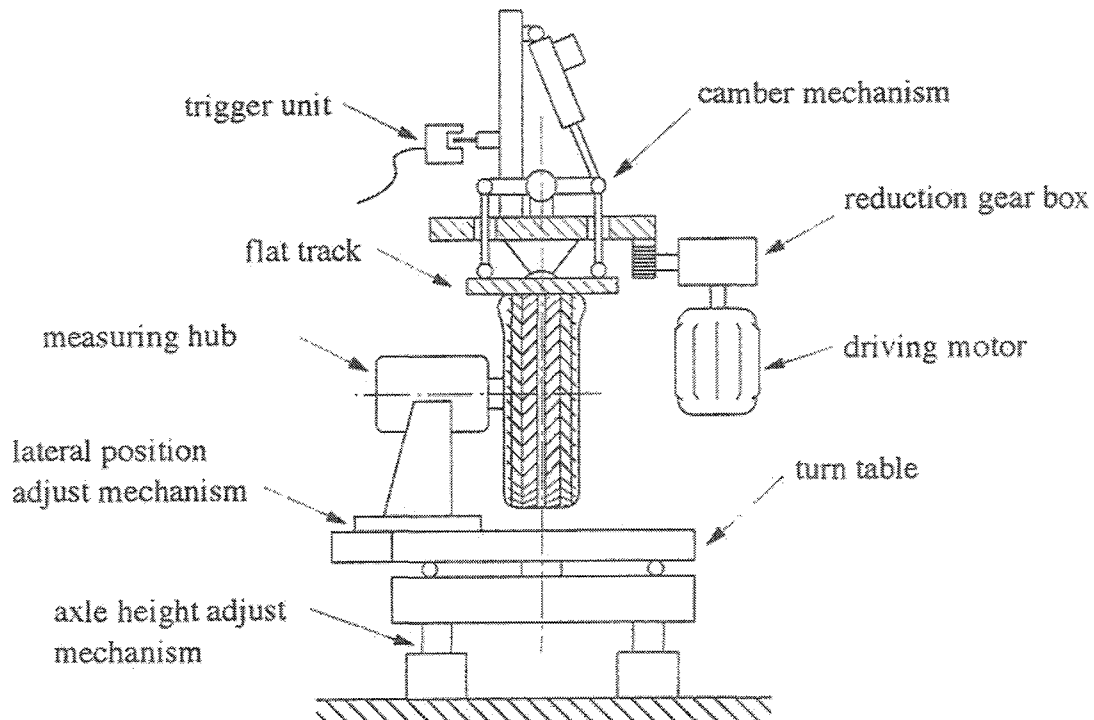
Figure 2.1 schematic view of the Flat plank tyre tester

Now every part shown in figure 2.1 will be discussed briefly.

Main frame

This is a large part of welded steel, which gives stiffness to the whole construction. It also ensures that the flat steel track cannot move vertical during movement.

Top part of the construction (Flat steel track, camber mechanism, driving motor with reduction gear box and trigger unit)

This machine has originally been developed as a so-called "Glass plate" tyre tester. The glass plate is no longer used and is replaced by a steel plate of 8m, which enables a greater travel and can be coated to give more realistic frictional properties. The steel track can be turned around the axis on its surface. This is done with the camber mechanism, which consist of a linear actuator. On the steel

track so called "Cleats" can be attached. This can be done to simulate bumps in the road. The whole steel track is moved with a driving motor with reduction gearbox. With this motor the flat steel track can achieve a speed of 47.5 mm/s. On the top of the machine a trigger unit is installed. This is done to make it easier to compare different measurements with each other, because they are started at exactly the same time. It also ensures that the same amount of data for each measurement.

Middle part of the construction (Measuring hub and brake)

With the measuring hub the forces acting on the tyre can be measured. How this is done exactly will be explained in section 2.3. There is a braking disc with 2 claws attached tot the measuring hub. At this moment it is not yet possible to use this braking disc with the claws, because there are no cylinders in the claws. This is a problem, which is known for a while. In Delft the following solution has been used: a pin is put in the braking disc to lock it up. In the future it must be possible to find a better solution for this problem, but in this research the brake will be locked with a pin.

Lower part of the construction (Turn table, axle height and lateral position adjust mechanism)

The turntable is used to give a certain slip angle to the tyre. This can be done with a wheel or a motor in combination with a set of gears. It is possible to rotate the table 360° but in practice + 90° and − 90° is used.

The vertical load can be adjusted by changing the axle height with a jack.

It is also possible to adjust the height with an air spring, which supports the lower part of the construction. This air spring in combination with a smart part of engineering is constructed at such a way that the stiffness is "0" at a range of 50mm. This can be useful for tests with cleats.

The lateral position of the tyre can also be adjusted so that no vertical movement is applied by camber. The lateral position can be adjusted with a jack.

§2.2 Input and output variables

Figure 2.2 depicts the basic quantities used in this report. The wheel rolls over a flat road with horizontal velocity V and an angular velocity Ω about its rotational axis. The longitudinal and lateral components of V are V_x and V_y respectively. The slip velocity of the wheel is V_s with which the tyre produces the horizontal force F_y and the aligning torque M_z. The product of angular velocity Ω and the effective rolling radius r_e is the rolling velocity V_r.

$$V_r = \Omega \cdot r_e \qquad\qquad [2.1]$$

The longitudinal and lateral components of the slip velocity V_s are given as follows:

$$V_{sx} = V_x - V_r \qquad\qquad [2.2]$$

$$V_{sy} = V_y \qquad [2.3]$$

With these quantities, the longitudinal slip κ and slip angle α are calculated.

$$\kappa = -\frac{V_{sx}}{V_x} \qquad [2.4]$$

$$\tan\alpha = -\frac{V_{sy}}{V_x} \qquad [2.5]$$

The slip angle is the angle between the travelling direction and the tyre heading direction (or rolling direction). We speak of sideslip when α is not zero and longitudinal slip when κ is not zero.
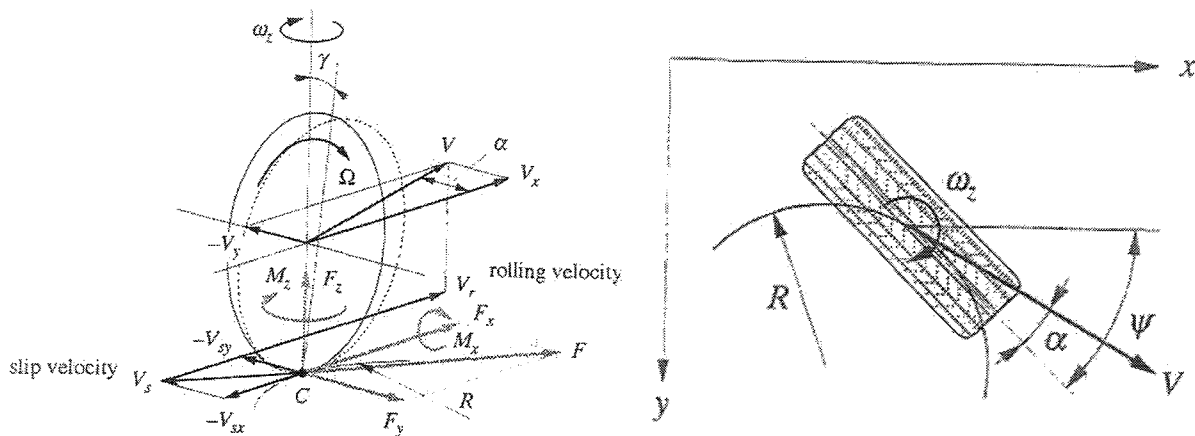
Figure 2.2 Basic quantities in this report (left) and steady state turn slip (right)

The angle between the wheel plane and the normal to the road is called camber angle γ. The measured forces and moments are longitudinal force F_x, side force F_y, overturning moment M_x, aligning torque M_z, and vertical load F_z. The pneumatic trail t_p is the ratio of M_z to F_y.

$$t_p = -\frac{M_z}{F_y} \qquad [2.6]$$

§2.3 Transformation of forces and moments

In reality it is very difficult to measure the forces and moments at the contact centre directly. We actually measure the forces at the axle and transform them into those at the contact centre.

Figure 2.3 depicts the measuring hub with five strain gauges used in the measurement. Two gauges are placed longitudinally to sense the forces G_{x1} and G_{x2} at the axle, other two vertically for the forces G_{z1} and G_{z2} at the axle, and one laterally for the force G_y at the axle. The distance "a" between two gauges, and "b" between the one closer to the tyre and the wheel centre plane are needed to calculate the moments at the axle correctly.
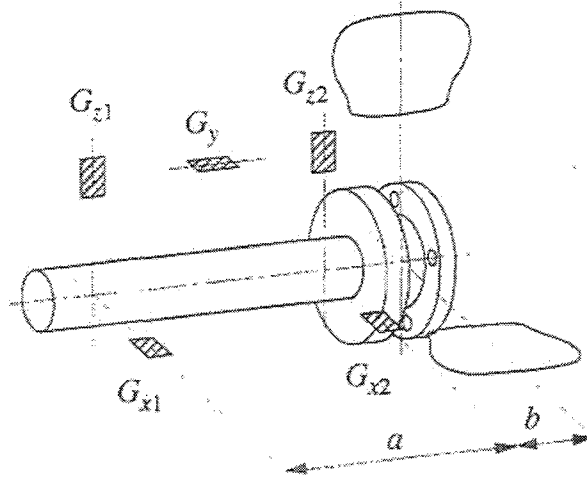
Figure 2.3 Measuring hub with five strain gauges

We write

$$K_x = G_{x1} + G_{x2}$$ [2.7]

$$K_y = G_y$$ [2.8]

$$K_z = G_{z1} + G_{z2}$$ [2.9]

$$T_x = G_{z1}(a+b) + G_{z2}b$$ [2.10]

$$T_y = 0$$ [2.11]

$$T_z = G_{x1}(a+b) + G_{x2}b$$ [2.12]

For the transformation to forces at the contact centre, according to figure 2.4:
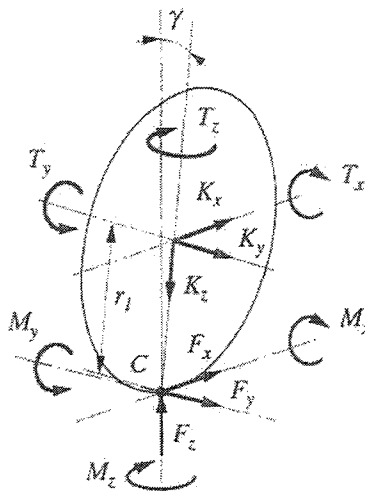
Figure 2.4 Forces and moments at the axle centre (K and T) and at the contact centre (F and M)

$$F_x = K_x$$ [2.13]

$$F_y = K_y \cos\gamma - K_z \sin\gamma$$ [2.14]

$$F_z = -K_z \cos\gamma - K_y \sin\gamma$$ [2.15]

$$M_x = T_x + K_y r_l$$ [2.16]

$$M_y = -T_z \sin\gamma - K_x r_l \cos\gamma$$ [2.17]

$$M_z = T_z \cos\gamma - K_x r_l \sin\gamma$$ [2.18]

Chapter 3 Data-Processing

It is very important to interpret measurements very carefully, because good results do not automatically follow from good measurements. This chapter is about how relaxation lengths, stiffnesses, parking parameters, effective rolling-radius and plysteer/conicity are calculated from the data. The procedures to carry out the measurements are described in the manual [Lit 4].

§ 3.1 Relaxation length

For 1 load and 1 pressure there are 6 files available: 3 measurements with a steering angle of 1°, and 3 measurements with a steering angle of 0° the socalled reference measurements. (See m-file in App I.1)
This is the procedure how relaxation length is calculated in matlab:
1) All the 6 files are loaded into matlab.
2) The F_y and x are calculated for each set of measurements (one 1° and one 0°).
   The F_y from the reference measurement is subtracted from the 1° measurement. This is done to delete the plysteer/conicity properties of the tyre.
3) F_y must be corrected, because it is very important that F_y starts with a value of 0 N when x is 0 m to get a good result from the fitting. This is so important, because the function, which is going to be fitted on the data, starts at 0. If the data is not corrected, an error can be introduced to the relaxation length. By moving the data down with the value of the first data-point the data is corrected.
4) The fitting procedure can start now. Fitting is done with the least square method (lsqcurvefit) in matlab. This is the function which is fitted on the data:

$$f(x) = Fstat \times (1 - e^{-x/R})$$
(3.1)

   There are 2 variables in this function: F_{stat} and R. F_{stat} is de value that F_y is going to reach if the tyre is totally rolled in. R is the relaxation length of the tyre. This fitting has to be done for all the measurements sets.
5) Now a relaxation length is known for each set of measurements, so there are 3 relaxation length known after the 3 fitting procedures. It is now important to look if they are about the same value. If this is not true than there is probably a wrong measurement in the set. If they are about the same value than the mean value of these 3 values can be seen as the relaxation length of this tyre for a certain load and pressure.

§ 3.2 Longitudinal stiffness

For 1 load and 1 pressure there are 3 files available. For each of these files a fitting procedure has to be followed. This is how the procedure looks like in steps:

1) The matlab file (see app I.2) asks the name of the file that must be studied.

2) X against F_x is plotted in a graph.

3) The computer asks for a starting (x-value) and an end point (x-value) of the straight line that must be fitted through the data. The points have to be selected carefully, because it is very important to select a part of the graph that is increasing with a fixed gradient. Of course it is important that as much relevant data as possible is chosen, because of the reliability of the solution.

4) The Matlab file extracts the data from the boundaries that are given in step 3.

6) The fitting procedure starts. The fitting is done with the least square method (lsqcurvefit) in matlab. This is the function which is fitted on the data:

$$f(x) = a(1) + a(2) \cdot x \tag{3.2}$$

5) Now the longitudinal stiffness of this measurement is known, because this is the a(2) value of the line.

The steps 1-6 have to be done 3 times for 1 load and 1 pressure. At the end 3 values for the longitudinal stiffness are available. Now the post processing can start for example in Excel. The average can be calculated and the values can be plotted in a graph. Now the longitudinal stiffness of the tyre is known at 1 load and 1 pressure.

§ 3.3 Steering effort during stationary parking manoeuvres

In total there are at least 4 measurements available (1 for each load). This data is plotted in 1 graph (M_z against the steering angle).
The next model is available [Lit 2]:

$$\dot{\Psi}_{def} = \left(1 - \left(\left|\frac{M_z}{M_{z\,max}}\right|\right)^{c_0}\right) \cdot \dot{\Psi} \quad \text{if } \text{sign}(\dot{\Psi}_{def}) = \text{sign}(\dot{\Psi}) \tag{3.3}$$

$$\dot{\Psi}_{def} = \dot{\Psi} \quad \text{if } \text{sign}(\dot{\Psi}_{def}) \neq \text{sign}(\dot{\Psi}) \tag{3.4}$$

$$Mz_{max} = f(Fz) = a_2 \cdot Fz^2 + a_1 \cdot Fz \tag{3.5}$$

$$K_\Psi = f(Fz) = b_2 \cdot Fz^2 + b_1 \cdot Fz \tag{3.6}$$

$$\Psi_{defm} = \frac{Mz_{max}}{K_\Psi} \tag{3.7}$$

$$\dot{\Psi}_{def2} = -\frac{1}{\tau} \cdot \Psi_{def} \tag{3.8}$$

$$\tau = \frac{X_{rel}}{\omega \cdot r} \tag{3.9}$$

$$\Psi_{def} = \int_0^t (\dot{\Psi}_{def} + \dot{\Psi}_{def2}) \cdot \delta t \tag{3.10}$$

$$Mz = K_\Psi \cdot \Psi_{def} \tag{3.11}$$

Mz :	Aligning Torque [Nm]
K_ψ :	Torsional stiffness of the tyre. [Nm/deg]
Ψ :	Yaw angle of the wheel plane [deg].
Mz_{max} :	Maximum Torque that can be generated by the tyre. [Nm]
Ψ_{def} :	Torsional deflection of the tyre. [deg]
Ψ_{defm} :	Maximum possible deflection of the tyre [deg]
X_{rel} :	Tyre relaxation length [m]
ω :	Tyre rotational velocity [rad]
r :	Tyre rolling radius. [m]
Fz :	Vertical load on the tyre [kN]
a_1, a_2, b_1, b_2, c_0 :	Model parameters.

The model for stationary parking manoeuvres is a bit less complex than the model mentioned above, because $\dot{\Psi}_{def2} = 0$ and $\omega = 0$.

This model was implemented in Simulink (see app II). This model is evaluated for four loads. At the end the 4 "models" are plotted in the same figure as the measurements. Now the "fitting" can start.

At this moment this must be done partly by hand, but it is possible to make a routine for this in Matlab in the future.

The model consists of 5 parameters: a_1, a_2, b_1, b_2 and c_0.

The parameter c_0 is for the radius of the corners.

The parameters a_1 and a_2 are for the maximum value of M_z.

The parameters b_1 and b_2 are for the gradient of the lines.

First the parameters a_1 and a_2 are calculated. This is done at this way:

$$\begin{bmatrix} load1 & load1^2 \\ load2 & load2^2 \\ load3 & load3^2 \\ load4 & load4^2 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \max(Mz_{load1}) \\ \max(Mz_{load2}) \\ \max(Mz_{load3}) \\ \max(Mz_{load4}) \end{bmatrix} \tag{3.12}$$

Parameters a_1 and a_2 can then be determined in a least squares sense.

The final step is to find the other 3 parameter-values. This is mainly some trial and error. For c_0 just look at the radius of the different curves and try to fit them. A good starting value for c_0 is about 1.2. For b_1 And b_2 look at the rising parts of the lines and try to fit the parameters to these part of the lines. A good start value for both: $b_1 = 15$ and $b_2 = 0.4$.

Some trial and error is needed to find the correct values for c_0, b_1 and b_2.

§ 3.4 Effective rolling-radius

For 1 load and 1 pressure there are 4 files available: 2 measurements for a different place on the track for rolling forward and 2 measurements for a different place on the track for rolling backwards.

This is the procedure how the effective rolling-radius is calculated in matlab (see m-file in App I.3):
1) All the 4 files are loaded into matlab.
2) For each file the effective rolling-radius is calculated. This is done by dividing the velocity of the track ([m/s]) through the rolling velocity of the tyre ([rad/s]).
3) An average for these values is calculated. This is the effective rolling-radius for this tyre for 1 pressure and 1 load.

§ 3.5 Plysteer / Conicity

For 1 load and 1 pressure there are 4 files available: 2 measurements for a different place on the track for rolling forward and 2 measurements for a different place on the track for rolling backwards.

This is how the plysteer is calculated in Matlab (app I.3):
1) All the 4 files are loaded into Matlab. 1 set data for one place on the track (forward and backward) and 1 set data for the other place on the track.
2) The F_y for plysteer is calculated by subtracting the F_y from the way back from the F_y from the way forward. Finally this $F_{y,sub}$ is divided by 2. This is done for both sets. So the $F_{y,plysteer}$ for both sets is known.
3) For each set the $F_{y,plysteer\_stat}$ must be calculated. This is done by fitting a curve through the data with the least square method (lsqcurvefit) in Matlab. This is the function which is fitted on the data:

$$f(x) = F_{plysteer}stat \times (1 - e^{-x/R})$$
(3.13)

4) Finally the average of these 2 values is calculated. Now for 1 load and 1 pressure the plysteer is known.

This is how the conicity is calculated in Matlab:
1) All the 4 files are loaded into Matlab. 1 set data for one place on the track (forward and backward) and 1 set data for the other place on the track.
2) The F_y for conicity is calculated by summing the F_y from the way back and the F_y from the way forward. Finally this $F_{y,sum}$ is divided by 2. This is done for both sets. So the $F_{y,conicity}$ for both sets is known.
3) Finally the average of these 2 values is calculated. Now for 1 load and 1 pressure the conicity is known.

§ 3.6 Effects of road unevenness

For one load, one pressure and a certain cleat, three files are available: one for each different starting position on the tyre. From the data from this measurement three quantities are interesting: vertical load F_z, longitudinal force F_x and effective rolling radius during the measurement. The only extra operation that has to be performed is averaging the three measurements.
The forces can be plotted easily, as they are available directly in the output from Labview (assuming the inclination angle $\gamma=0$).

Plotting the rolling radius against the travelled distance is more difficult because the signals with track velocity and angular velocity of the wheel contain a lot of noise. This is because these signals are calculated by differentiating the position signals. If the rolling radius would be calculated directly from these signals, it would also be a very noisy signal. Therefore the velocity signals are digitally filtered with a second order low-pass filter with a cut off frequency of 1 Hz.

So this is how the effective rolling radius is calculated in Matlab (see App I.4):
1. Load the three files belonging to a certain load and pressure
2. Filter the velocities of all three files
3. Calculate the effective rolling radius for the three files
4. Calculate the mean of the three effective rolling radii.

Chapter 4 Comparing and analyzing the measurements

First we will compare the relaxation and longitudinal stiffness measurements performed at the TU/e to those performed at Delft. This is done to check if the machine still functions well. After that also some other tests are performed. The procedures for performing the experiments are described in the manual [Lit 4]. The way to process the data is described in chapter 3.

§ 4.1 Relaxation tests

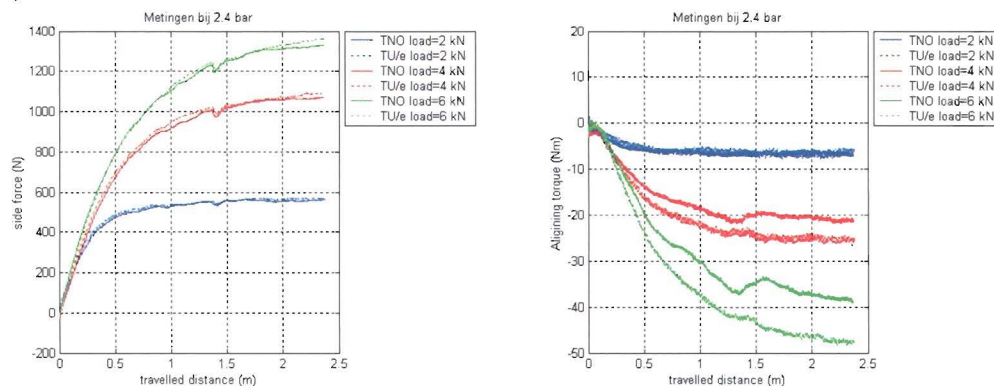After correction with the reference measurements the lateral force and aligning torque look like this:

Figure 4.1 Example of the side force and aligning torque for different loads

As can be seen from figure 4.1 the side force seems to be almost the same for the two measurements. The aligning torque shows a larger difference, but the torque measured here is pretty small, so a small error in the measurement is relatively large deviation from the measurements performed at Delft.

In the left figure one can see a small dip in the side-force (after 1.4 m). This is present in all measurements and always after about 1.4 m. This means it is caused by the track and not by the tyre. If it is caused by the tyre, it would show up at different travelled distances, because the tyre is rotated 120° after each measurement. The fact, that the dip lays the same for the measurements performed at the TU/e and at Delft, implies that the measurements have been started from the same position on the track.

Next the relaxation length and steady state value for each measurement is determined as described in Chapter 4. The results are shown in figures 4.2 – 4.4. Figures 4.2 and 4.3 show that the relaxation lengths of almost all pressure and load combinations lie between ± 5% of the measurements performed at Delft. Except for the measurements with a vertical load of 2 kN and a pressure of 2 bar. But if we take a look at the individual measurements it can be seen that one measurement performed at Delft shows a very large deviation from the mean. If this measurement is left out, the difference is much smaller. The same goes for the measurements at load 2kN and pressure 2 bar. Furthermore it is clear that the relaxation length increases with increasing load and decreases with increasing tyre pressure.
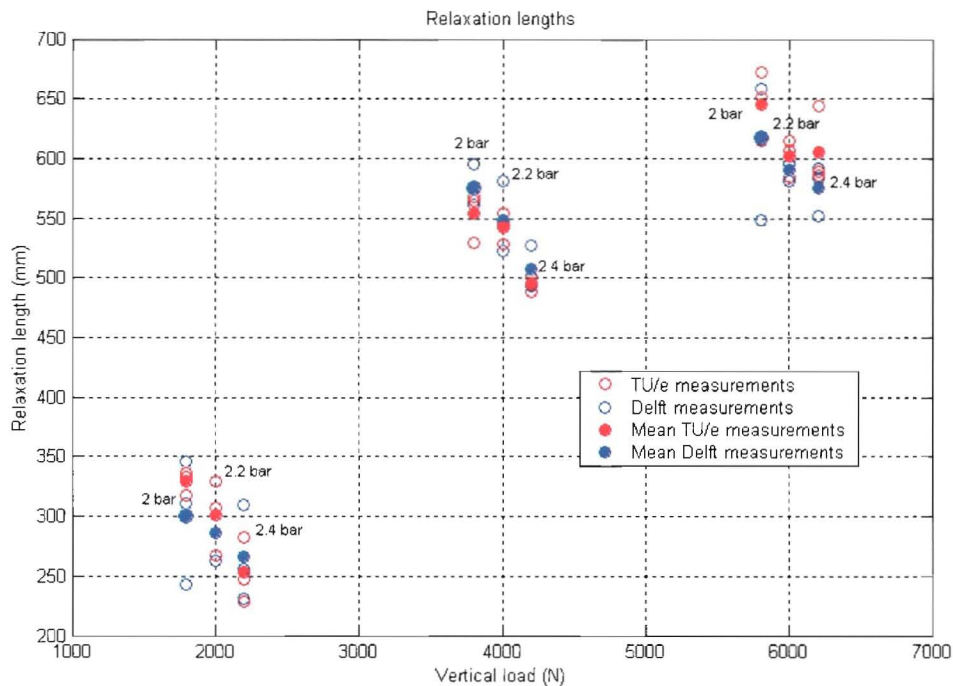
Figure 4.2 Relaxation lengths
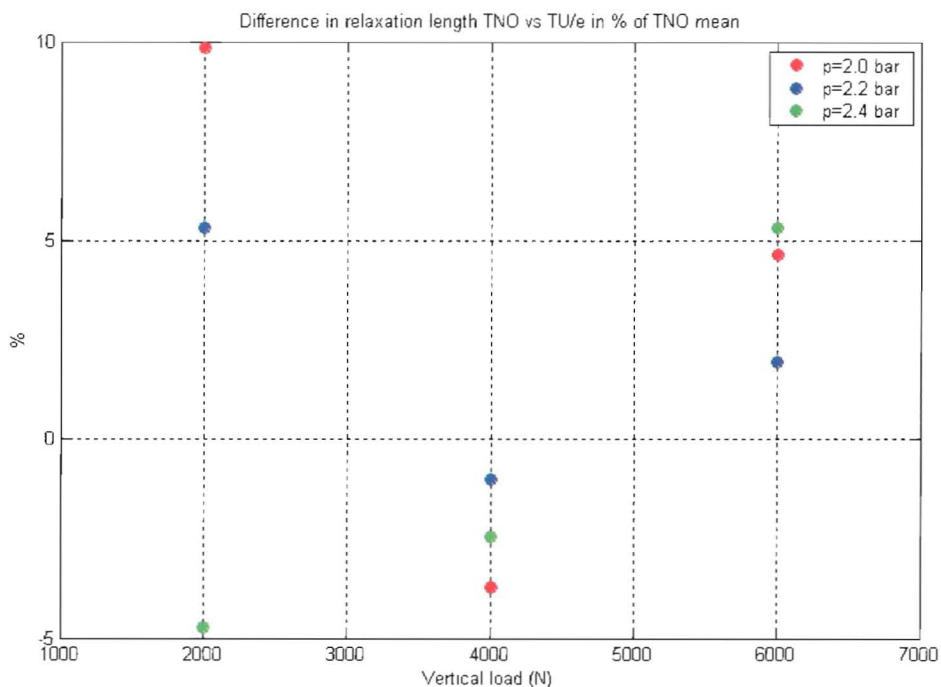
Figure 4.3 Relaxation length difference relative to the mean of TNO measured at Delft.

Figure 4.4 shows the steady state side-force for different loads and tyre pressures. It is clear from this figure that the steady state side force increases with increasing pressure, the influence of the tyre pressure is less clear.
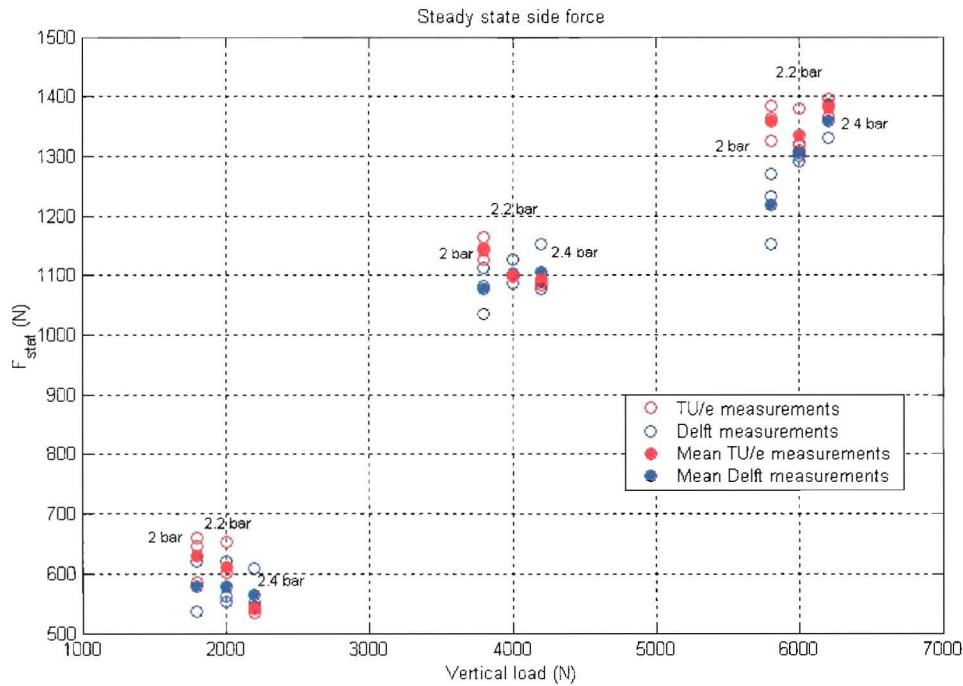
Figure 4.4 Steady state side-forces
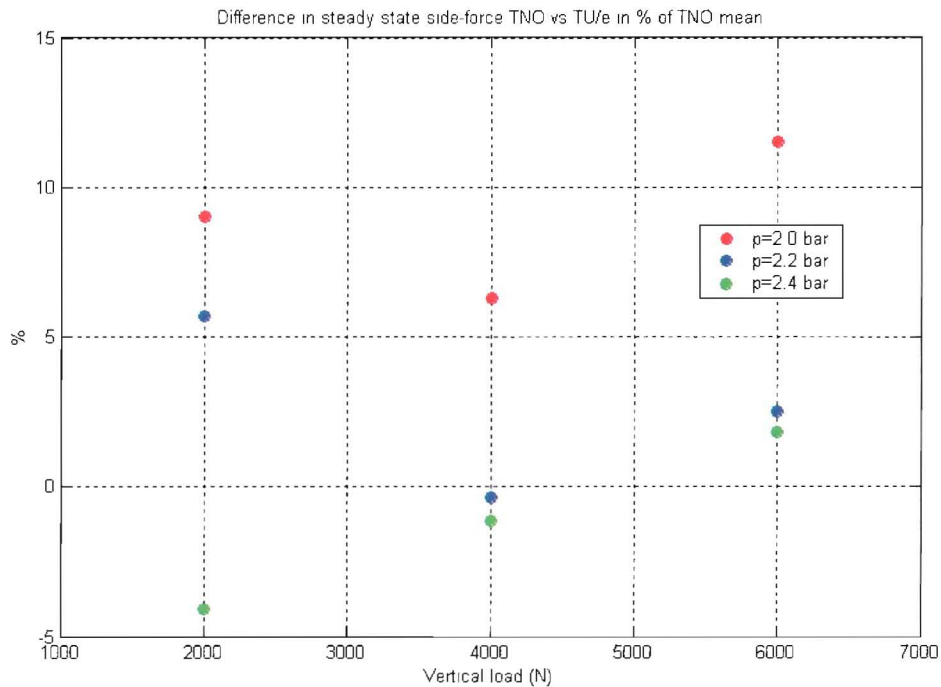
Figure 4.5 Steady stat side force difference relative to the mean of TNO measured at Delft.
The steady state values for the pressures 2.2 and 2.4 bar are within 5 % of the mean of Delft. The values for a pressure of 2.0 bar are all too high. To check whether no mistakes have been made in this measurement, the tests at 2 bar have been repeated. This makes no difference and the mean values are still much higher then those measured at Delft. An explanation can be, that the person that did the measurements in Delft read off the slip angle false, for example 0.95° instead of 1°.

§ 4.2 Longitudinal stiffness tests

The measurements performed for different loads look like this:
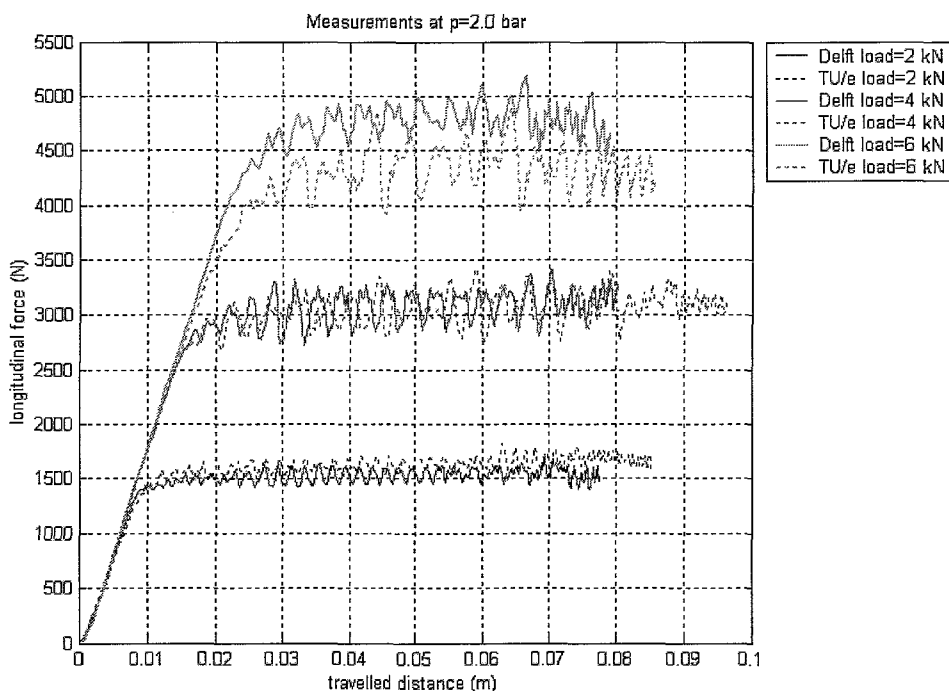
Figure 4.6 Longitudinal stiffness measurements preformed at different loads

Next the longitudinal stiffness of every measurement is determined (see chapter 4) and the mean of these stiffnesses is plotted in figure 4.7.
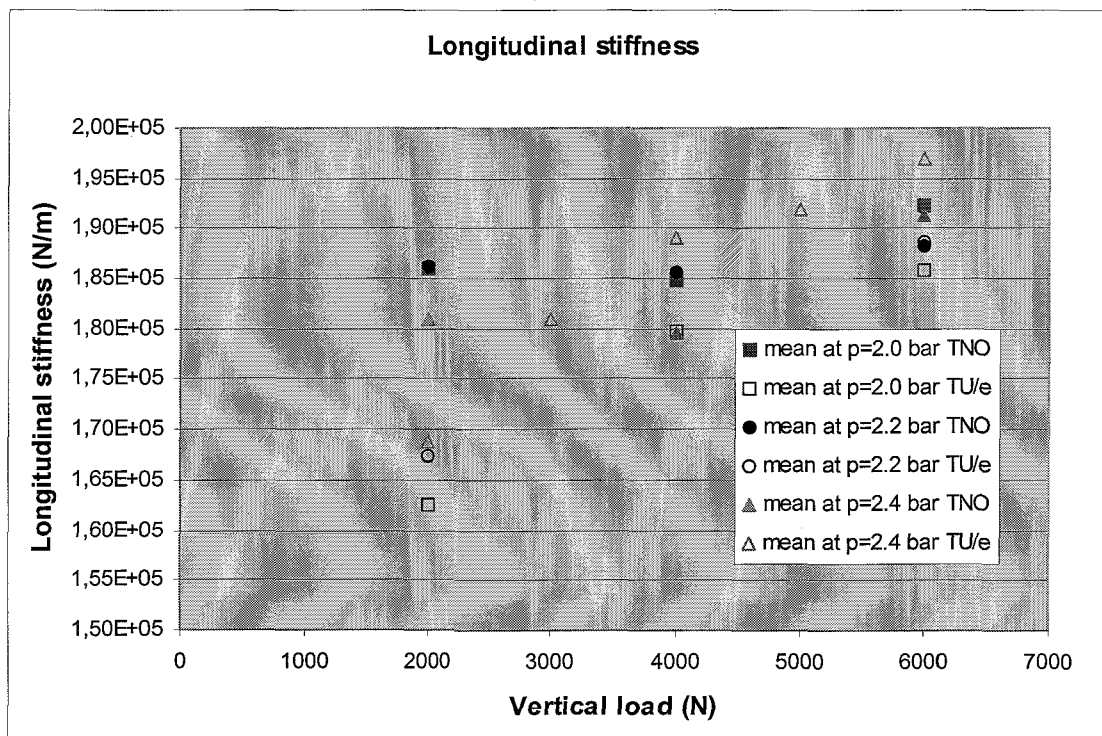
Figure 4.7 Longitudinal stiffness

According to the measurements performed at Delft the stiffness should be more or less independent of the load. Yet in the measurements performed at TU/e the stiffness increases with increasing load. To check this, measurements were also performed at loads of 3kN and 5kN (p=2.4 bar). These measurements lie between the others and also increase with increasing load. In the measurements of the TU/e the stiffness also increases with increasing tyre pressure. This is not seen in the measurements performed at Delft.
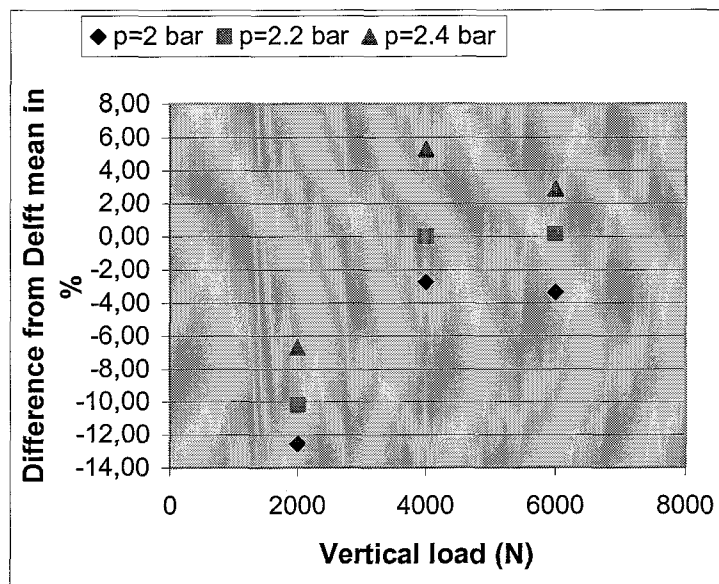
Figure 4.8 Longitudinal stiffness difference relative to the mean of TNO measured at Delft.

Looking at the relative differences between the mean longitudinal stiffnesses (figure 4.8), it is clear that the measurements performed at higher loads (4kN and 6kN) resemble the measurements from Delft relatively good. The measurements performed at a load of 2kN show a large difference with the measurements from Delft. These measurements are repeated to check whether no mistake has been made during the measurements, but this makes no difference. An explanation for this difference is that the travelled distance before the tyre start sliding at a load of 2 kN is very short. This means that there is just a small amount of data available for fitting. The shorter the "linear" part of the measurement, the less reliable the calculated stiffness.

Although the results from these 2 experiments are not exactly the same, the deviations from the experiments done at Delft are relatively small. Especially at the higher pressures (2.2 and 2.4 bar) and higher loads (4 and 6 kN). The resemblance with the results from Delft is good.

From this it is concluded that the right procedures were followed carrying out the measurements and that the machine operates correctly.

§ 4.3 Plysteer, conicity and effective rolling radius

The resulting lateral force from one of these measurements can be seen in figure 4.9:
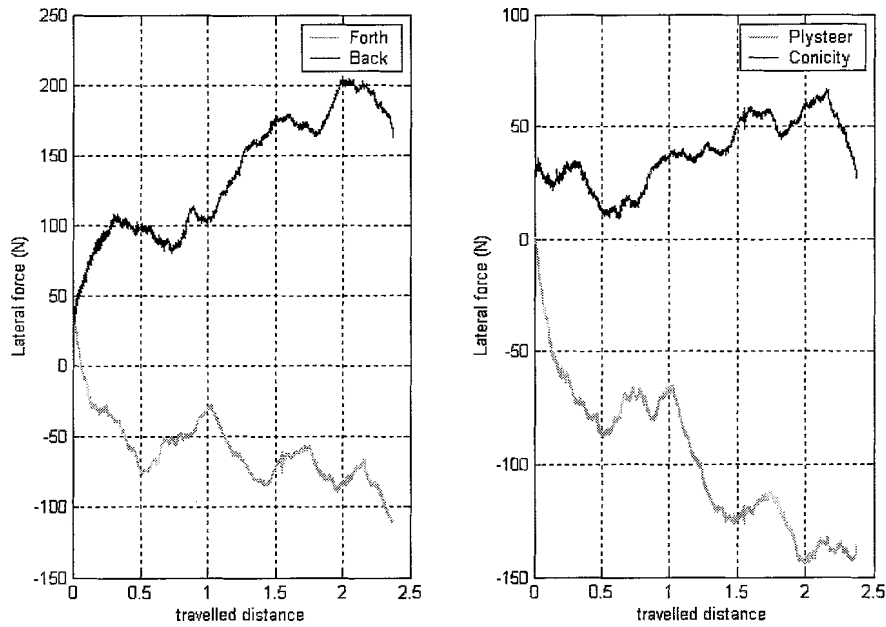
Figure 4.9 Left: lateral forces for forward and backward motion. Right: Part of the forward motion resulting from conicitiy and plysteer.

From these measurements the effective rolling radius (r_e) can also be calculated:

$r_e = \dfrac{V_x}{\omega}$, where V_x is the track velocity and ω is the rotation velocity of the wheel.

The way the data is processed is described in chapter 4.

The results of the measurements are shown in figures 4.10 and 4.11.
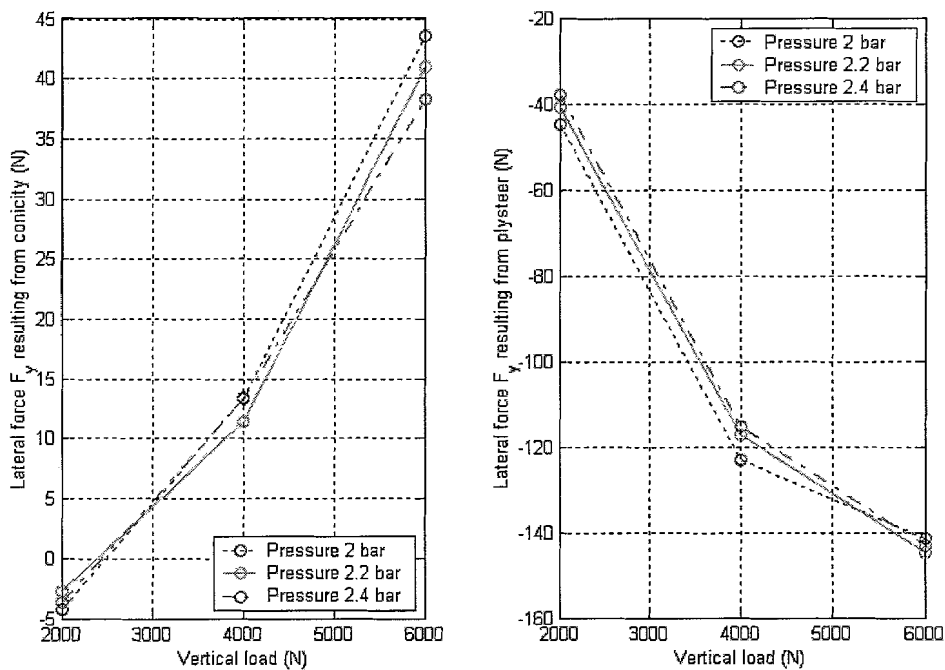
Figure 4.10 Lateral forces resulting from conicity and plysteer for different vertical loads and tyre pressures

Figure 4.10 shows that both the part resulting from conicity as the part resulting from plysteer increase with increasing vertical load. This makes sense, because plysteer can be seen as a pseudo slip angle and the conicity as a pseudo camber angle. And for a constant slip and camber angle the lateral force also increases with increasing vertical load. There is almost no difference between different tyre pressures.

Effective rolling radius o/t Kuhmo Solus 195 60R15 ---> $r_{freerolling}=0.3075$ m
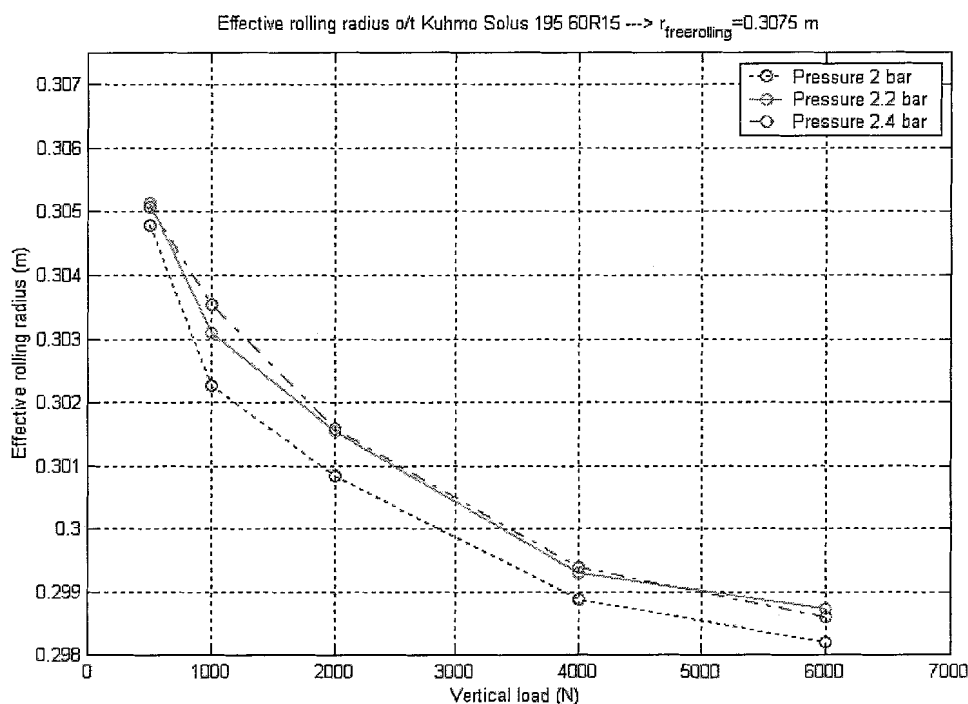
Figure 4.11 Effective rolling radius for different loads and pressures

Figure 4.11 shows the effective rolling radius for different vertical loads and tyre pressures. The effective rolling radius decreases with increasing vertical load, which is understandable because it is compressed more at higher loads. Lowering the tyre pressure decreases the effective rolling radius (if the vertical load is held constant). This is because the tyre has to be compressed further to achieve the same vertical force.

§ 4.4 Parking manoeuvre test

The model described in chapter 3 was implemented in Simulink. This yields figure 4.12.

The cycle clearly shows hysteresis. After completing the cycle M_z is not equal to the M_z in the starting position. The parameters for the model have been chosen based on the measurements at 3 and 5 kN. Afterwards the measurement at 4 kN was also plotted together with the model. Although the parameters were not based on this measurement, the model fits the measurement well.
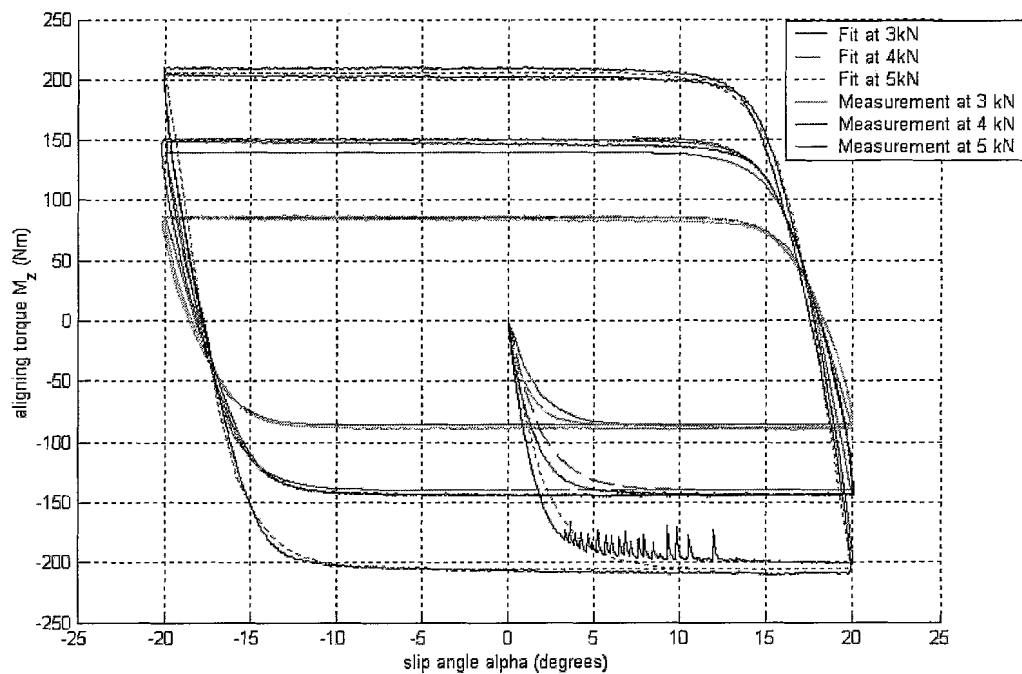
Figure 4.12 Results of the parking maneuver experiment.

§ 4.5 Small obstacle test

For this test 2 obstacles were used:
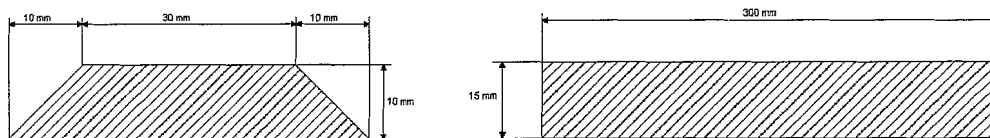
Figure 4.13 The two cleats used for this test.

Figure 4.14 shows the vertical and longitudinal force when rolling over cleat 1. The vertical load clearly has a different response for the three loads. This is probably due to the fact that the stiffness of a tyre decreases when the sidewalls of the tyre bulge out. The higher the load, the more they bulge out. So at 6 kN the stiffness of the tyre, when exactly above the cleat, is lower than at 2 kN. The influence of the tyre pressure is also pretty clear: higher pressure, higher force.

Figure 4.15 shows the effective rolling radius when rolling over cleat 1. Because the velocity (of the track and the wheel) is calculated by differentiating the position signal, it contains a lot of high frequency noise. For this reason these signals have been filtered using a second order low-pass filter with a cut-off frequency of 1 Hz.

Two things can be seen in these figures. Firstly, with increasing load, the distance between the two peaks increases also. This is because the contact patch increases with increasing load. Secondly, as the load increases from 4 to 6 kN, a peak arises at s=0 for p=2.0 bar. This may have to do with the fact that the tyre

touches the track in front of and behind the cleat at this lowest pressure. With rising pressure one can see that the peak disappears.
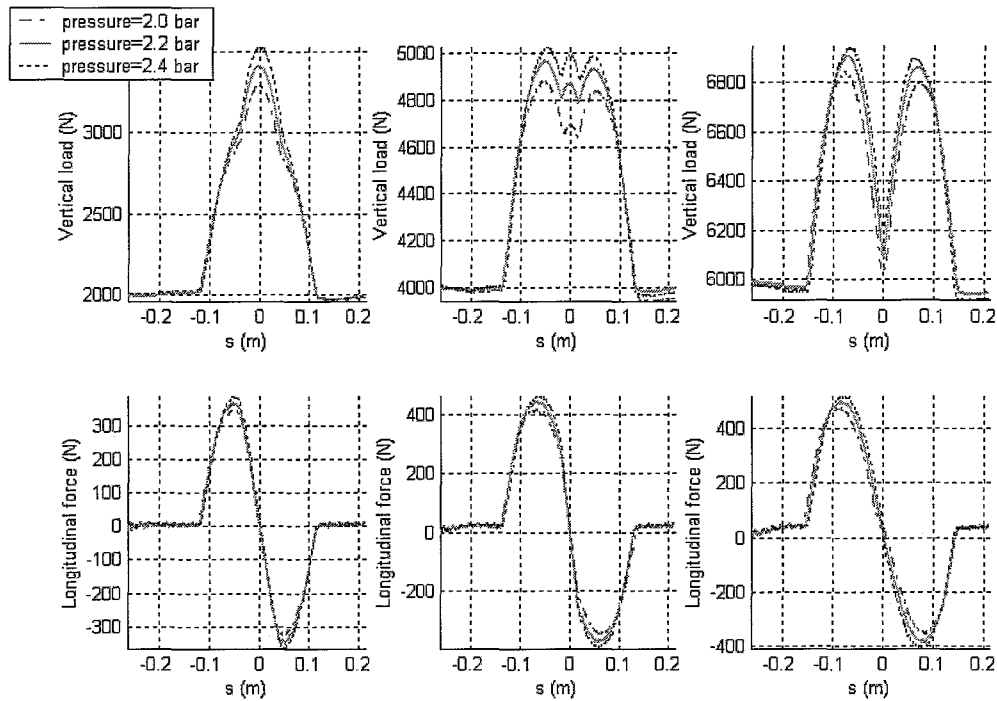
Figure 4.14 Vertical and longitudinal force for different pressures. s is the distance from the middle of cleat 1.(trapezium)
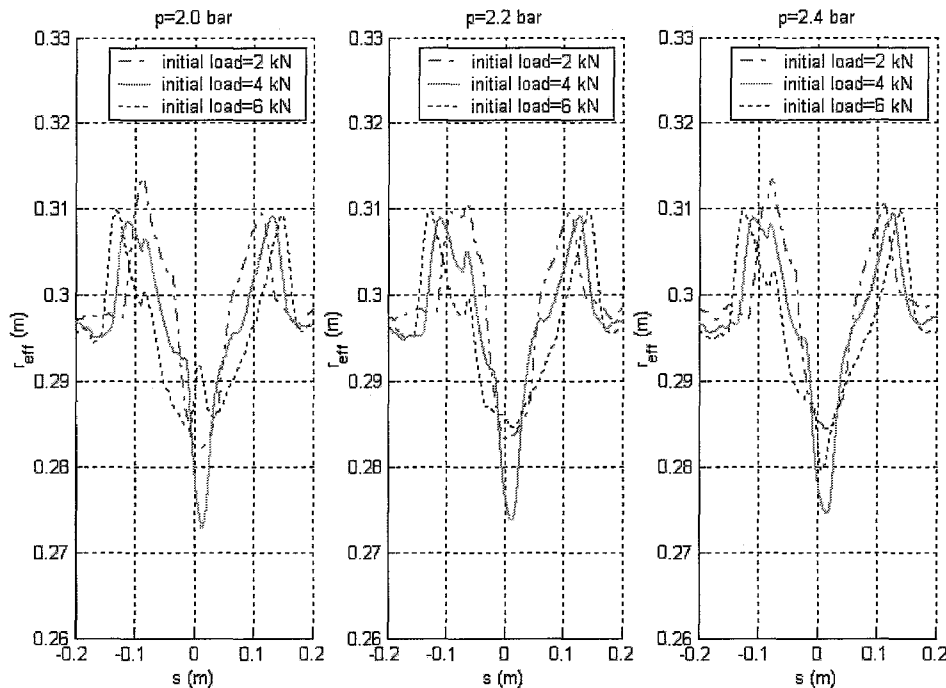
Figure 4.14 Effective rolling radius for different pressures. s is the distance from the middle of cleat 1.(trapezium)

Figure 4.15 shows the vertical and longitudinal force when rolling on cleat 2. The tyre is not rolled over the entire cleat. It is rolled until the whole contact patch has passed the step.

This measurement is only done for initial loads of 2 kN and 4 kN. At an initial load of 6 kN the measuring hub might be overloaded.

For this cleat the vertical load also has a different response for the two initial loads. But the difference is not as obvious as for cleat 1. The influence of the tyre pressure is pretty clear: higher pressure, higher force.
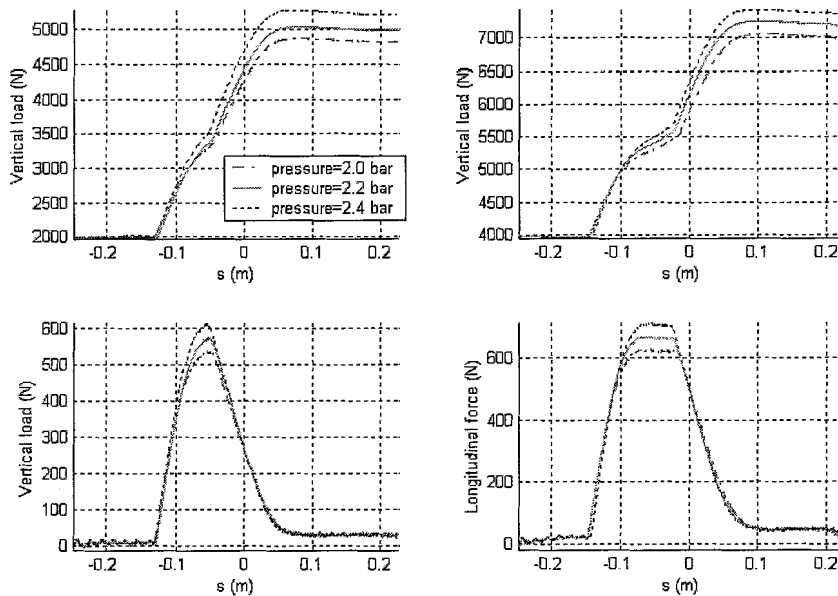
Figure 4.15 Vertical and longitudinal force for different pressures. s is the distance from the start of cleat 2.(step)
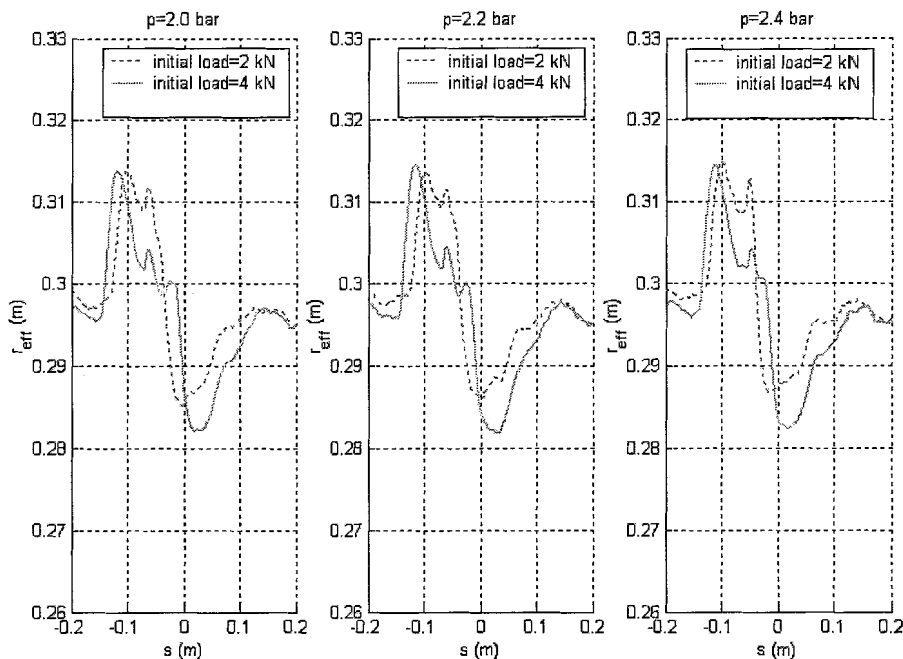
Figure 4.16 Effective rolling radius for different pressures. s is the distance from the start of cleat 2.(step)

Figure 4.16 shows the effective rolling radius when rolling over cleat 2. The track velocity and angular velocity of the wheel have also been filtered using a second order low-pass filter with a cut-off frequency of 1 Hz. When assuming a constant track velocity, the angular velocity decreases when the first part hits the step and increases when the center of the wheel has passed the step.

The results of these measurements agree with results obtained by Zegelaar [Lit 5], which are also mentioned by Pacejka [Lit 3].

Chapter 5 Conclusion & recommendations

§ 5.1 Conclusion

The relaxation length and stiffness measurements carried out at the TU/e on the Kuhmo Solus 195 60R15 seem to resemble the measurements from Delft well. Except for some measurements concerning the longitudinal stiffness, the difference between the measurements carried out at the TU/e and at Delft is less than 5 %. Furthermore some other tests are carried out, which also show the expected trend. Finally recommendations are made for improving the machine and making it easier to operate.

§ 5.2 Recommendations

To make it easier to carry out tests on the flat plank tyre tester some recommendations concerning the machine are made in this chapter.

Trigger

To make it easier to check whether the trigger is in the right position before starting the measurement, it must be possible to see the trigger signal in Labview. For example a warning light which lights when the trigger is in the right position. This requires an extension of the Labview program.

Motor control

There are already two control devices present. It might be possible to connect these to the computer. This way is must be possible to control these movements (the track movement and the slip angle adjustment) from the computer. The third movement (vertical displacement of the wheel) can also be motorized. These adjustments will make the operation of the machine a lot more user friendly. It will also allow for one person doing all tests. The test for parking behaviour for example now has to be done by two people.

Side slip angle adjustment

Because the slip angle that is commonly used for doing relaxation measurements (1 degree) is small, a small deviation from this 1° leads to a large difference in steady state force. The side slip angle has to be read off a scale with increments of 0.2 degrees. This makes it difficult to precisely adjust the slip angle. At the moment a encoder is present for measuring the slip angle. This way only a relative angle (to the starting position) can be measured. To be sure that the angle is correct some sort of absolute measuring system must be made.

Track alignment

When two measurements are done starting from the same position on the track, but from different positions on the tyre the peaks still coincide (see figure 5.1).
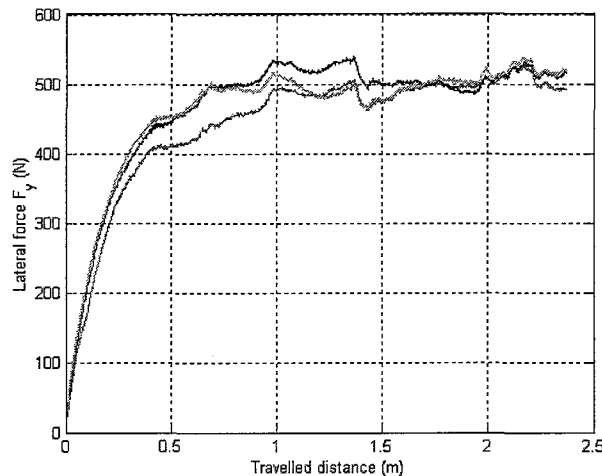
Figure 5.1 Lateral side force at slip angle of 1 degree and vertical load of 2kN at three different starting points on the tyre.

Because the peaks coincide, the track must be the cause of the peaks. This might be improved by aligning the track.

Locking the wheel

At this moment, the wheel is locked by placing two pins in the brake-disc. It is difficult to do this exactly the same every time. This problem gets even bigger if different people carry out the measurements. This makes it difficult to compare the measurements. Therefore another way has to be found to lock the wheel. It might be an option to fix the brake, from which some parts are still present on the machine.

Using the air spring

To adjust the pressure and amount of leakage of the air spring correctly, the person adjusting this must know the actual vertical load. Because at this moment the computer is on the other side of the machine, two people are needed to do tests with the air spring involved. Moving the computer to the other side is no solution, because the same problem then arises when tests with constant axle height have to be done. One solution, and probably the fastest to realize, is to connect a second screen to the computer and place this on the other side of the machine. Another solution would be to use another, more advanced, control system for the pressure and leakage.

References

[1] Higuchi,A. (1997). *Experimental study on transient response of tyres,* Delft

[2] Jagt,P. van der, (2000) *Prediction of steering efforts during stationary or slow rolling,* Aachen.

[3] Pacejka,H.B. (2002). *Tyre and vehicle dynamics,* Oxford: Butterworth-Heinemann

[4] Vissers, J.P.M./Blom, R.E.A. (2003). *Manual for the flat plank tyre tester,* Eindhoven

[5] Zegelaar, P.W.A. (1998). *The dynamic response of tyres to brake torque and road unevenness,* TU Delft

List of symbols

Symbol	Quantity	Unit
a_0, a_1, b_0, b_1, c_0	Model parameters	-
F_{stat}	Steady state force	N
F_x	Longitudinal force at contact patch	N
F_y	Lateral force at contact patch	N
F_z	Vertical force at contact patch	N
G_{x1}, G_{x2}	Longitudinal forces measured by strain gauges	N
G_y	Lateral force measured by strain gauge	N
G_{z1}, G_{z2}	Vertical forces measured by strain gauges	N
K_ψ	Torsional stiffness of the tyre	Nm/deg.
K_x	Longitudinal force at axle centre	N
K_y	Lateral force at axle centre	N
K_z	Vertical force at axle centre	N
M_x	Moment at contact patch around longitudinal axis	Nm
M_y	Moment at contact patch around lateral axis	Nm
M_z	Moment at contact patch around vertical axis	Nm
$M_{z,max}$	Maximum Torque that can be generated by the tyre	Nm
p	Tyre pressure	bar
R	Relaxation length	m
r	Tyre rolling radius	m
r_e	Effective rolling radius	m
r_l	Loaded wheel radius	m
t_p	Pneumatic trail	m
T_x	Moment at axle centre around longitudinal axis	Nm
T_y	Moment at axle centre around lateral axis	Nm

Symbol	Quantity	Unit
T_z	Moment at axle centre around vertical axis	Nm
V_x	Longitudinal component of V	m/s
V_y	Lateral component of V	m/s
X_{rel}	Tyre relaxation length	m
α	Side slip angle	degrees or rad.
γ	Camber angle	degrees
κ	Longitudinal slip	-
Ψ	Yaw angle of the wheel plane	deg
Ψ_{def}	Torsional deflection of the tyre.	deg.
Ψ_{defm}	Maximum possible deflection of the tyre	deg.
ω	Tyre rotational velocity	rad/s
Ω	Angular velocity	rad/s

Appendix I m-files

§ I.1 Relaxationlength

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Relaxationlength %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%% 2003 - Ron Blom - John Vissers - 2003 %%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all
close all
Rel=[];
RL_here=[];
RL_tno=[];
kleurtje=['cmb'];
soort=['--:.'];
Fstat_tno=[];
Fstat_here=[];
%%%%%%%%%%%%%%%%%%%%%%%% load the files created by labview %%%%%%%%%%%%%%%%%%%%%%%%%%%
for p=2:2:6
    pres=num2str(p+18);
    abc=['abc'];
    for l=[2 4 6];
        for b=1:3
            disp(num2str([p l b]))
            disp('Loading data');
            letter=abc(b);
            eval(['Data0=load(''\p',pres,'l',num2str(l),'a0',letter,''');']);
            eval(['Data1=load(''\p',pres,'l',num2str(l),'a1',letter,''');']);
            eval(['Data2=load(''\n4p',pres,'l',num2str(l),'a0',letter,''');']);
            eval(['Data3=load(''\n4p',pres,'l',num2str(l),'a1',letter,''');']);
            disp('Data loaded');


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%% Extract the data from the files %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            disp('Extracting data');
            Fy=Data1(1:2500,2)-Data0(1:2500,2);
            Fy_here=Data3(1:2500,2)-Data2(1:2500,2);
            x=Data0(1:2500,11);
            x_here=Data2(1:2500,11);
            disp('Data extracted');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% Fitting %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
            disp('Start fitting');
            ydata=Fy-Fy(1,1)*ones(2500,1);
            ydata2=Fy_here-Fy_here(1,1)*ones(2500,1);
            xdata=x;
            xdata2=x_here;

            fun = inline('(x(1)*(1-exp(-xdata/x(2))))','x','xdata');
            fun2 = inline('(x(1)*(1-exp(-xdata2/x(2))))','x','xdata2');

            x1=lsqcurvefit(fun,[1000 0.3],xdata,ydata);
            x2=lsqcurvefit(fun2,[1000 0.3],xdata2,ydata2);

            RL_tno(l/2,b,p/2)=x1(2);
            RL_here(l/2,b,p/2)=x2(2);
            Fstat_tno(l/2,b,p/2)=x1(1);
            Fstat_here(l/2,b,p/2)=x2(1);
            disp('End fitting');
        end
    end
end

RL_tno=1000*RL_tno;
RL_here=1000*RL_here;
%   plotwork %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('Starting plotwork')
if p>=2
    Fz20=[2000-200 2000-200 2000-200;4000-200 4000-200 4000-200; 6000-200 6000-200
6000-200];
end
if p>=4
    Fz22=[2000 2000 2000;4000 4000 4000; 6000 6000 6000];
end
```

```
if p==6
    Fz24=[2000+200 2000+200 2000+200;4000+200 4000+200 4000+200; 6000+200 6000+200
6000+200];
end

if p>=2
    Fz220=[2000-200 4000-200 6000-200];
end
if p>=4
    Fz222=[2000 4000 6000];
end
if p==6
    Fz224=[2000+200 4000+200 6000+200];
end

RL_tno_mean=mean(RL_tno,2);
RL_here_mean=mean(RL_here,2);
Fstat_tno_mean=mean(Fstat_tno,2);
Fstat_here_mean=mean(Fstat_here,2);

if p>=2
    figure(1)
    plot(Fz20,squeeze(RL_tno(:,:,1)),'bo');hold on;
    plot(Fz20,squeeze(RL_here(:,:,1)),'ro');hold on;
    plot(Fz220,squeeze(RL_tno_mean(:,:,1)),'b*');hold on;
    plot(Fz220,squeeze(RL_here_mean(:,:,1)),'r*');hold on;

    figure(2)
    plot(Fz20,squeeze(Fstat_tno(:,:,1)),'bo');hold on;
    plot(Fz20,squeeze(Fstat_here(:,:,1)),'ro');hold on;
    plot(Fz220,squeeze(Fstat_tno_mean(:,:,1)),'b*');hold on;
    plot(Fz220,squeeze(Fstat_here_mean(:,:,1)),'r*');hold on;
end
if p>=4
    figure(1)
    plot(Fz22,squeeze(RL_tno(:,:,2)),'bo');hold on;
    plot(Fz22,squeeze(RL_here(:,:,2)),'ro');hold on;
    plot(Fz222,squeeze(RL_tno_mean(:,:,2)),'b*');hold on;
    plot(Fz222,squeeze(RL_here_mean(:,:,2)),'r*');hold on;

    figure(2)
    plot(Fz22,squeeze(Fstat_tno(:,:,2)),'bo');hold on;
    plot(Fz22,squeeze(Fstat_here(:,:,2)),'ro');hold on;
    plot(Fz222,squeeze(Fstat_tno_mean(:,:,2)),'b*');hold on;
    plot(Fz222,squeeze(Fstat_here_mean(:,:,2)),'r*');hold on;
end
if p==6
    figure(1)
    plot(Fz24,squeeze(RL_tno(:,:,3)),'bo');hold on;
    plot(Fz24,squeeze(RL_here(:,:,3)),'ro');hold on;
    plot(Fz224,squeeze(RL_tno_mean(:,:,3)),'bd');hold on;
    plot(Fz224,squeeze(RL_here_mean(:,:,3)),'r*');hold on;

    figure(2)
    plot(Fz24,squeeze(Fstat_tno(:,:,3)),'bo');hold on;
    plot(Fz24,squeeze(Fstat_here(:,:,3)),'ro');hold on;
    plot(Fz224,squeeze(Fstat_tno_mean(:,:,3)),'b*');hold on;
    plot(Fz224,squeeze(Fstat_here_mean(:,:,3)),'r*');hold on;
end

figure(1)
hold off;
xlabel('Vertical load (N)');
ylabel('Relaxation length (mm)');
axis([1000 7000 200 700]);
grid;

figure(2)
hold off;
xlabel('Vertical load (N)');
ylabel('F_s_t_a_t (N)');
axis([1000 7000 500 1500]);
grid;

%%% Calculate difference in percentage of TNO measurement %%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(3)
difference=100*(RL_here_mean-RL_tno_mean)./RL_tno_mean;
```

```
if p>=2
    plot(Fz222',squeeze(difference(:,:,1))','r*');hold on;
end
if p>=4
    plot(Fz222',squeeze(difference(:,:,2))','b*');hold on;
end
if p==6
    plot(Fz222',squeeze(difference(:,:,3))','g*');hold on;
end
xlabel('Vertical load (N)');
ylabel('%');
title('Difference in relaxation length TNO vs TU/e in % of TNO mean');
grid;
hold off;
axis([1000 7000 -5 10]);


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%% Calculate difference in percentage of TNO measurement %%%%%%%%%%%%%%%%%%%%%%%%
figure(4)
difference=100*(Fstat_here_mean-Fstat_tno_mean)./Fstat_tno_mean;
if p>=2
    plot(Fz222',squeeze(difference(:,:,1))','r*');hold on;
end
if p>=4
    plot(Fz222',squeeze(difference(:,:,2))','b*');hold on;
end
if p==6
    plot(Fz222',squeeze(difference(:,:,3))','g*');hold on;
end
xlabel('Vertical load (N)');
ylabel('%');
title('Difference in steady state side-force TNO vs TU/e in % of TNO mean');
grid;
hold off;
axis([1000 7000 -5 15]);
%% end of file %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

§ I.2 Longitudinal stiffness

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Program for analysing data from the flat plank tyre tester. The program can   %%%
%%% analyse data concerning a relaxation length test and a stiffness test. The    %%%
%%% output the program generates depends on the type of data. If it is data from a %%%
%%% relaxation length test the following ... are plotted: Longitudinal force, Side %%%
%%% force, vertical load, overturning moment, aligning moment and travelled        %%%
%%% distance. Furthermore a curve is fitted to determine the relaxation length. If %%%
%%% the data is from a stiffness test the only output is the longtudinal force Fx. %%%
%%% A line is on the linear part, which has to be selected by the user. The slope  %%%
%%% of this line is the stiffness.                                                 %%%
%%%                     Created by Ron Blom & John Vissers                         %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
clear all; close all;
testsort=input('What kind of test is this? (1=relaxation length 2=stiffness): ');
if testsort==1
    file0=input('Which reference file do you want to analyse? (Enter filename)','s');
    data0=load(file0);
    file1=input('Which file do you want to analyse? (Enter filename)','s');
    data1=load(file1);
elseif testsort==2
    file=input('Which file do you want to analyse? (Enter filename)','s');
    data=load(file);
end

if testsort==1
    choice=input('What output do you need (1=plots only, 2=all, 3=fit of Fy only)?');
end
%%% relaxation length %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if testsort==1
%%% plotwork %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    if  sum(choice==1:2)==1
        subplot(231);
        plot(data1(:,11),data1(:,1)-data0(:,1));
        title('Longitudinal force');
        xlabel('Travelled distance(m)');
        ylabel('F_x (N)');
```

```
    grid on;

    subplot(232);
    plot(data1(:,11),data1(:,2)-data0(:,2));
    title('Side force');
    xlabel('Travelled distance (m)');
    ylabel('F_y (N)');
    grid on;

    subplot(233);
    plot(data1(:,11),data1(:,3));
    title('Vertical load');
    xlabel('Travelled distance (m)');
    ylabel('F_z (N)');
    %axis([0 max(data1(:,11)) 0 max(data(:,3))]);
    grid on;

    subplot(234);
    plot(data1(:,11),data1(:,4)-data0(:,4));
    title('T_x');
    xlabel('Travelled distance (m)');
    ylabel('T_x (Nm)');
    grid on;

    subplot(235);
    plot(data1(:,11),data1(:,5)-data0(:,5));
    title('Aligning moment');
    xlabel('Travelled distance (m)');
    ylabel('M_z (Nm)');
    grid on;

    subplot(236);
    plot(data1(:,11),data1(:,10));
    title('Track Velocity');
    xlabel('Travelled distance (m)');
    ylabel('Track velocity (m/s)');
    axis([0 1.5 0 0.1]);
    grid on;
end

%%% fit data %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if sum(choice==2:3)==1
    datasplit=input('Select data points for fit (1=all 2=selection): ');
    if datasplit==1
        xdata=abs(data1(:,11));
        ydata=data1(:,2)-data0(:,2);
    elseif datasplit==2
        datastart_t=input('Select start x value: ');
        dataend_t=input('Select end x value: ');
        datastart_temp=[];
        dataend_temp=[];
        for i=1:length(data1(:,11));
        if abs(data1(i,11))<datastart_t;
        datastart_temp=[datastart_temp data1(i,11)];
        end
        end
        for i=1:length(data1(:,11));
        if abs(data1(i,11))<dataend_t;
        dataend_temp=[dataend_temp data1(i,11)];
        end
        end
        datastart=length(datastart_temp)+1;
        dataend=length(dataend_temp)+1;
        xdata=data1(datastart:dataend,11);
        ydata=data1(datastart:dataend,2)-data0(datastart:dataend,2);
    end

    fun = inline('x(1)*(1-exp(-xdata/x(2)))','x','xdata');
    x1=lsqcurvefit(fun,[sign(data1(100,2))*(max(abs(data1(:,2))))
0.5],xdata,ydata);
    RL=round(x1(2)*1000);

    lab=sprintf('Fit van F_y ---- relaxatielengte=%d mm',RL)

    figure(2)
    hold on;
```

```
        plot(abs(data1(:,11)),data1(:,2)-data0(:,2),abs(data1(:,11)),x1(1)*(1-exp(-
abs(data1(:,11))/x1(2))));
        title(lab);
        xlabel('Travelled distance');
        ylabel('Side force (N)');
        hold off;
        grid on;
    end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end


%%% stiffness %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
if testsort==2

    plot(abs(data(:,11)),data(:,1))
    xlabel('Travelled distance (m)');
    ylabel('Longitudinal force (N)');
    grid on;

    % fit data %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    disp('number of data points:');
    datapoints=length(data(:,1))
    i1=0;
    while i1==0
            datastart_t=input('Select start x value: ');
            dataend_t=input('Select end x value: ');
            datastart_temp=[];
            dataend_temp=[];
            for i=1:length(data(:,11));
            if abs(data(i,11))<datastart_t;
            datastart_temp=[datastart_temp data(i,11)];
            end
            end
            for i=1:length(data(:,11));
            if abs(data(i,11))<dataend_t;
            dataend_temp=[dataend_temp data(i,11)];
            end
            end
            datastart=length(datastart_temp)+1;
            dataend=length(dataend_temp)+1;
            xdata=data(datastart:dataend,11);
            ydata=data(datastart:dataend,1);

        figure(2)
        plot(abs(xdata),ydata);
        title('Selected part');
        xlabel('Travelled distance (m)');
        ylabel('Longitudinal force');
        grid on;
        i1=input('Is this OK ? (yes=1,no=0): ');
    end
    i2=0;
    while i2==0
        x0=input('Give initial guess [offset stiffness]: ');
        fun = inline('x(1)+x(2)*xdata','x','xdata');
        x1=lsqcurvefit(fun,x0,xdata,ydata)
        S=(x1(2));

        lab=sprintf('Fit van F_x ---- stijfheid=%d mm N/m',S)

        figure(1)
        hold on;
        plot(abs(xdata),x1(1)+x1(2)*xdata,'m');
        title(lab)
        hold off;
        grid on;

        figure(2)
        hold on;
        plot(abs(xdata),x1(1)+x1(2)*xdata,'m');
        hold off;
        grid on;
        i2=input('Is this OK ? (yes=1,no=0): ');
    end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
```

§ 1.3 Plysteer/conicity

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Created by Ron Blom & John Vissers 2003                           %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all; clear all;
tire_pres=[20,22,24];
for p=1:3;
    pres=tire_pres(p);
    for l=2:2:6;
        for k=1:2
          eval(['datah=load(''\n2p',num2str(pres),'l',num2str(l),'pc',num2str(k),''');']);
    eval(['datat=load(''\n2p',num2str(pres),'l',num2str(l),'pc',num2str(k),'t',''');']);
              con_Fy=(datat(:,2)+datah(:,2))/2;
              ply_Fy=(datah(:,2)-datat(:,2))/2;

              %plysteer fitten
              fun = inline('x(1)*(1-exp(-xdata/x(2)))','x','xdata');
              x1=lsqcurvefit(fun,[-10 0.5],datah(:,11),ply_Fy);
              F_stat_ply=x1(1);

              %conicity fitten
              F_stat_con=mean(con_Fy);
              Conicity(p,l/2,k)=F_stat_con;
              Plysteer(p,l/2,k)=F_stat_ply;
              disp(num2str([pres l k]))

              %effectieve rolstraal bepalen
              R_eff(p,l/2)=mean([datah(:,10)./datah(:,8);
                                 datat(:,10)./datat(:,8)]);

              R_eff_std(p,l/2)=std([datah(:,10)./datah(:,8);
                                    datat(:,10)./datat(:,8)]);
        end
    end
end

%%% extract data for plotting %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
con_p20=squeeze(Conicity(1,:,:));
con_p22=squeeze(Conicity(2,:,:));
con_p24=squeeze(Conicity(3,:,:));

ply_p20=squeeze(Plysteer(1,:,:));
ply_p22=squeeze(Plysteer(2,:,:));
ply_p24=squeeze(Plysteer(3,:,:));
%%%%% plotwork %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
F=1e3*[2 4 6];
subplot(121)
%%% Conicity plotten %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
plot(F,mean(con_p20,2),'bo-',F,mean(con_p22,2),'go-',F,mean(con_p24,2),'ro-')
grid on;
legend('Pressure 2 bar','Pressure 2.2 bar','Pressure 2.4 bar',4);
xlabel('Vertical load (N)');
ylabel('Lateral force F_y resulting from conicity (N)');


%%% Plysteer plotten %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(1)
subplot(122)
plot(F,mean(ply_p20,2),'bo-',F,mean(ply_p22,2),'go-',F,mean(ply_p24,2),'ro-')

grid on;
legend('Pressure 2 bar','Pressure 2.2 bar','Pressure 2.4 bar');
xlabel('Vertical load (N)');
ylabel('Lateral force F_y resulting from plysteer (N)');


%%% R_eff plotten %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
figure(4)

R=16*0.0254/2+0.205*.55;
plot(F,R_eff(1,:),'bo-',F,R_eff(2,:),'go-',F,R_eff(3,:),'ro-');
grid on
legend('Pressure 2 bar','Pressure 2.2 bar','Pressure 2.4 bar','Free rolling radius');
xlabel('Belasting (N)');
ylabel('Effectieve rolstraal (m)');
```

axis([1000 7000 0.298 0.302])

§ I.4 Effective rollig radius while rolling over obstacles

```
clear all; close all;
cleat=2;
if cleat==1
    ref=-0.271; %cleat1
    loads=[2 4 6];
elseif cleat==2
    ref=-0.256; %cleat 2
    loads=[2 4];
end
datastart=4;
dataend=5000;
fcutoff=1;
Fs=500;
% Determine the filter coefficients
[b,a]=butter(2,fcutoff/(Fs/2));

for l=loads
    color=['rgb'];
    for p=20:2:24

eval(['dataa=load(''\p',num2str(p),'l',num2str(l),'cl',num2str(cleat),'a',''');']);
eval(['datab=load(''\p',num2str(p),'l',num2str(l),'cl',num2str(cleat),'b',''');']);
eval(['datac=load(''\p',num2str(p),'l',num2str(l),'cl',num2str(cleat),'c',''');']);

        % Apply the filter to the input waveform
        V_fa=filter(b,a,dataa(datastart:dataend,10));
        w_fa=filter(b,a,dataa(datastart:dataend,8));
        V_fb=filter(b,a,datab(datastart:dataend,10));
        w_fb=filter(b,a,datab(datastart:dataend,8));
        V_fc=filter(b,a,datac(datastart:dataend,10));
        w_fc=filter(b,a,datac(datastart:dataend,8));

        re_f=mean([V_fa./w_fa V_fb./w_fb V_fc./w_fc],2);

        subplot(1,3,(p-18)/2)
        hold on
        plot(dataa(datastart:dataend,11)+ref*ones(1,dataend-
datastart+1)',re_f,color(l/2))
        hold off
        axis([-0.2 0.2 0.260 0.33])
        grid on
        disp(num2str([l p]));
    end
end

subplot(131)
legend('initial load=2 kN','initial load=4 kN','initial load=6 kN')
xlabel('s (m)')
ylabel('r_e_f_f (m)')
title('p=2.0 bar')

subplot(132)
legend('initial load=2 kN','initial load=4 kN','initial load=6 kN')
xlabel('s (m)')
ylabel('r_e_f_f (m)')
title('p=2.2 bar')

subplot(133)
legend('initial load=2 kN','initial load=4 kN','initial load=6 kN')
xlabel('s (m)')
ylabel('r_e_f_f (m)')
title('p=2.4 bar')
```
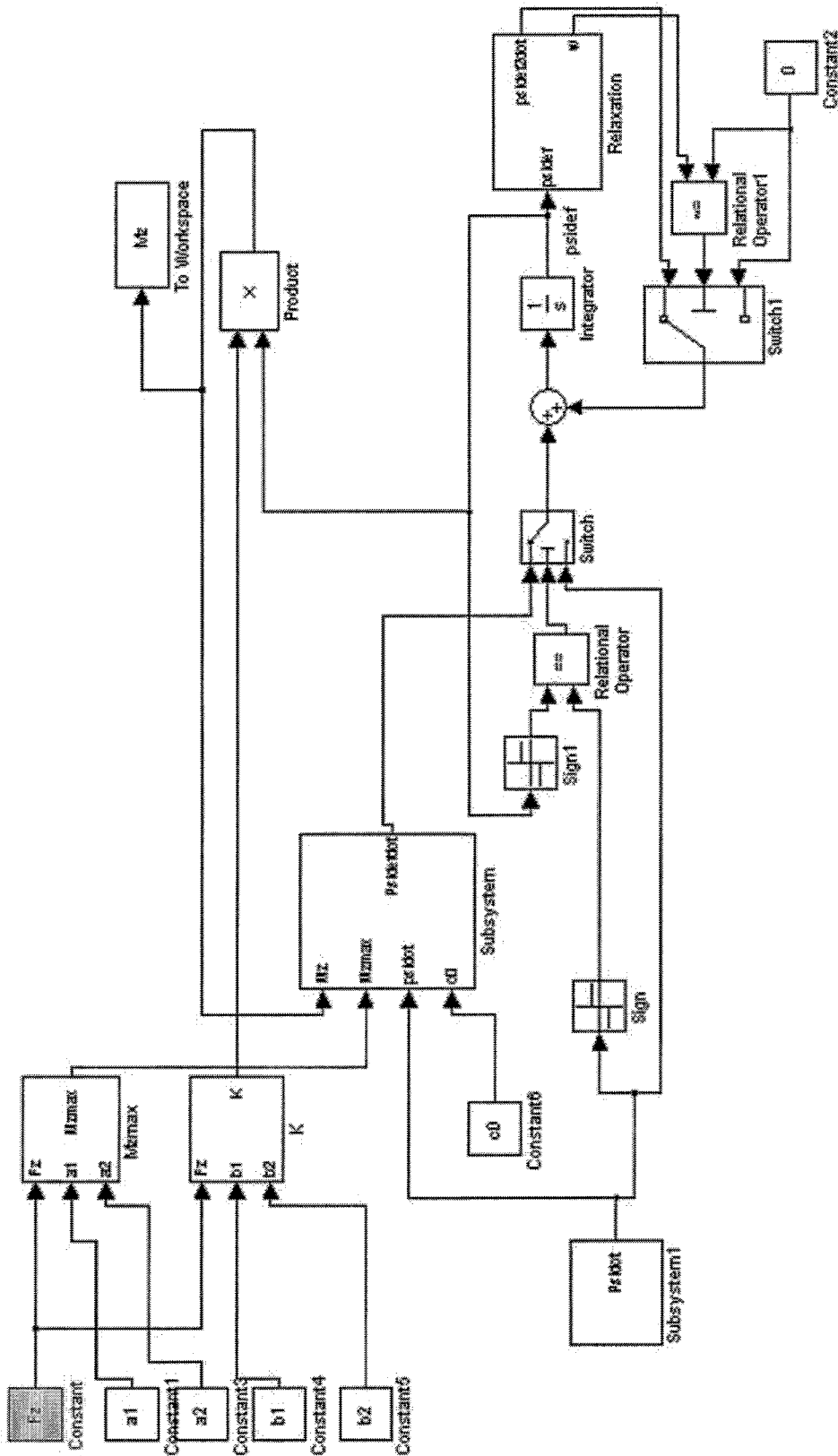
Appendix II Simulink model

Figure II.1 Simulink model for parking behaviour