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Wheel Clearance Testing in a Test Rig Simulation with Operational Chassis Displacement

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Abstract

Volvo Cars proving ground in Hällered is a place for cars to be tested around the clock, in the most rough environments. Testing the wheel clearance today is done by putting modelling clay in the wheelhouse, and then drive through several different obstacles. By doing this, the wheel clearance can be measured where the wheel has left a mark on the modelling clay. The thesis is based on a question if wheel clearance testing can be performed on a test rig, and therefore the issue we decided to work with was what differences in the modelling clay marks could be observed between running the test on the proving ground and simulating the same movement on the test rig. We have made several limitations, the most obvious limit we have chosen is to only focus on the movement in vertical direction.

We used a camera measuring system that was mounted onto our test vehicle. It measures the position from a set origin to the wheel centre in three dimensions over time. We ran tests out on the proving ground, focusing on one obstacle. The test was run for two reasons, to get the imprints from the tire on the clay and to obtain the measurement data from the measuring system. We then identified the maximum reached positive wheel position in vertical direction by using a MATLAB script. We then used the test rig to position the front wheels in the same three-dimensional positions as when the wheel centre reached its maximum vertical value according to the measuring data mentioned above. We measured the imprints of the wheel in the modelling clay after the positioning procedure in the test rig and began to compare the different clay imprints and evaluating the results.

The measurements indicated a significant difference between the two, even though the positioning used in the three dimensions were identical. We discuss the possible reasons for any source of error that we could think of. We also come up with suggestions how to reduce the impact of some of the sources of error.

Sammanfattning

Volvo Cars testbana i Hällered är en plats där bilar testas dygnet runt i de mest extrema förhållandena. Tester av hjulfrigång utförs idag genom att sätta modellera i hjulhusen, för att senare köra igenom olika hinder. Genom dessa körningar kan avtrycken i leran mätas. Denna uppsats grundar sig i frågan om hjulfrigångstesterna kan utföras på en testrigg. Vi valde därför att ställa oss frågan, vilka skillnader i leravtrycken kan observeras mellan att utföra hjulfrigångstest på testbanan och sedan simulera samma rörelse i riggen? Vi har begränsat arbetet i stor grad, den mest påtagliga vi har valt är att enbart fokusera på hjulets vertikala rörelse.

Vi har använt ett kamerabaserat mätsystem som fästes på vårat testfordon. Det mäter positionen mellan ett bestämt origo och hjulcentrums mittpunkt i tre olika dimensioner i realtid. Vi utförde testerna på provbanan, med endast ett hinder på provbanan i fokus. Testerna utfördes av två anledningar, för att däcket ska göra ett avtryck på modelleran och för att erhålla mätfiler från mätsystemet. Vi identifierade den maximala uppnådda position i vertikalled genom att använda ett MATLAB-script. Vi använde sedan testriggen för att positionera de främre hjulen i samma tredimensionella position som när hjulcentrum uppnådde dess maximala vertikala värde enligt de ovannämnda mätfilerna. Vi utförde mätningar på avtrycken i modelleran efter att ha utfört positioneringsproceduren i testriggen och började sedan jämföra resultaten mellan de olika mätningarna.

Mätningarna visade på en märkbar skillnad mellan de två, trots att positioneringen i de tre dimensionerna var identiska. Vi diskuterar vilka anledningar som det skulle kunna bero på och även de mest troliga felkällorna vi kan tänka på. Vi presenterar även förslag på hur det skulle kunna vara möjligt att reducera påverkan av några av felkällorna.

Nomenclature

Pitch	The rig will tilt the centre table around the y-axis. Causing the vehicle to lean forward and backward.
Roll	The rig will tilt the centre table around the x-axis. Causing the vehicle to lean from side to side.
Bounce	The centre table will move vertically. Causing the vehicle to move up and down.
Ride height	Ride height or ground clearance. The specific distance that the chassis is located from z=0. Can be measured in different velocities.
Total Weight	The permitted weight with 5 passengers, luggage and fluids.
Test vehicle	The test vehicle that is reffered to in this thesis is a Volvo S90, T6.
Weigh hall	There is a weigh hall on the proving ground where the vehicle is weighted. It shows the weight distribution for each wheel. Sand bags and lead weights are used to reach the desired total weight.
Lead weight	Rectangular and about 20 mm thick plates made of lead. They weigh 5 kg each and are loaded into the vehicle in steel constructions to simulate the passengers weight.

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Preface

We want to propose a great thank you to our supervisor Peter Augustsson and our manager Per Hesslund at Volvo Cars for providing us with great knowledge and experience during our 10 weeks at Hällered. We would also like to thank our supervisor and examiner at Linköping's University, Victor Fors and Jan Åslund, for assistance with questions regarding the report.

1 Introduction

1.1 Background

Customer inputs are a crucial part early in the prototype stage when developing a new car (Ramanujam & Tacke, 2016). Volvo Cars is not an exception and they work closely with their customer requirements (Volvo Cars, 2017). Alongside with the requirements from the customer goes "The Volvo Way". That is what Volvo call their core values, which are the following; safety, quality and care for the environment (Volvo Cars, 2017). To achieve their core values, the cars are put through several challenges, testing the cars handling and the components of the chassis. (Volvo Cars Corporation, 2010). Volvo Cars Corporation Proving Ground in Hällered is a place for these challenges (Volvo Cars Corporation, 2010). This is where the cars take a beating around the clock on the very rough tracks (Volvo Cars Corporation, 2010). One of the quality measures are to ensure that the wheel of the car does not come in any physical contact with the wheelhouse. This is called wheel clearance testing.

Since the cars today gets sportier and have lower chassis (Jakobsson, 2014), the wheel clearance is important to test. Currently the tests are performed according to a number of test codes, a test code specifies what maneuver, which obstacle and the correct speed to perform a wheel clearance test in. To obtain the wheel clearance, a test vehicle is prepared with green modelling clay that is attached to the plastic panel in the wheel arches.

The modelling clays characteristics can be described as a balance between softness and firmness and it will cause the tire to leave an imprint on the clay when it has any physical contact with the wheel arch. The engineers can then manually measure how big wheel clearance they received from the test. The problem with this method of testing is the Swedish climate. Some of the wheel clearance tests cannot be performed on wet surface, because the tires need full friction. Unfortunately Borås is one of the cities in Sweden with the most amount of rainy days per year (Håkansson, 2017).

Volvo Cars has a kinematic and compliance test rig (K&C rig) in their facilities at Hällered. Today the K&C rig is only used for other purposes than wheel clearance testing. Therefore, there is an interest at the proving ground in Hällered to investigate if it is possible to perform wheel clearance testing indoors on the K&C rig.

1.2 Motivation

The test period for a new car is short and therefore time is of great importance. A car is driven for a year at the proving facility corresponding to the cars lifetime (Volvo Cars Corporation, 2010). If the wheel clearance testing could be performed on the K&C rig, this could spare the test drivers and engineers to loose precious time working with the vehicles. This thesis is performed to create a basis for further investigation in this matter by comparing different wheel clearance test data. It is important since it is difficult to find any research material that is related to simulate wheel movement on any test rig.

1.3 Purpose

For reasons that wheel clearance testing cannot be completed due to bad weather conditions, the purpose of this thesis is to investigate if wheel clearance testing can be done in the kinematic and compliance test rig, this will give the engineers an advantage and a better possibility to ensure desired quality.

1.4 Issue

What difference in the prints on the modelling clay, marked by a vertical wheel movement can be observed between a test performed on a K&C rig compared to a test performed on Volvo's proving ground? What could be the possible reasons for any eventual difference between the two types of testing?

1.5 Limitations

During a measurement out on the track, the movement of the wheel centre is measured in six degrees of freedom. This thesis has been limited to focus on the wheels vertical movement. The thesis will also be limited to:

- Static state only, when operating in a test rig.
- Focus only on the most critical *position* in vertical wheel movement.
- Investigating the results of the *front* wheels only.
- Only performing a test code for one obstacle in 90 km/h.

2 Theory

2.1 Hällered Proving Ground

Volvo Cars run most of their testing on vehicles at the proving ground facility in Hällered, 15 km from Borås. Everything from concept cars, to cars that are already in production are being tested here (Volvo Cars Corporation, 2010). For this thesis, considering the proving ground, focus will only be on the part of the test track that is used for the wheel clearance testing.

The obstacle that the test vehicle will be tested at, is known as ”Fyra bulor och en svacka” at Hällered and is a part of a test routine that Volvo Cars test engineers follows during wheel clearance testing. The English translation for the obstacle is "Series of depressions and elevation". This obstacle is one of the most demanding for wheel clearance testing in vertical direction. It is located on the comfort track at Hällered, see *Appendix 1* for more information.

2.2 Air suspension

The test vehicle is equipped with Volvo’s rear air suspension. The advantage of an air suspension is that you experience a better comfort and driving performance even if the car is heavy loaded (Volvo Cars, 2017). The air suspension is constantly regulating itself according to speed, road surface and the driver’s behaviour. When the vehicle reaches higher speeds, the air suspension will regulate the ride height to a lower level to reduce wind resistance and to increase the stability. (Volvo Cars, 2017)

2.3 The K&C rig

Anthony Best Dynamics Limited hands this machine. The K&C rig can measure both kinematics due to suspension and steering geometries, but also do compliance measurements on anti-roll bars, different bushings and springs. (Anthony Best Dynamics Limited, 2013)

The K&C test rig controls the test vehicle´s movement through a hydraulic platform that is clamped to the chassis of the vehicle, this platform will be referred to as centre table from now on. The centre table can move in three degrees of freedom by using movement patterns such as *pitch*, *roll* and *bounce*. The pitch movement is when the vehicle is leaning forwards or backwards, roll is when the vehicle is leaning to the right or to the left, and bounce is when the vehicle is moving vertically up or down. The limitations of the centre table are that it cannot handle inputs to perform a vertical movement for the wheels separately. Another limitation in the K&C rig is that it cannot rotate the wheels to simulate the vehicle moving forwards or backwards.

The test rig can steer the wheels separately in x- and y-direction through four XY tables where the four wheels of the vehicle stands on. The XY tables are discs equipped with friction tape to simulate the friction that is normally caused by asphalt. In *figure 2.4.1* the K&C rig, centre table and the XY tables can be studied.

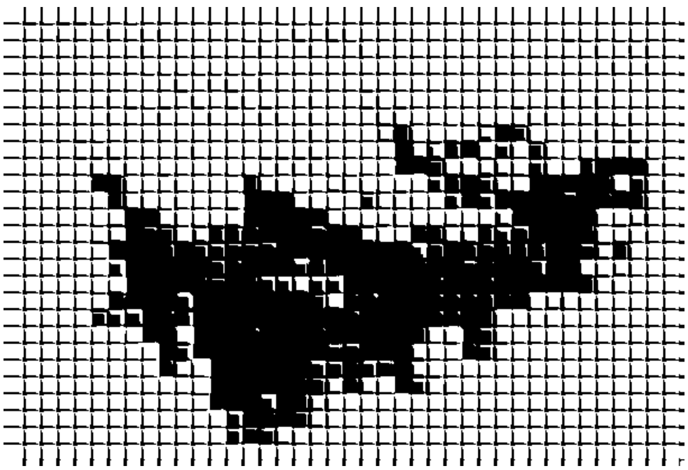

Figure 2.4.1. The figure shows the K&C-rig. The "Wheel Stations" are the XY-tables and the "Roll Pitch Bounce Mechanism" is the centre table. (Anthony Best Dynamics Limited, 2008).

The K&C rig can operate in both static and dynamic mode. In this thesis, the test will only be performed in static mode. This mode will move the centre table and the XY tables to a specific position that has been set and then back again. It will only concern positioning and not time. It is possible to set the test rig to operate with a displacement- or a force control to prevent damage on the vehicle and the rig. (Anthony Best Dynamics Limited, 2013)

Regardless the rig runs a static or dynamic test, the measurements always starts and stops at the K&C rig´s origin for the XY tables respectively the centre table. A typical test cycle time is 60 seconds, but can differ from 10 to 240 seconds depending on which test you run. Typically, a test is performed with 2 cycles per test. The first cycle is to stabilize the vehicle´s characteristics regarding steering and suspension, and the second cycle is generating the results. (Anthony Best Dynamics Limited, 2013)

A software controls the K&C rig. The software has different templates that has been adjusted by Anthony Best Dynamics to meet Volvo Cars demands. None of this templates are today used for wheel clearance testing. It is possible to create own templates with text-files to the software (Anthony Best Dynamics Limited, 2013), this could be an opportunity to implement a new kind of test method.

The following limitations of the test rig when it comes to force and displacement are preset. The peak displacement of the bounce movement is ± 150 mm and the maximum velocity is 140 mm/s. The vertical peak load for each wheel is 40 kN. (Anthony Best Dynamics Limited, 2008)

2.4 Coordinate systems

In this report, the interpretation of coordinate systems will play a great role. Several coordinate systems, with different origins will be dealt with. To fully understand the report, the coordinate systems will be defined under the theory chapter.

2.4.1 Volvo's Coordinate system

Every Volvo car that is designed has a standardized origin defined by Volvo Cars. It is difficult to define exactly where the origin is placed in proportion to the car, since this will differ depending on the car model. To get an idea of the origin of the test vehicle, see *figure 2.4.1.1*. Measurements to the right of origin in y-direction will have a positive value and to the left of the origin, the value will be negative.

The coordinate system is fixed on the chassis, when measuring the movement of the wheel centre with AICON WheelWatch, which will be part of the method for this thesis.

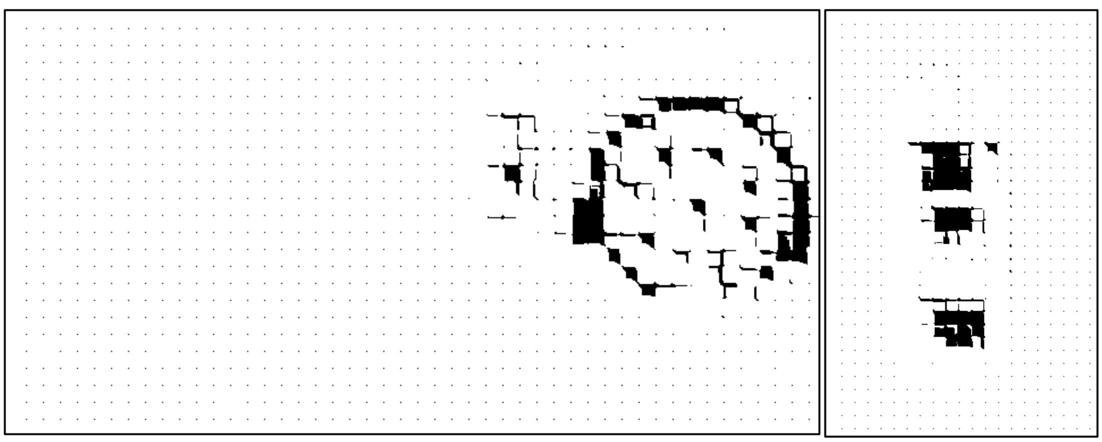

Figure 2.4.1.1. An approximation of the origin of Volvo's coordinate system.

2.4.2 The K&C rig´s coordinate system

The K&C rig includes two type of coordinate systems, these two are illustrated in *figure 2.4.2.1*. The amount in total, for the K&C rig can be described to have five separate coordinate systems. One for the centre table and one for each XY table. Both coordinate systems have its origin in the middle of the movable components. X-direction is facing the car´s headlight direction and y-direction is the opposite of what Volvo Cars is using. The values to the left of the origin in y-direction is positive, and the values to the right are negative.

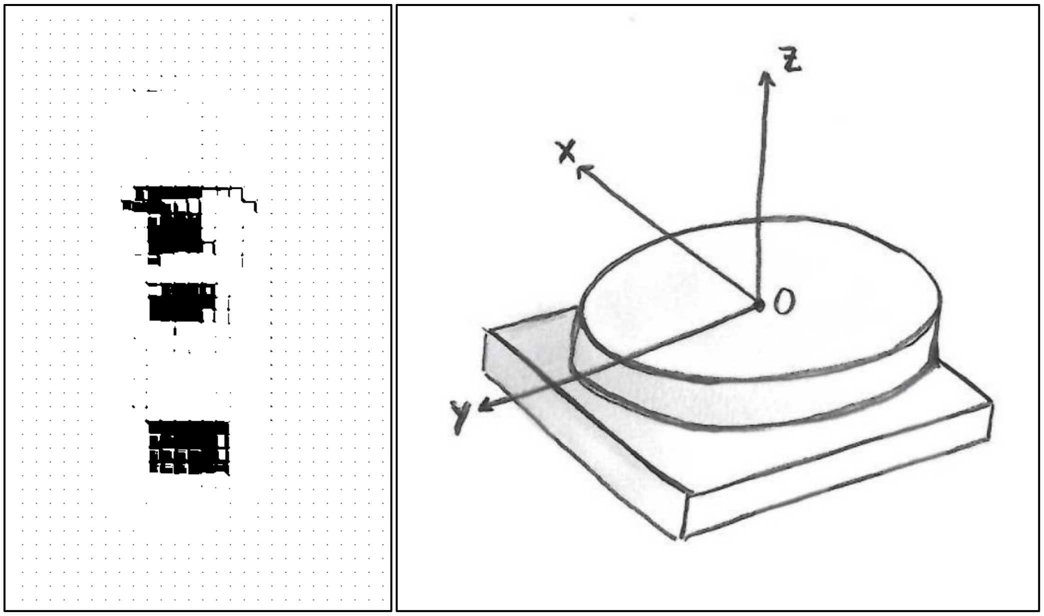

Figure 2.4.2.1. The figure illustrates the coordinate system that is paired with the centre table to the left and the XY tables coordinate system to the right.

2.5 AICON WheelWatch

AICON WheelWatch is a system that measure wheel- or engine movements in real time. The system consists of four cameras with short shutter speed, reference targets, wheel adapters, carbon fibre tubes and aluminium profiles that are used to mount the cameras. Each camera is pointed to a special made carbon fibre adapter that is mounted to each wheel. These adapters are calibrated to the vehicle´s coordinate system together with the reference targets on the fender. The measurements always refers the movement between the reference targets on the fender versus the wheel adapters. (AICON 3D Systems, 2017)

Figure 2.5.1. The picture shows the AICON WheelWatch system most important components. Number 1. is the high performance camera that is pointed to each wheel, number 2. is the wheel adapter and number 3. is the reference targets on the fender.

The system is controlled by two softwares. *TraceCam F* is used during testing, and *AICON 3D Studio* is used during calibration of the cameras. The test results from TraceCam F are received in a text file with time, positions and orientations in all three dimensions with an accuracy of ± 0,1 mm in up to 490 Hz. (AICON 3D Systems, 2017)

3 Method

3.1 Preparing the test vehicle for wheel clearance test

The testing includes preparation, in this chapter the steps are explained.

3.1.1 Loading the vehicle

The vehicle is taken to a weight hall on the proving ground, here the vehicle is weighted, showing the weight distribution for each wheel. Further the vehicle is loaded with a steel construction containing several 5 kg lead weights both in the passenger seat and the back seats. The purpose is to put in a weight of 70 kg in all passenger seats to reach the total weight of the test vehicle. The total weight corresponds to five passengers, luggage and fluids. The total weight of the test vehicle is 2400 kg (Volvo Cars, 2017). The weight needs to be distributed evenly on the left- and right side of the vehicle as well as front- and rear axle. The trunk is loaded with sand bags that weigh 10 kg each to reach the total weight of the vehicle. The sand bags are also an aid to get an even weight distribution in the vehicle. The weight distribution for the loaded test vehicle can be seen in *Appendix 2*.

3.1.2 Preparing the wheelhouse for wheel clearance test

Volvo use modelling clay that is fixed to the wheel house, both in the front and rear of the vehicle. The clay procedure is very straight on. The green clay is applied to about ten different spots throughout the wheelhouse. The modelling clay is formed to pyramidal walls that are about 30 mm thick. In *figure 3.1.2.1* a demonstration of the clay is shown.

Figure 3.1.2.1. Prepared wheelhouse with modelling clay.

When the test is executed on the track, the tire will leave a print and deform the modelling clay where the wheel clearance is critical. After the test, the deformation is measured and analysed.

The spots where the tire has left a deformation in the modelling clay are documented with small number tags. These number tags are photographed and measured with a vernier caliper where the modelling clay has been the most deformed. The number tags are placed from left to right in the wheelhouse. The front left wheel will be marked with 10-19, and the front right wheel will be marked with 20-29. If the rear wheels were to be marked, 30-39 would be the left side and 40-49 on the right side.

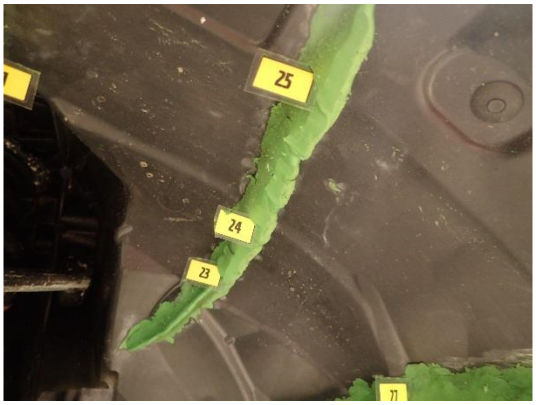

Figure 3.1.2.2. The number tags that points out where the clay has been deformed.

3.1.3 Tire pressure

When the vehicle is heavy loaded, the tire pressure needs to be increased. This is a common measure when a vehicle is heavy loaded, to get a longer life span of the tires and decrease the fuel consumption (Gröna bilister, 2017). The test code often specifies the vehicle to be loaded to its total weight, therefore the tire pressure must be increased to 2.6 Bar of air pressure according to the owner's manual (Volvo Cars, 2017).

3.2 Method for AICON WheelWatch

3.2.1 Calibration of the AICON WheelWatch

The purpose with this method is to create a 3D coordinate system of the vehicle that the AICON WheelWatch cameras can refer to. When calibrating, origin is set to match Volvo Cars own standard coordinate system. This will allow the output data to be compared with any other wheel clearance test result made by Volvo Cars.

The coordinate system is set up by using calibration equipment provided by AICON WheelWatch, combined with the cameras. The calibration equipment consists of the following. A large number of stickers, each with a unique pattern of reflecting dots. These are called ANCO reference targets, and are illustrated in *figure 3.2.1* on the next page.

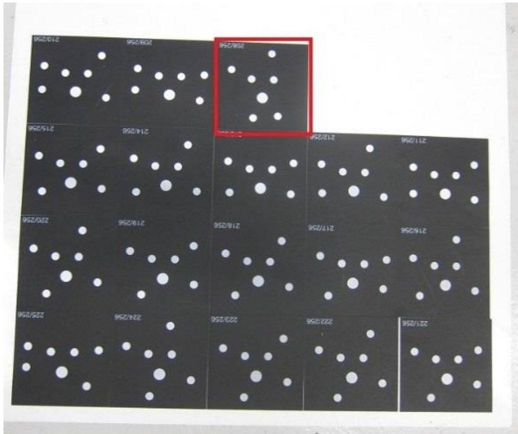

Figure 3.2.1. A sheet of ANCO reference target stickers.

Seven ANCO reference targets are attached to each fender of the vehicle, as seen in *figure 3.2.2*, in total 28 references. The references will be used by the AICON WheelWatch cameras during a measurement out on the track.

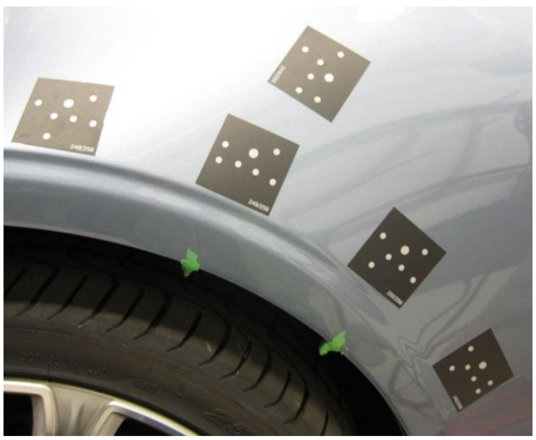

Figure 3.2.2. An example of how five out of the seven ANCO reference targets are attached on a fender.

Next is the 14-digit targets, as seen in *figure 3.2.3*. A large number of these are to be placed on the vehicle with a distance of about 30-40 cm between each. About 100-150 14-digit targets in total will cover the vehicle. (Augustsson, 2017)

Figure 3.2.3. A 14-digit target tile, each tile is unique.

Two scale bars and an "*X/Y-cross*" are placed on the vehicle. The "*X/Y-cross*" is placed on either of the vehicles side, somewhere between the front wheel and the rear wheel. It serves as the origin for the coordinate system that is being set up, the cross itself however does not require any specific positioning. (Augustsson, 2017)

Figure 3.2.4. The "X/Y-cross" sets the origin of the coordinate system.

Figure 3.2.5. One scale bar is placed on the hood of the vehicle and the other scale bar on the opposite side of the "X/Y-cross". (Augustsson, 2017)

To start the calibration, a wheel adapter is mounted on each wheel. To do this, three wheel bolts on each wheel will be substituted with special manufactured wheel bolts. A metal disc is attached onto the new bolts so that the wheel adapters can be mounted onto the wheels.

Figure 3.2.6. In step 1. three original bolts are replaced. In step 2. the metal disc is tightened. In step 3. the wheel adapters is mounted.

Before the calibration can begin, help reference targets must be attached to the vehicle. Each help reference target has its own coordinate in the room that refers to Volvo Cars own coordinate system, with an accuracy of one micrometer (Augustsson, 2017). Eight help reference targets are placed on each side of the vehicle, left and right. The method of the setup for these help reference targets will not be dealt with in this report.

Figure 3.2.7: Two help reference target can be seen in this figure. They consist of a reflecting dot with a black circle around it.

At this point, the calibration starts. Photos are taken with a camera using flash. The camera is set up with a high ISO-value, a short exposure time and in grayscale. This setup will keep the reflecting dots in focus. The software, AICON 3D Studio, uses the reflecting dots to setup the AICON system to match with Volvo´s coordinate system. The software is provided by AICON 3D systems. Preferably the first photo is taken on the "*X/Y-cross*", after that, several photos are taken in different angles and views, all around the vehicle. The photos are imported into AICON 3D Studio and by using the unique ANCO-targets and the 14-digit targets, AICON 3D Studio is able to identify position of each target in its three dimensions.

If a quantity of photos are of good quality, AICON 3D Studio creates a 3D view of the targets, as seen in *figure* 3.2.8.

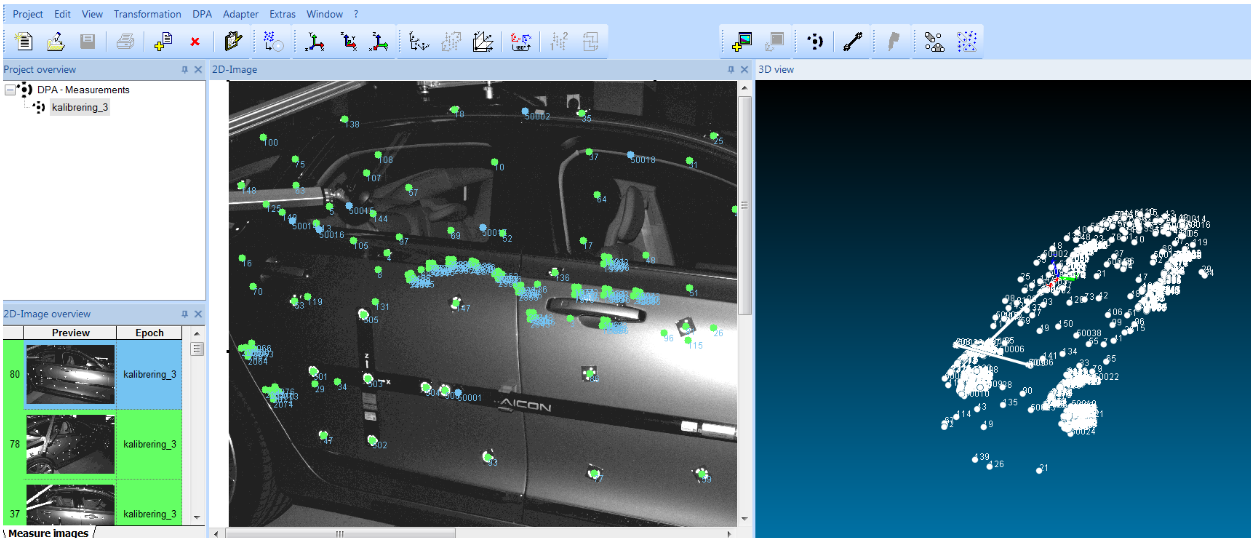

Figure 3.2.8. To the left, it is seen how the targets has been recognized in AICON 3D Studio. To the right is the 3D view of the vehicle that consists of the different reference targets.

The 3D view has its origin in the "*X/Y-cross*" which is its only reference data. To change this, the user must create new reference data. The new data should be the coordinates of the help reference targets. By using the utility "Best fit transformation" in AICON 3D Studio, the coordinate system with origin in the "*X/Y-cross*" is transformed into the coordinate system of the help reference targets, that is, Volvo Cars own coordinate system.

3.2.2 Rig the AICON WheelWatch to the test vehicle

To secure the AICON WheelWatch cameras onto the vehicle, aluminium profiles and carbon fibre tubes are used. The tubes are attached to the bonnet and the roof of the vehicle using suction cups. The AICON WheelWatch cameras are then attached onto the aluminium and carbon fibre construction to be about 50 cm above and 50 cm out from the wheel centre (Augustsson, 2017). This is illustrated in *figure* 3.2.1.1.

Figure 3.2.2.1. The AICON WheelWatch fully mounted to the test vehicle.

3.2.3 On the test track

The vehicle was taken to the test track to see how much the velocity affected the ride height and to see how much the air suspension is regulating. Measurements were performed at the brake and handling track at 0-, 30-, 50-, 70-, and 90 km/h on a flat surface. The test runs were short and the wheel centre displacement was captured in 200 Hz, these measurements were then exported to Excel where the mean value of the ride height in different speeds were calculated.

After the measurements from the brake and handling track were evaluated in Excel, it was time for the first run at the depressions. The test run follows a specific test code that is involved in Volvo Cars wheel clearance testing routines, which will be the basis for the method.

The wheel clearance obstacle has a very short acceleration distance before the first depression, it therefore demands a hard acceleration in the beginning and a challenge to keep the vehicle as close to 90 km/h as possible through the depressions. One go is all you need to collect data to evaluate and to analyse the print marks on the modelling clay in the wheelhouse.

3.2.4 Analysing the measurements

The results of the test using AICON WheelWatch were collected as text-files from the computer that has been used in the vehicle during the test. Each camera produce its own text file with a result consisting of seven columns with time (t) furthest to the left and then the three axis, followed by rotation of these axis. A MATLAB script, seen in *Appendix 8*, is used to illustrate the vertical movement for the left wheel center in a graph, plotted over time. It also gives the maximum z-value as an output variable when running the script. The script can also be used to do subplots and show two plots of two different runs or different wheels.

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0.027004;	1617.100;	-846.526;	481.594;	0.1086;	22.0239;	1.8884

Figure 3.2.4.1. Example of a text file from an AICON WheelWatch result. The results concern the front left wheel.

3.3 From AICON WheelWatch to the K&C rig

3.3.1 Parameters needed to simulate in the K&C rig

The reason to simulate the test run in a K&C rig is to be able to make a comparison of the print marks on the modelling clay in the wheelhouse. The K&C rig will be operated in a static mode, the only position needed is the absolute maximum z-position that has been captured by AICON WheelWatch.

When the vehicle is driven through the depressions, the wheels and suspension suffers a heavy vertical load, this causes the two front wheels to slightly move away from each other, one wheel in positive, while the other in negative y-direction. It will cause a very small impact on the wheels in negative x-direction. This is taken into consideration in attempt to get an as authentic simulation as possible. The maximum vertical position is obtained for either the left or right wheel centre using MATLAB. This maximum value will be used as an input for the K&C rig. At the same moment as the vertical movement reaches its peak, the x, and y-positions for both left and right wheel centre are needed for the K&C rig to perform a realistic wheel position.

If the two front wheels, for any reason, differs in maximum vertical position. The test has to be run in the K&C rig two times. This is necessary because of the rig´s limitations with controlling the wheels individually in vertical direction.

3.3.2 Creating a program for the K&C rig

The text files from the measurements done with AICON WheelWatch does not instantly work as input files for the K&C rig. First, an offset has to be done so that the two different coordinate systems can relate to each other.

The text file is created with small linear steps up to the maximum value. The steps are made to avoid rapid movements between two values, without these steps it may cause the centre table moving too fast. Rapidly compressing the stiff springs, demand a large force and could cause the force limit control to be activated. This will stop the procedure until it is moving back to its starting position (Anthony Best Dynamics Limited, 2013). To create smooth steps, Excel was used.

The maximum vertical displacement value of the wheel centre is subtracted with the result of the mean ride height at 90 km/h, this will give the absolute vertical displacement of the wheel centre. This is needed because the centre table in the K&C rig will start from a zero position.

A test always starts and stops at the K&C rig´s mid position (Anthony Best Dynamics Limited, 2013). This means that the input files cannot start nor stop with any other value than zero. Every step in the program will increase 1/30 of the maximum value until it is reached. The value will then decrease, following the same scale. The text file made for this experiment will consist of 61 values, excluding the zeros in the beginning and the end of the program.

3.3.3 Preparing the test vehicle

If the modelling clay is not heavily deformed or scraped of the wheelhouse due to the wheels rotation, the clay used when driving on the comfort track can be heated up and moulded back to a pyramidal shape. The clay will serve the same purpose now as in the wheel clearance obstacles on the comfort track, to evaluate the wheel clearance. The test vehicle was clamped onto the test rig. The vehicle needs some special preparation before the rig can start to operate. The rig technicians were in charge of this specific unmentioned preparation. The extra weight was removed from the test vehicle before loading it onto the rig. The K&C rig will be able to simulate the total weight of the test vehicle by lowering the centre table.

3.3.4 Simulate with K&C rig

To recreate the movement that was performed at the test track, the K&C rig for starters need information about the ride height. This can be set by using two different methods. Either by measuring the distance between the wheel centre and the fender when fully loaded, then measuring the same distance when the test vehicle is unloaded. The difference between the two measurements is the distance the vehicle has to be lowered in order to simulate the ride height. The other method is to lower the centre table, until desired force is applied on each wheel. To get the correct weight distribution, the table is tilted around its x-, and y-axis. In the rig, these movements are called, roll respective pitch. The method used to set the ride height was by dragging the vehicle down, applying a desired force.

The force that each wheel causes when the vehicle is at rest when fully loaded can be calculated using equation (1).

$$F = ma \qquad (1)$$

F is the force applied by the wheel. m is the mass distributed on a wheel and a is the acceleration of the wheel.

(MERIAM & Kraige, 2012)

When the vehicle is in a static mode the acceleration a is equal to the gravity g, and the force F is equal to the normal force N, hence equation (1) can be rewritten to equation (2).

$$N = mg \qquad (2)$$

The calculation for the correct force to be applied on the front left wheel is:

$$N = 596{,}5 * 9{,}81 = 5851{,}665\ N$$

The calculation for the correct force to be applied on the front right wheel is:

$$N = 587{,}0 * 9{,}81 = 5758{,}47\ N$$

The mass distribution for each wheel, m is found in *Appendix* 2.

When the vertical force has been applied on the front axis, to simulate the ride height, in total five input files were needed for the next step. These input files were created as described in 3.2.3. *Analysing the measurements.*

To reach the maximum vertical wheel centre position, the test rig will be using the commando D+ for Bounce to simulate the vehicle moving in z-direction. This is where the first input file goes. As seen in *figure* 3.3.4.1 below, the remaining four input files are loaded into the commando D+ for X and Y, left- respectively right wheel. The programs used can be seen as a summary in an Excel document in *Appendix* 3, notice that the programs inserted into the test rig software are text files.

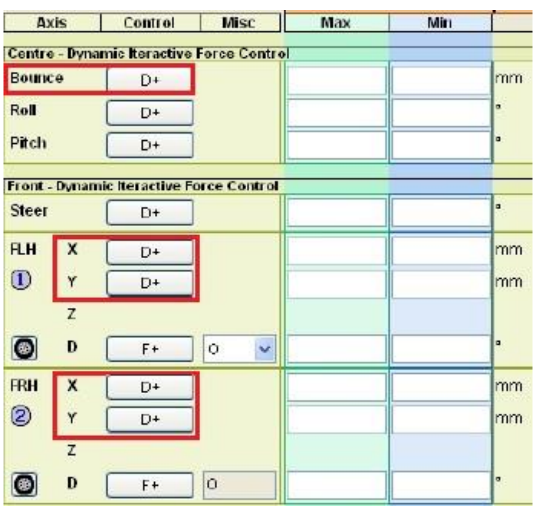

Figure 3.3.4.1. A sample from the K&C rig software.

The software will show a preview of the movement for the different axis using a graph. The x-axis displays the time and the y-axis displays the movement in the graph. The maximum value will be shown in the "*Max*" column, it is the fourth column from the left.

NOTE! The air suspension *had* to be set to service mode when operating the test vehicle on the K&C rig. Not doing this could have caused damage on the vehicle.

Before the test starts, the rig will perform a few automatic move actions, these action are mentioned as *'loading a vehicle'* and *'lift cycle'* in the SPMM User Guide (Anthony Best Dynamics Limited, 2013). These steps are semi-automatic and performed by the rig technicians. The method for the automatic move actions are not necessary to mention in this thesis.

The rig technician will follow the instructions and then start the test that has been created in advance. The centre table and XY tables will move according to the test procedure. The results will be presented as graphs in the K&C rig´s software and as imprints in the modelling clay.

Now it is important to have in mind how the measurements have been done and if the chassis moves closer to the wheel centre or vice versa. In the K&C rig, the chassis moves closer to the wheel centre. What has to be taken into consideration though, is that the wheel centre is also moving closer to z=0 (the XY table). To calculate the result regarding how much the wheel centre has approached the fender, the displacement for the centre table in z-direction is subtracted with the wheel centre displacement. This can be seen in *Appendix 5* and *Appendix 7*.

The wheel centre displacement is then set as an offset for the program made for the centre table in z-direction and the test is run again. The wheel centre will move more this time, and another offset is obtained. Repeat with the new offset until the error is negligible, this means when the wheel centre moves very little relative to the previous test with an offset. When the results are obtained, the automatic move *'unload a vehicle'* is performed.

3.4 Understanding the results

The results are presented as the position of the wheel centre in z-direction. A friendly reminder is that this result is presented in Volvo Cars coordinate system. When measuring with AICON WheelWatch, the chassis will always have the same distance to the origin in z-direction, this is because the origin is fixed on the chassis.

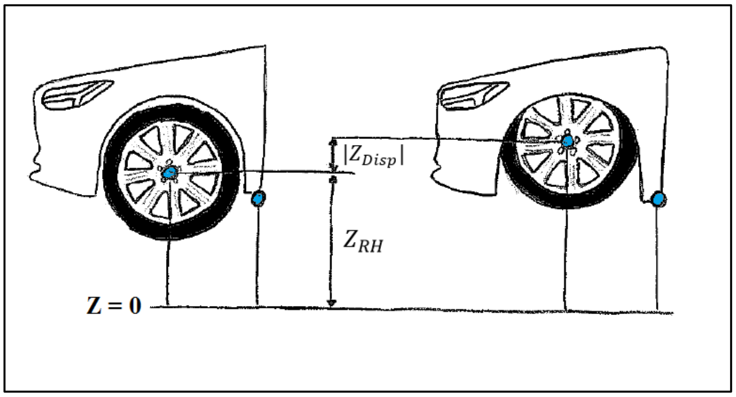

Figure 4.1.1. Position of the wheel in z-direction. $|Z_{Disp}|$ is the wheel centre´s absolute displacement, and Z_{RH} is the ride height.

Using the *figure 4.1.1* above, it is easier to understand the results. The displacement shown in the result is obtained by measuring the vertical displacement $|Z_{Disp}|$, that is to say, how much the chassis have moved in relation to the wheel centre. Add this with the ride height Z_{RH} and that is how the results can be interpreted.

4 Result

4.1 Results for the ride height in different speeds

Table 1 below show the test result for the front axis of the vertical position driving in a steady speed.

Table 1. A summary of the vertical position when driving on a flat surface.

SUMMARY DRIVING IN 30, 50, 70, 90 KPH ON FLAT SURFACE		
SPEED	***FRONT [mm]***	***REAR [mm]***
0KPH	484.657	516.523
30KPH	484.292	468.934
50KPH	482.8	468.9
70KPH	482.44	469.121
90KPH	483.437	469.15

4.2 Results for the first and second test run

With the AICON WheelWatch still ready for use and the wheelhouse prepared for wheel clearance testing, the test vehicle was taken to the comfort track. Due to the driver´s lack of experience running these kinds of test, the test was not executed at 90 km/h all the way through. The test vehicle was still accelerating when entering the series of depressions and kept accelerating to about 95 km/h. Halfway through the depressions, the driver let the foot off the gas pedal, which caused the test vehicle to loose speed at the end of the obstacle.

It was not possible to determine the wheel clearance from this test. There were no prints from the wheel touching the clay in the wheelhouse. Looking at a graph for the positioning of the left front wheel centre that has been created using MATLAB. It is seen that the maximum impact of the wheel in vertical direction increases for each depression.

More modelling clay was added to the wheelhouse and the test vehicle was once again taken to the comfort track for a second test run. This time the test run was able to be executed at a more established speed of 90 km/h. The results can be seen in the *figure 4.3.1* below as a comparison of the first and second run.

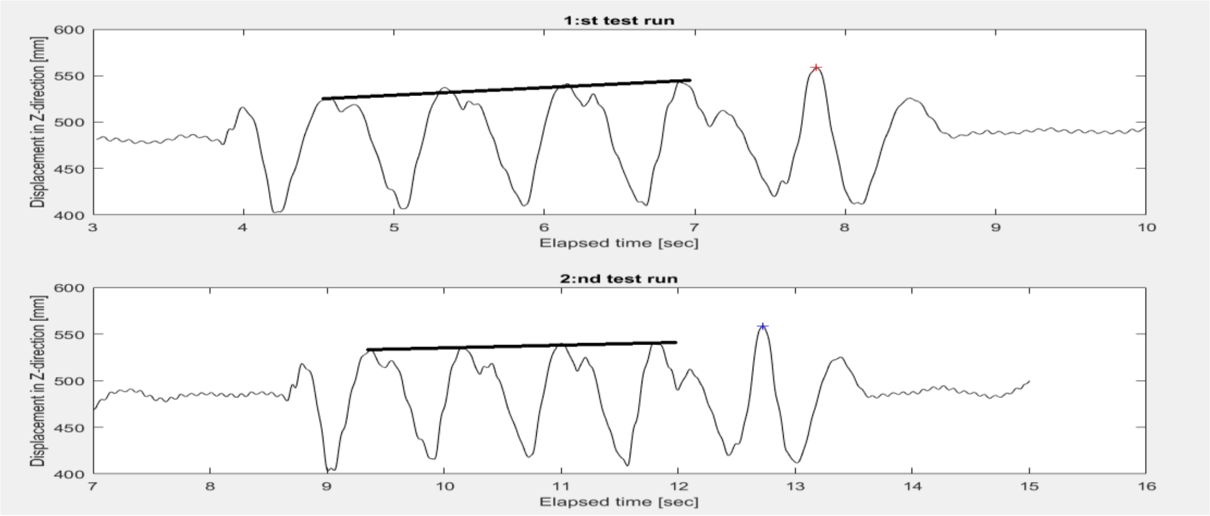

Figure 4.3.1. A subplot illustrating the positioning of the wheel centre in z-direction of the first and second test run. Linear graphs are illustrated to show the importance of a consistent speed.

Table 2: The table illustrates the max z-position for the two test runs. It can also be explained as the ride height and adding the wheels vertical movement.

Test run	Z-position [mm]
1:st test run	558,608
2:nd test run	559,173

4.3 Result for the K&C rig

The goal was to get the distance between the wheel centre and the fender to be the same distance that was measured when driving on the track. The distance to set the vertical bounce movement for the front left wheel is calculated below.

$$Maximum\ vertical\ displacement = 559{,}173\ mm$$

$$Steady\ state\ vertical\ position\ at\ 90KPH = 483{,}437\ mm$$

$$Maximum\ vertical\ position - steady\ state = 559{,}173 - 483{,}437 = 75{,}736\ mm$$

The bounce movement is set to 75,736 mm. This correspond to the maximum displacement for the left front wheel that was obtained with the AICON WheelWatch measurement.

The results for the positions measured by the K&C rig can be seen in *Appendix 4-7*. In the second column of *Table 3* below, it is presented how much the chassis has moved in vertical direction. The second and third column, presents the vertical displacements for the left and right front wheel centre in proportion to the chassis. The fourth and last column presents the displacement of the left wheel centre in proportion to the origin in vertical direction of the rig. The table has one row for each of the three runs that had to be done, correcting the offset value two times to reach the final result.

Table 3: A summary of all the results. RW stands for Right Wheel, LW stands for Left Wheel. The results are presented in Appendix 4-7.

Vertical wheel movement, front wheels [mm]				
	Bounce (with offset)	*LW (chassis to wheel centre)*	*RW (chassis to wheel centre)*	*LW centre movement*
First run	75,736+0=75,736	64,245	64,801	10,89
First correction	75,736+10,89=86,626	71,227	72,128	14,226
Second correctio	75,736+14,226=89,962	73,212	74,22	15,24

4.4 Results for clay deformation on the comfort track

These test results are measured after the second test run. The wheel clearance is measured from the plastic panel in the wheelhouse to where the modelling clay has been the most deformed. The number tags indicates where the measurement has been done.

Figure 4.5.1. The picture to the left is clay deformation on the front left wheel; the right picture displays the clay deformation on the right wheel of the vehicle.

Table 4. Summary of the measurements of clay deformation.

Front left			**Front right**	
Number tag	*Wheel clearance [mm]*		*Number tag*	*Wheel clearance [mm]*
10	17		20	23
11	13,1		21	21,91
12	13,5		22	22,5
13	23		23	21,1
			24	22,4
			25	19,4
			26	19,84
			27	20,71

4.5 Results for clay deformation in the K&C rig

The result is based on the same thickness and length of the modelling clay as in the test on the test track. The same maximum vertical position that is reached on the test track, is used in the K&C rig. These are the imprints that are comparable with the test track measurement. The results can be seen in *figure 4.6.1* and *Table 5*.

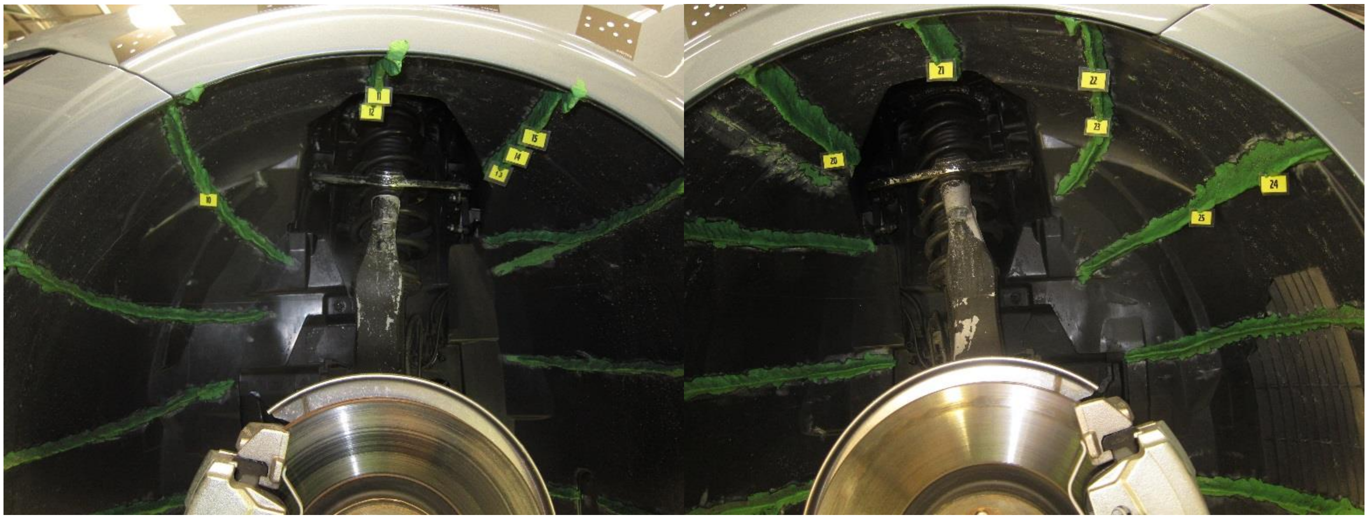

Figure 4.6.1. The picture to the left is clay deformation on front left wheel; the right picture displays the clay deformation on the right wheel of the vehicle.

Table 5. Summary of the measurements of clay deformation.

Front left			**Front right**	
Number tags	*Wheel clearance [mm]*		*Number tags*	*Wheel clearance [mm]*
10	26,80		20	31,56
11	25,88		21	35,65
12	26,71		22	27,63
13	26,44		23	32,81
14	27,56		24	24,25
15	27,06		25	24,75

4.6 Comparing the results of clay deformation

Table 6, and *Table 7* below, displays the comparison between the clay imprints from the K&C rig versus the test track. The right column shows how much the clay deformation differ between the two test methods, measured in millimeter. The number tags that are displayed in *Table 6* and *Table 7* correspond to the imprints at approximately the same spots, both on the test from the comfort track as well as the K&C rig.

Table 6. Front left wheelhouse clay deformation comparison.

Front left	
Number tags [K&C-rig vs test track]	*Wheel clearance difference [mm]*
11 vs 10	*9,80*
12 vs 12	*12,78*
15 vs 13	*3,71*

Table 7. Front right wheelhouse clay deformation comparison.

Front right	
Number tags [K&C-rig vs test track]	*Wheel clerance difference [mm]*
20 vs 20	*8,56*
21 vs 21	*13,74*
23 vs 24	*10,41*
24 vs 26	*4,41*

5 Discussion

5.1 Deformation on the modelling clay in the wheelhouse

We see that the prints on the modelling clay caused by the tire, differs between the K&C rig and test track. Looking at the comparison between the prints on the modelling clay that can be seen in *Table 6* and *Table 7*, we can see that it differs as much as 13,74 mm. This is a lot for this matter, having in mind that the wheel clearance is sometimes less than 13,74 mm. The different possible sources of error that will be discussed are many, one of them is how the clay deformation is affected by the vehicle dynamics. Since we are comparing one measurement that was ran on the track (dynamic mode), and comparing it to a test executed in on the test rig (static mode). We will also discuss the possible effects of the tire deformation, the wheel rotation and the ride height. We will also mention how the driver´s performance might had an impact on the results and inconvenience caused by using a vehicle equipped with air suspension.

5.2 Sources of error

5.2.1 Ride height

The first thing we will discuss is about the first result we got, where we measured the ground clearance, or ride height. We did this because we supposed that the aerodynamics when driving the test vehicle at 90 km/h would have an impact on the ground clearance. Looking at the results in *figure 4.2.1* we can see that the air resistance causes the vehicle to lift - increasing the ground clearance. It increases until the vehicle reaches a speed of 70 km/h, and at 90 km/h the test vehicle´s chassis starts to lower.

We believe that it has to do with the air suspension, as mentioned earlier, it adjusts the ride height, lowering the vehicle at higher speeds to improve aerodynamics. It does however only adjust the rear suspension, but we believe this is the cause of the result. The test was only ran once, and therefore it is difficult to draw any conclusion. If the vehicle would not has been equipped with air suspension, we believe that the ride height would follow a more linear curve, plotted against the velocity, or maybe even show some indication of an exponential curve. We did however see a difference in ride height of about one millimeter between standing still with the test vehicle and driving at 90 km/h. Without the air suspension the ride height may have differed three or four millimeters between 90 km/h and standing still. We do not know how much. This should be investigated further because we think it is important to use the correct ride height for 90 km/h in the K&C. Not taking this into account when simulating in the K&C can be crucial for the wheel clearance testing and cause quality issues.

5.2.2 Human reliability

We did perform two tests following the same test code on the comfort track. We believed, following the same test code twice would most likely give two identical results. The test vehicle is often driven by humans and not robots, and therefore one driving sequence will never be identical to the other.

In *figure 4.3.1* the result of the two test runs can be seen. If we look at the linear curve going through the peaks in z-direction for each bump, we see that the curve illustrated in the second run is not as inclined as for the one for the first run. We choose therefore to use the results for the second run since they are a more accurate measurement according to Volvo Cars test code. A small change in velocity can cause large deviations in the vertical displacement peaks of the wheel centre. To get more authentic data from the series of depression and elevation for the K&C rig, the test should be run a large number of times, collecting a mean value for the vertical peaks. Doing this will make the results more relevant for further work and thereby decrease the sources of error.

5.2.3 Tire deformation

One of the biggest issues we encountered when using the K&C rig to simulate the most critical point for wheel clearance was the tire deformation caused by the great forces applied by the K&C rig when operating with the chassis vertical displacement. We did see that the wheel centre had moved towards the XY table in vertical direction. If we subtracted the ride height to the critical z-point, we got the absolute displacement. This was the maximum vertical value that our program for K&C rig would reach. However, the vertical displacement that we used as input for the bounce movement tells the K&C rig how much the chassis should move. The K&C rig lowered the chassis the same distance that the wheel centre moved up, according to AICON WheelWatch. The result was presented as the distance the wheel centre had moved from the chassis. We could see that it differed considerably from the input in how much the chassis moved. The distance that the wheel centre had moved was also measured, in the first simulation on the K&C rig it was 10,89 mm as seen in *Table 3* and *Appendix 5*. This distance was discovered as the tire deformation caused, we therefore added the wheel centre displacement as an offset, and then ran the test again. The tire is also deformed when running the obstacle on the track, unfortunately, the AICON WheelWatch does not measure this.

Adding the extra 10,89 mm to the bounce movement command caused the spring to compress more. This in turn applied a greater pressure on the tires, and due to the greater pressure the tire deformed even more. The second run it deformed 14,226 mm, seen in *Table 3*. Another offset was added, about 3,3 mm which corresponded to the difference in wheel centre movement between the second and third run. Now we got close to the value we wanted. But not quite, another adjustment of the offset could had been done.

We were satisfied enough with our result, and we think that for every time an offset is added to correct the displacement due to tire deformation, it will cause an even greater pressure, that will deform the tire even more. This means that the error will never disappear, but only be corrected closer to zero. The more we correct the error, the more force will be applied to the test vehicle; we believe the rig might reach its maximum force control limits if we keep correcting the error too much.

5.2.4 Wheel rotation

When we study the imprints of the modelling clay, we can see the clay deformation caused when driving on the test track pushes the clay in the rotation of the wheel. While studying the K&C rig´s imprint it only leaves a tire mark. We believe it is obvious that the wheel rotation has something to do with it. Looking closely at *figure 4.5.1* we can divine that it is the force of the rotating wheel that have pushed and deformed the clay. The pyramidal walls made from the modelling clay are long and thin and cannot withstand the forces of the rotating wheel. This kind of clay deformation cannot be seen in the K&C rig due to its limitations.

This is something that we need to accept when comparing the clay deformation. Important to mention is that the wheel rotation will differ from car to car. The tires are not perfectly symmetric and the same goes with the rims. The wheel characteristics will thereby be different for every vehicle that is tested, and thereby the imprint on the clay.

5.2.5 Static versus dynamic

When driving the vehicle out on the test track the road is not perfectly symmetric. This means that the tires and suspension constantly correct this disturbance. When vehicle pass through the depressions with high speed the vehicle´s centre of gravity is changing constantly and the vehicle is nearly lifting when driving off from the top of the depressions. This causes dynamic forces that we did not achieve in the K&C rig. The forces are depending on acceleration, weight distribution and angle of the wheel impact. We are sure there are more parameters that we have not thought off. We believe some of these forces can be better simulated if the pitch angle is applied during the test, but this will be further discussed in chapter *6.2. A static "dynamic" position* under *future work.*

5.2.6 Air suspension

A vehicle without air suspension would be easier to simulate with on the K&C rig. In the K&C rig the air suspension is deactivated and a source of error will therefore arise. This means that the rear of the vehicle cannot be measured properly, and the front will not be regulated in the same way on the K&C rig as it does on the test track. When the air suspension is set to service mode, the suspension is no longer regulating. Imagine the vehicle standing on a bag of air that is constantly leaking air since the air suspension does not regulate anymore. At last, the bag of air is empty due to the leaking and the vehicle will be equipped with a rear suspension with poor characteristics.

The same characteristics are therefore not achieved in the K&C rig as on the test track. This means that the imprints on the modelling clay are not that easy to compare. We do not know how much the air suspension actually helps the front wheels from preventing heavy impact on the modelling clay on the test track when the air suspension is regulating. A regular spring suspension is therefore preferably when simulating wheel clearance in the K&C rig. The spring suspension does not need any service mode and the characteristics would be the same on the K&C rig as it is on the test track.

6 Future work for K&C rig

6.1 Tire deformation

To achieve a more comparable clay imprint result in the K&C rig, we believe a mathematical expression for the tire deformation could serve as good support. Tire dynamics is a complex and important parameter and we do not have the possibility to predict it.

If the tire deformation was to be measured with the AICON WheelWatch, or any other suited measuring system, we believe that a mathematical expression could be introduced. With the help of the real tire deformation that occurs running the obstacle, an integral may be able to solve the offset needed to achieve the correct wheel centre displacement, also known as the tire deformation.

Looking at *Appendix 6* we discovered an exponential function behavior with force and position when adjusting the offset. This indicate that it is possible to create a function of force and position. One way to study the tire attributes and the function is to experiment with a vehicle that is rigged to the K&C rig and measure the positions and forces.

6.2 A static "dynamic" position

As described in 5.2.5. *Static versus dynamic*, improvements can be done to replicate the scenario at the test track in the K&C rig. To achieve a more aggressive force impact on the wheel, a pitch angle could be set so that the vehicle is tilted to the same angle as when it has when hitting its maximum vertical displacement during the elevations. This pitch angle is preferable set when the ride height is determined. If the measurements are run with four AICON WheelWatch cameras, one for each wheel, the results would tell the position for both the front and rear wheel centres in a specific moment. Together with the wheelbase measurement, a triangle is arising. With this triangle, a pitch angle can be calculated. This pitch angle can be used to replicate the angle when the vehicle is ditching in to the elevation.

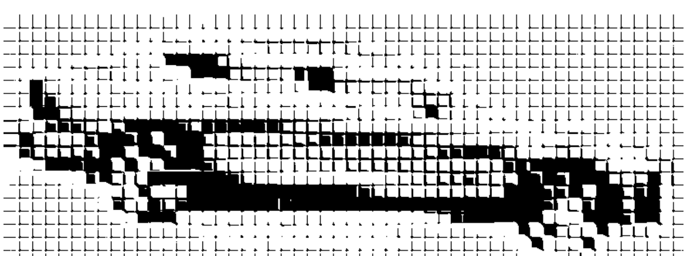

Figure 6.2.1 The figure illustrated the angle α, that occurs between the front and rear axis when the vehicle drives through the several depressions. ΔZ is the vertical distance in mm between the front and rear axis.

When the pitch angle is set as ride height, the same input files that were created for the K&C rig can be used. We believe this will give a better imprint in the clay.

6.3 Dynamics in the K&C rig

To simulate forces that are arising during the wheel clearance test on the test track, the dynamic mode in the K&C rig should be further investigated. The K&C rig has the ability to simulate movements in real time, this will put stress to the suspension and wheels. We believe the result as the clay imprints will differ significant from the static test. The limits for how fast the centre table and move will hence determine if the Several depressions and elevation can be simulated in “full speed”. The obstacle does not cause very rapid wheel movements. Though, running other type of test codes in the K&C in “full speed” could be problematic.

7 Conclusions

- We were not able to obtain the same clay imprints in the K&C rig and the test track using our method. It could be interesting to further develop the method used in this thesis.
- The wheel rotation cannot be simulated in the K&C rig, this prevents us from getting imprints caused on the track and on the K&C rig to have the same characteristics. They are therefore difficult to compare.
- A mathematical expression for tire deformation seen to force relative to position would help to simulate a more correct wheel clearance result in the K&C rig.
- A test vehicle without air suspension is preferable when simulating in the K&C rig to receive the same suspension characteristics on the K&C rig as on the test track.
- It is important to measure the ride height at 90 km/h and use it in the K&C rig. The ride height differs one millimeter between 0 to 90 km/h. According to our tests and will probably differ more without air suspension.

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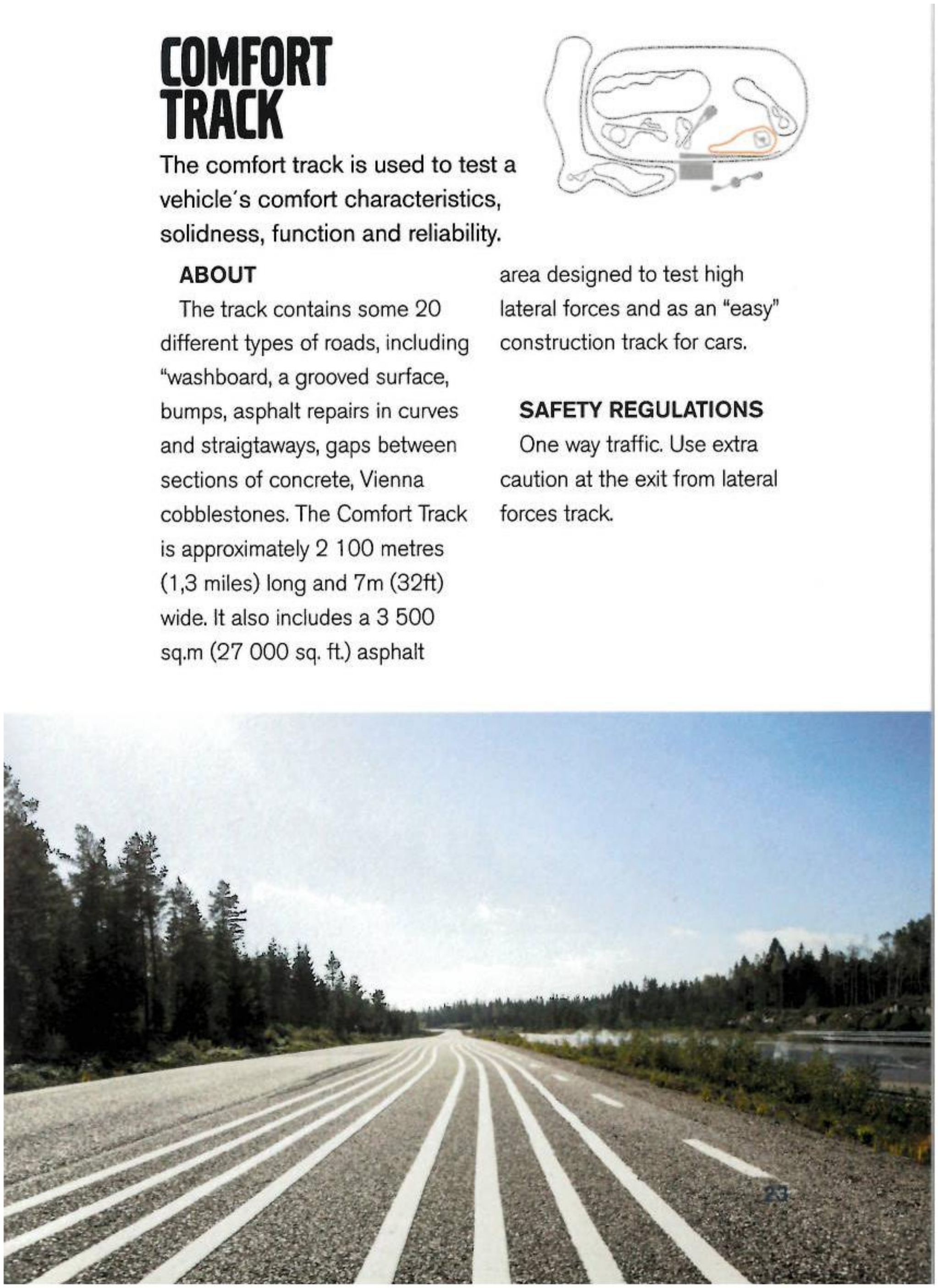
[Accessed 25 04 2017].

8 Appendix

8.1 Appendix 1 Comfort track



COMFORT TRACK

The comfort track is used to test a vehicle´s comfort characteristics, solidness, function and reliability.

ABOUT

The track contains some 20 different types of roads, including "washboard, a grooved surface, bumps, asphalt repairs in curves and straigtaways, gaps between sections of concrete, Vienna cobblestones. The Comfort Track is approximately 2 100 metres (1,3 miles) long and 7m (32ft) wide. It also includes a 3 500 sq.m (27 000 sq. ft.) asphalt area designed to test high lateral forces and as an "easy" construction track for cars.

SAFETY REGULATIONS

One way traffic. Use extra caution at the exit from lateral forces track.

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Figure 8.1.2. Short information about the Comfort track at Hällered.

8.2 Appendix 2 Weight distribution

VOLVO PERSONVAGNAR AB
PROVBANAN HÄLLERED
505 91 BORÅS

Löpnr	Datum/Tid	Fram vä	Fram hö	Framaxel
1158	2017-04-10 14:48	596,5kg	587,0kg	1183,5kg
Bilnr	Signatur	Bak vä	Bak hö	Bakaxel
S90	Martin	603,0kg	610,0kg	1213,0kg

Anmärkning:
Referens:
Reserv:

Total
2396,5kg

Figure 8.2.1. Weight distribution, weighed in the weigh hall

8.3 Appendix 3 Input files to K&C rig

Appendix 3 illustrates how the different input files looked like for the K&C-rig tests. The x- and y-values corresponds to the same moment on the timeline as when the used z-value is reached. It keeps the same value for four steps so that it is easier to spot when the maximum point is reached.

Table 8. The table shows the input files to the K&C rig.

HF_X	HF_Y	VF_X	VF_Y	Z_BOUNCE
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	-2,511
0	0	0	0	-5,036
0	0	0	0	-7,561
0	0	0	0	-10,086
0	0	0	0	-12,611
0	0	0	0	-15,136
0	0	0	0	-17,661
0	0	0	0	-20,186
0	0	0	0	-22,711
0	0	0	0	-25,236
0	0	0	0	-27,761
0	0	0	0	-30,286
0	0	0	0	-32,811
0	0	0	0	-35,336
0	0	0	0	-37,861
0	0	0	0	-40,386
0	0	0	0	-42,911
0	0	0	0	-45,436
0	0	0	0	-47,961
0	0	0	0	-50,486
-0.2153	-0,880	-0,103	1,025	-53,011
-0.4306	-1,763	-0,207	2,055	-55,536
-0.6459	-2,645	-0,310	3,085	-58,061
-0.8612	-3,527	-0,413	4,115	-60,586
-1.0765	-4,409	-0,517	5,145	-63,111
-1.2918	-5,291	-0,620	6,175	-65,636
-1.5071	-6,174	-0,723	7,205	-68,161
-1.7224	-7,056	-0,826	8,235	-70,686
-1.9377	-7,938	-0,930	9,265	-73,211
-2.153	-8,820	-1,033	10,295	-75,736
-2.153	-8,820	-1,033	10,295	-75,736
-2.153	-8,820	-1,033	10,295	-75,736
-2.153	-8,820	-1,033	10,295	-75,736
-1.9377	-7,938	-0,930	9,265	-73,211
-1.7224	-7,056	-0,826	8,235	-70,686
-1.5071	-6,174	-0,723	7,205	-68,161
-1.2918	-5,291	-0,620	6,175	-65,636
-1.0765	-4,409	-0,517	5,145	-63,111
-0.8612	-3,527	-0,413	4,115	-60,586
-0.6459	-2,645	-0,310	3,085	-58,061
-0.4306	-1,763	-0,207	2,055	-55,536
-0.2153	-0,880	-0,103	1,025	-53,011
0	0	0	0	-50,486
0	0	0	0	-47,961
0	0	0	0	-45,436
0	0	0	0	-42,911
0	0	0	0	-40,386
0	0	0	0	-37,861
0	0	0	0	-35,336
0	0	0	0	-32,811
0	0	0	0	-30,286
0	0	0	0	-27,761
0	0	0	0	-25,236
0	0	0	0	-22,711
0	0	0	0	-20,186
0	0	0	0	-17,661
0	0	0	0	-15,136
0	0	0	0	-12,611
0	0	0	0	-10,086
0	0	0	0	-7,561
0	0	0	0	-5,036
0	0	0	0	-2,511
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0

8.4 Appendix 4 First run in the K&C rig

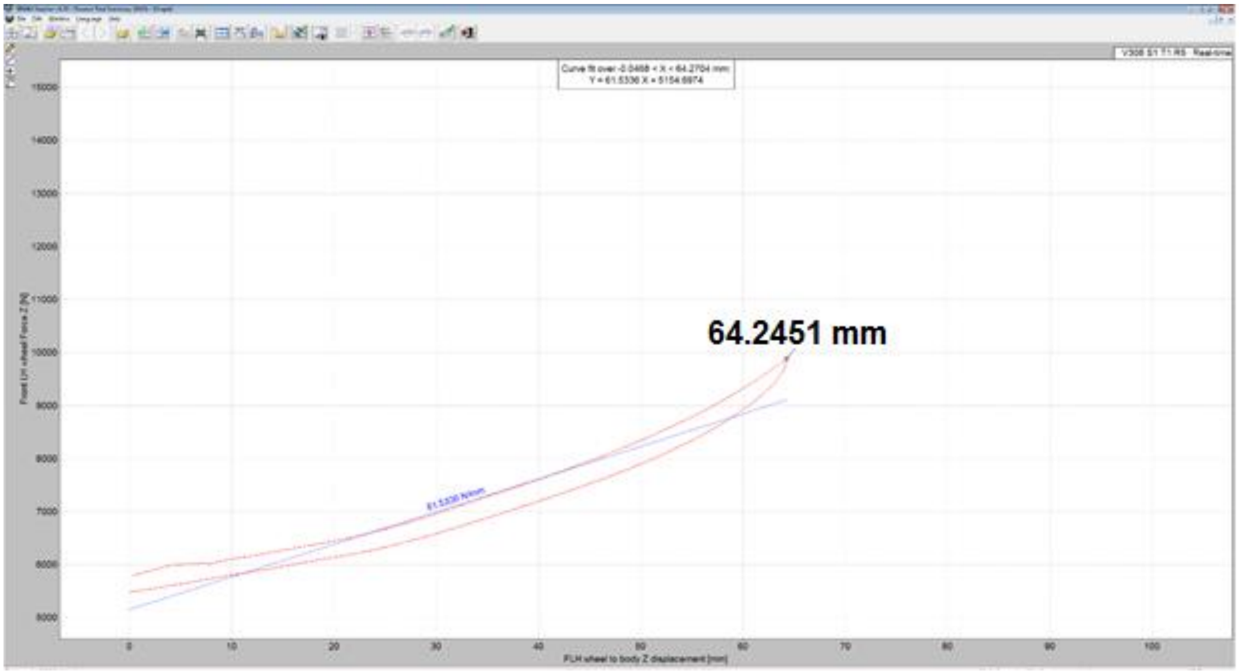

Figure 8.4.1: K&C- test result. First run, z-displacement from wheel centre to fender, left wheel.

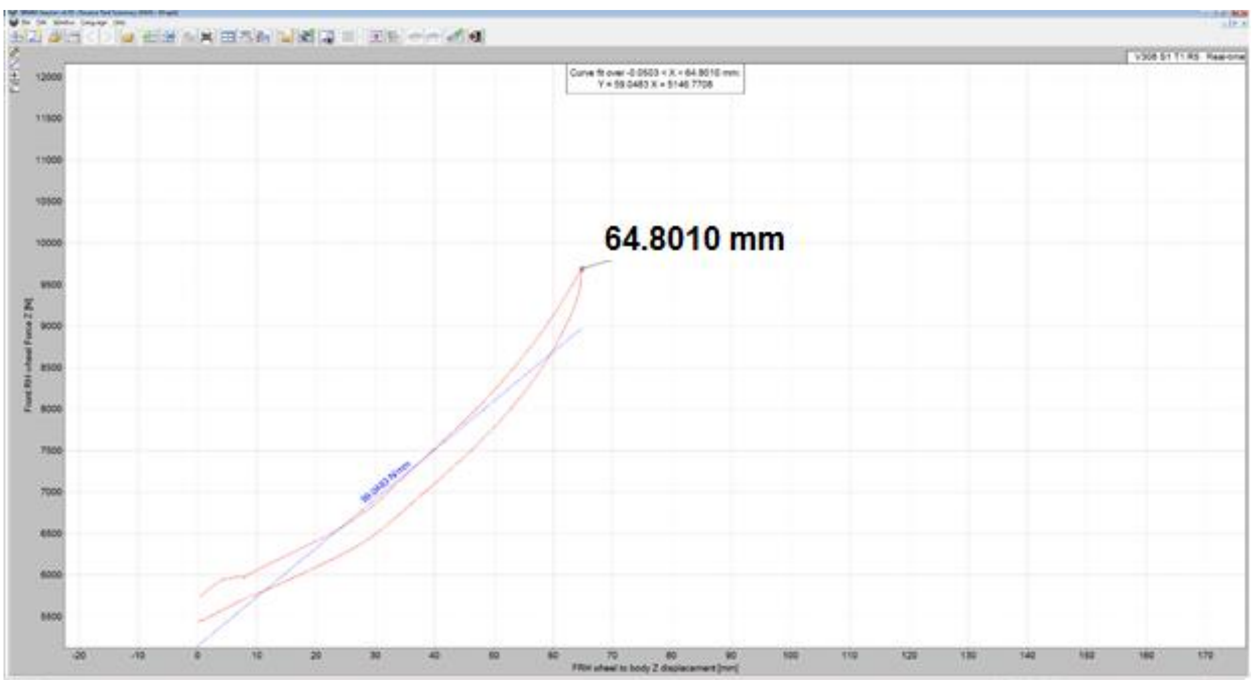

Figure 8.4.2: K&C- test result. First run, z-displacement from wheel centre to fender, right wheel.

8.5 Appendix 5 Wheel centre movement, first run

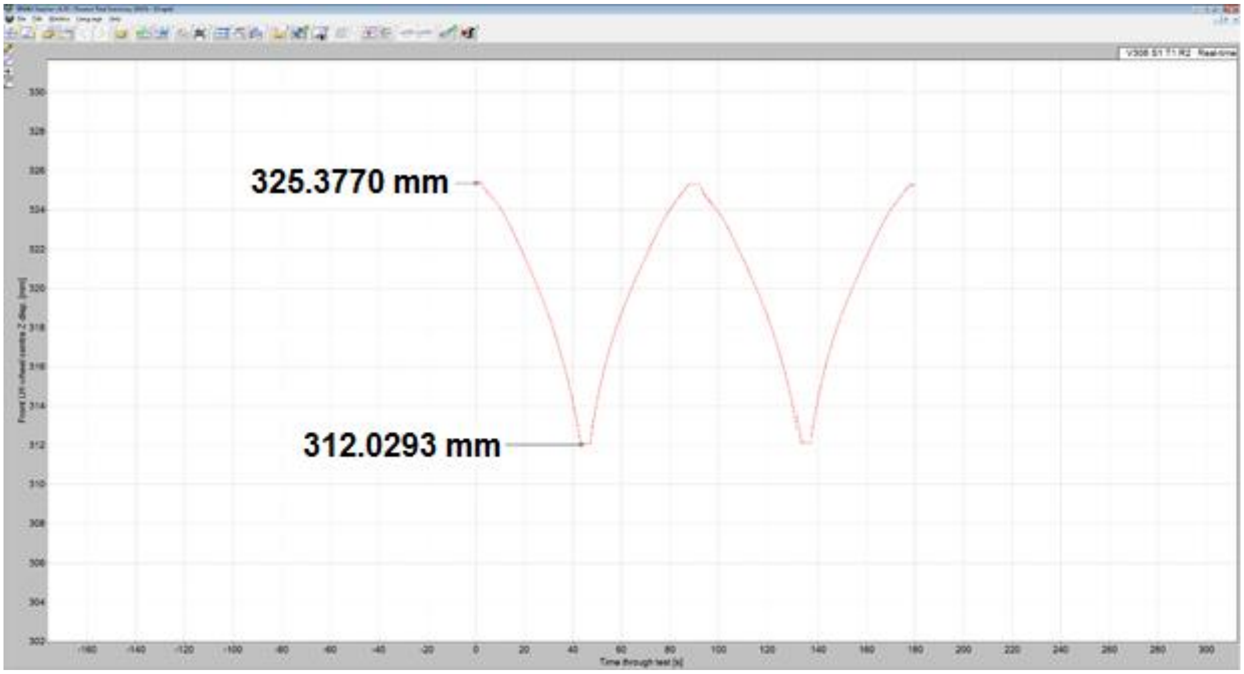

Figure 8.5.1: K&C- test result. First run, wheel centre movement in z-direction, left wheel.

8.6 Appendix 6 Second correction in the K&C rig

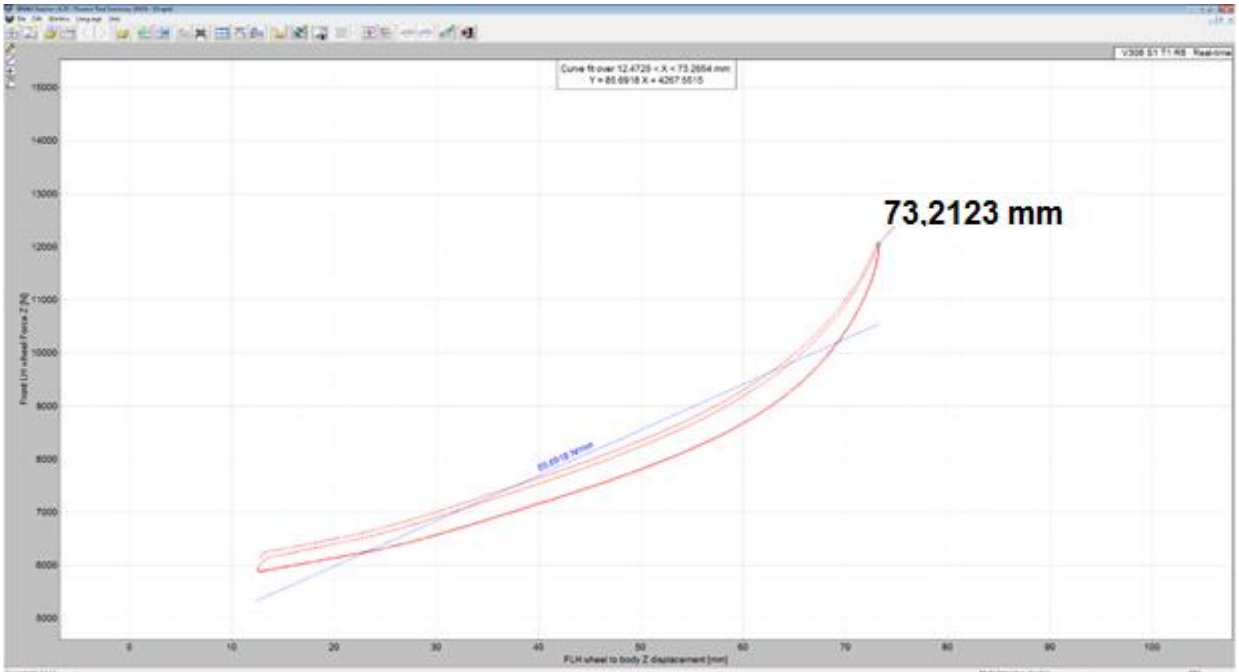

Figure 8.6.1. K&C- test result. Second correction, z-displacement from wheel centre to fender, left wheel.

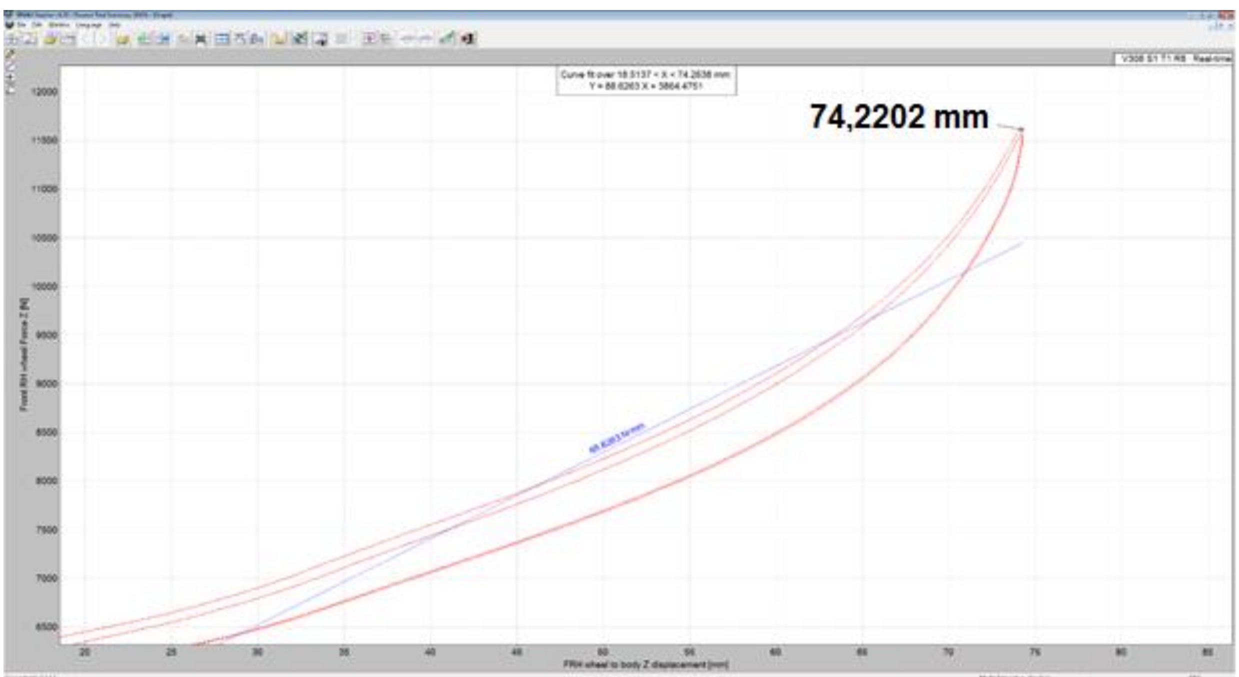

Figure 8.6.2. K&C- test result. Second correction, z-displacement from wheel centre to fender, right wheel.

8.7 Appendix 7 Wheel centre movement, second correction

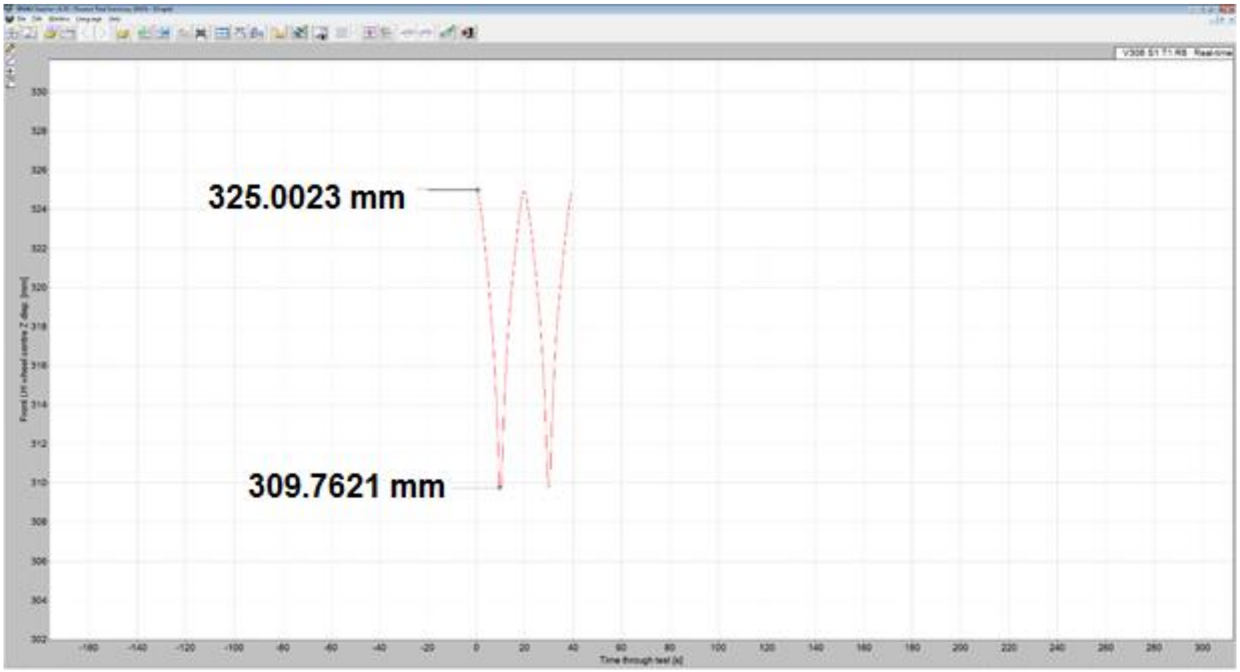

Figure 8.7.1. K&C- test result. Second correction, wheel centre movement in z-direction, left wheel.

8.8 Appendix 8 MATLAB script

This script is used when creating the input files for the K&C rig.

```
%Excel files that has been created of the AICON measurement text
files.
%First column (A) is time, second column (B) should be the
desired value,
%in this case, vertical movement, therefore z-value.

[t1_values,~,~] = xlsread('4bulor1svacka_korning1.xlsx', 'A:A');
[z1_values,~,~] = xlsread('4bulor1svacka_korning1.xlsx', 'B:B');

[t2_values,~,~] = xlsread('CO1234B1S.xlsx', 'A:A');
[z2_values,~,~] = xlsread('CO1234B1S.xlsx', 'B:B');

[run1,j]=max(z1_values);disp(run1),disp(t1_values(j));
[run2,k]=max(z2_values);disp(run2),disp(t2_values(k));
%_________________1_________________
subplot(2,1,1), plot(t1_values,z1_values, 'black')
hold on
plot(t1_values(j),z1_values(j), 'r+');
hold off

title('1:st test run');
xlabel('Elapsed time [sec]');
ylabel('Displacement in Z-direction [mm]');

%_________________2________________

subplot(2,1,2), plot(t2_values,z2_values, 'black')
hold on
plot(t2_values(k),z1_values(j), 'b+');
hold off

title('2:nd test run');
xlabel('Elapsed time [sec]');
ylabel('Displacement in Z-direction [mm]');
```