CHALMERS
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Investigation of repeatability and reproducibility of steering characteristics’ measurement

Bachelor’s Thesis in Mechanical Engineering

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Abstract

The study covers an investigation on the repeatability and reproducibility of the steering characteristics test procedure at Volvo Car Corporation (VCC). The steering characteristic test series is performed in six different sub test, responding to different driving scenarios. The project was brought up after VCC performed three series of steering characteristic tests on three different occasions, during similar conditions and with the same car. The results were separated from each other without any explanation. In this study, the causes of spread in results were investigated.

Starting by performing three series of tests to clarify if the same set of data results were separated as the ones in the previous three tests. Different sets of result data separated, clarifying that it is not certain which subtests that obtain an uncertainty. Due to time limitations, the three subtests that appeared as "the worst" were selected for further investigation, creating a smaller series containing the selected sub tests. This shorter test set was performed 8 times, 4 times per operator, to collect as much data time could provide.

The data was analysed with ANOVA (analysis of variance) to specify spread in data within groups of test set number, operator and turning direction if applicable to test. To observe the influence of external factors, a linear regression model was fitted between each result metric and external factors.

The result showed that different tests were affected by different factors, preventing the determination of a certain factor causing the spread in the test procedure. Some tests appeared to be influenced by the calibration of the steering robot, some by the tire conditions and in some cases, no cause of spread could be found.

The study has created a good knowledge for further investigation. Even though several important conclusions were made, there is a lot more to dig into and a long list of recommendations in further investigation was achieved.

Key words: Vehicle dynamics, steering characteristics, objective metrics, R&R, repeatability and reproducibility.

Contents

Preface

This study covers an investigation in steering characteristic measurement. The study has been carried out from January 2018 to June 2018. The study is an initial investigation in the cause of measurement result spread on behalf of Volvo Car Corporation, department 91838 - Vehicle & Rig-testing.

The study has been performed with Test Engineer Ajay Daniel as Volvo Car Corporation supervisor, CAE Engineer Mohit Asher at Volvo Car Corporation as support in statistic evaluation and Professor Bengt Jacobson at Chalmers University of Technology as project supervisor and examiner.

We appreciate all involvement from all parties throughout the study. It should be noted that neither the testing nor the evaluation would be possible without the commitment from Vehicle & Rig-testing department staff.

Finally we would like to thank PhD-student Tushar Chugh at Chalmers Univerity of Technology for the support in the authoring of this thesis report.

Gothenburg, June

Henrik Eriksson, Linus Tapper

Nomenclature

Ay	Lateral acceleration. Acceleration along the vehicles transverse axis. Can be measured on front and rear axle separately or from the body's local coordinate centre. [m/s^2]
HPG	Hällered Proving Ground
Jerk	Time derivative of Ay. [$(m/s^2)/s$]
R&R	Repeatability and Reproducibility
Roll	Rotation around the vehicles longitudinal axis. [deg]
SDNA	Steering DNA. VCC terminology, steering characteristics measurement.
SWA	Steering wheel angle. The rotational angle of the steering wheel measured from the steering neutral point. [deg]
SWT	Steering wheel torque. Torque from/to the driver to the steering wheel. [Nm]
VCC	Volvo Car Corporation
Vx	Longitudinal velocity. [km/h]
Yaw	Rotation of the vehicle around its vertical axis. [deg]

1 Introduction

The study covers an investigation in how accurate the test procedure of steering characteristic determination is in terms of repeatability and reproducibility.

1.1 Background

Testing is an important part of Volvo Car Corporations development. Durability, comfort, performance, reliability and safety are qualities that are constantly tested on Volvo Car’s test tracks, primarily at Hällered Proving Ground. Hällered is a facility located 80 km outside of Gothenburg, where cars are tested to their maximum capacity, over a series of test responding to a car’s entire lifecycle of normal usage (Volvo Car Corporation, 2010). In chassis development VCC determines the steering characteristics, (referred to as SDNA in VCC terminology), of a car by simulating different handling situations on proving grounds.

The physical testing on proving grounds is being used to determine how the car's handling respond to different scenarios in terms of body roll, generated g-forces and input steering wheel torque etc. When testing steering characteristics, results from tests can vary between occasions. Even when testing during similar conditions, a spread in the results occur.

One of Volvo's major priority of making cars with a premium feel, the development in how the car interacts with the driver becomes utterly significant. Combining a car that works seamlessly with e.g. autonomous lane assists and straight road stability with good handling and feeling to the road surface, is a challenge that requires precise structural design within the chassis. To determine and validate suspension design etc, testing requires more precise results to rely on.

1.2 Problem Motivating the Project

The major reason this project was brought up, comes from that a test engineer suspected variation in results and performed three identical tests on three different occasions with the same vehicle individuals. The conclusion was that the results varied more than expected but without any obvious reason.

These tests are crucial when determining the handling and interaction between the driver and the vehicle. The spread in results from previously mentioned tests is an uncertainty that VCC want to distinguish. Today it's not known why spread in results occur, and it is also unknown which factors that prevents spreads from being eliminated.

By declaring which factors provide a spread in the results, and learning how to minimize the measurement spread, more effective testing can be accomplished. With more certainty in testing, fewer tests can be performed with better precision, and therefore reduce development time drastically. The problem with spread in results does not affect the customer in any significant way because a new chassis will be developed until a certain characteristic is achieved, which is evaluated by several SDNA tests, CAE engineering and also a subjective evaluation from experienced test drivers.

1.3 Research Questions

- What factors influence measurement spread in the results?
- Does this spread occur when results are separated between operators?
- Does the general spread differ between right and left turn sequences?

1.4 Limitations

- The project will be limited to analysis of the existing testing procedure and not include development of such.
- The tests will be performed according to Volvo Car's standardized test codes.
- The full SDNA test series will be evaluated and the test plan will during the project be reduced to the tests and metrics that holds the biggest spreads.
- The project will focus on the tests and the test results, factors like post-processing of data and calculations behind the scenes will not be evaluated.

1.5 Method

Starting by performing a literature study of the SDNA to create a solid understanding in how the existing test codes are created and how the results from the test procedure correspond to the entire steering characteristics.

The test process will be measured and evaluated regarding the repeatability and reproducibility (R&R, see chapter 2.6). Possible causes of variation in steering metrics will be investigated and analysed with both ANOVA (see chapter 2.6) and linear regression (see chapter 2.6.2) to define the correlation to external factors. A test plan (see chapter 3) will be created and several tests will be performed.

Three Full test series will be performed to determine which subtests that should be further investigated. One full test series includes the following six subtests which are further described in Chapter 2.5:

- Parking Effort, PE
- On Centre, OC
- Low G swept steer, LSS
- High G swept steer, HSS
- Frequency Response, FR
- Sine with dwell steer, SWD

2 Theory

The major theoretical knowledge required on the study is how a test series is performed (Chapter 2.4) and what the Gage R&R test method (Chapter 2.5) is intended to cover.

2.1 Conditions

Test conditions are all according to Volvo Car Corporation internal test code documents. The test series will be performed on the Brake and Handling Area at Hällered Proving Ground, which is an open tarmac area with a minimum camber offset of 2 degrees. It is known to the test engineers that big parts of the surface obtain this camber offset, which is believed to generate a difference in left versus right sequences. The Brake and Handling Area is shown in figure 2.1.

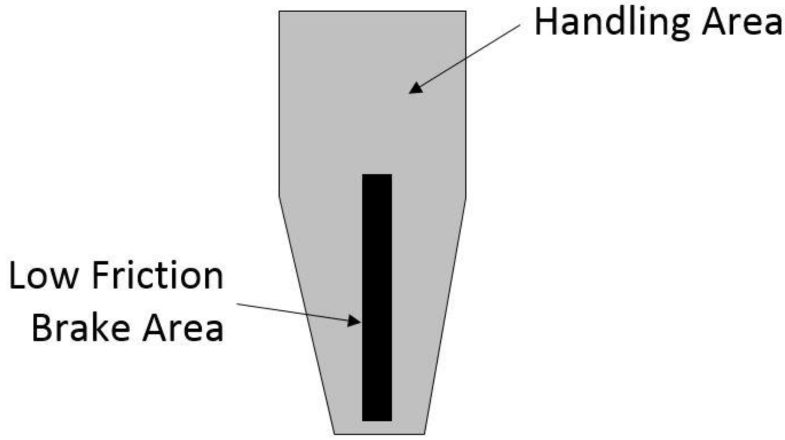

Figure 2.1 Brake and Handling Area at Hällered Proving Ground.

2.2 Equipment

The hardware equipment used in the study will be consistent during the entire study.

2.2.1 Vehicle

The vehicle that will be used in this study is a test vehicle that will not be presented due to confidential reasons but will be the same throughout the study. None of the vehicle individuals will be changed throughout the study. The active safety systems in the vehicle, like ABS (Anti-Lock braking) and ESC (Electronic Stability Control) will be turned on during all the tests.

2.2.2 Robot

To ensure constant steering wheel input value and vehicle velocity each time, the vehicle is operated by a robot. The robot is mounted in a test vehicle and consists of a steering robot mounted to the steering wheel and an accelerator robot mounted to the accelerator pedal.

2.2.3 IMU - Inertial Measurement Unit

The IMU-unit is used to give accurate absolute position, velocity and acceleration information of the vehicle. The unit also uses GPS-technology with accuracy within 2-3 cm. The values from the IMU-unit is used as measurement factors and as input values for the robots.

2.2.4 Mounting of the Robot and the IMU

When mounting the robot and the IMU in the car, there are a few variables that need a certain amount of accuracy. The steering wheel robot needs to be centred to the steering column because a steering wheel is slightly eccentric and not perfectly circular.

The force sensors that are used to determine the SWT needs to be adjusted so that there are no built-in stresses that affect the measurements.

The IMU needs a set of dimensions to determine the IMU's position in relation to a set of hardpoints. Due to confidential matters, the position of the IMU-unit will not be presented.

2.2.5 Operating the Robot

Before the test procedure starts, the steering robot needs to be calibrated. This process is called "Homing" and it means that the operator sets the end positions of the steering wheel and locate the steering neutral point, referred to as zero-steer. The zero-steer homing requires the operator to drive in a straight line during the time that the robot is calibrating, at which SWA the car is going straight.

When operating the vehicle with the robot, the operator has different options. The robot is pre-programmed with steering wheel input and vehicle speed to each different test. The operator must determine if there is enough space to reach required speed and to perform the actual test. Sometimes the best way is to accelerate the vehicle and activate the robot by hand, for e.g. the frequency response test. In some tests there is a pre-programmed GPS-path that will lead the vehicle to the correct position where the test starts. In these cases, the operator can activate the robot when the vehicle is stationary and let the robot accelerate and operate the car.

The operator has some responsibility to the measurement results. In some tests the vehicle needs to reach required, for e.g. lateral acceleration. To tune this parameter the operator needs to change the amplitude of the SWA input value. In some other tests the SWA will increase until the vehicle reaches the minimum required lateral acceleration and it is up to the operator to stop the test when the lateral acceleration is high enough.

In case of danger, the operator always has the ability to cancel an ongoing test by releasing the trigger button and take back the control of the vehicle.

2.3 Vehicle Dynamics

Determination of steering characteristics is, for instance, measured as a relation between SWA or SWT and a handling response such as lateral acceleration or yaw. Measuring these relations returns a graph, corresponding to the steering input a certain dynamic requires to be achieved.

A car that achieve a large amount of lateral acceleration at a small steering wheel input can provide the feeling of being too agile and returns an insecurity with the driver and the ride feels stressful and requires quick reflexes and small, quick corrections. On the other hand, a car that achieves a small amount of response feels saggy, and in the opposite way also gives an insecurity in terms of the driver cannot trust that the car will respond the way the driver expects it to.

Yaw is also a tricky response to balance. A high response in body rotation, returns the feeling of an agile and playful car but is not something that is applicable with the general driver. A too low response in yaw returns bad handling, slow turning response and is also dangerous in terms of handling during avoidance of collision. In an everyday car, understeer is preferred because a stable car with no signs of skids is both often safer and more relaxing for the driver. (Jacobson, 2016)

2.4 SDNA – Test Procedure

One SDNA test series is divided into 6 subtests, to determine steering characteristics in different driving situations. Each of the following test descriptions are all described in general according to Volvo Car Corporations internal test code documents. Due to confidential matter, none of the specific input values will be presented and all tests will only be briefly described. All SWA input plots are only examples and does not correspond to the actual input values. Neither will the actual target values in terms of handling responses such as Ay, Yaw or Jerk be presented.

2.4.1 PE – Parking Effort

Parking effort test has the main objective of determining the required SWT at a certain SWA in low speed situations. The test is performed both standing still and in slow speed. The sequence starts by making a turn of the steering wheel at a certain rate until maximum SWA in one direction is reached, then in the opposite direction until maximum SWA is reached in the other direction and finally back to a SWA of 0 [deg]. Each set includes 4 runs, one run in each Vx and with opposite turn direction.

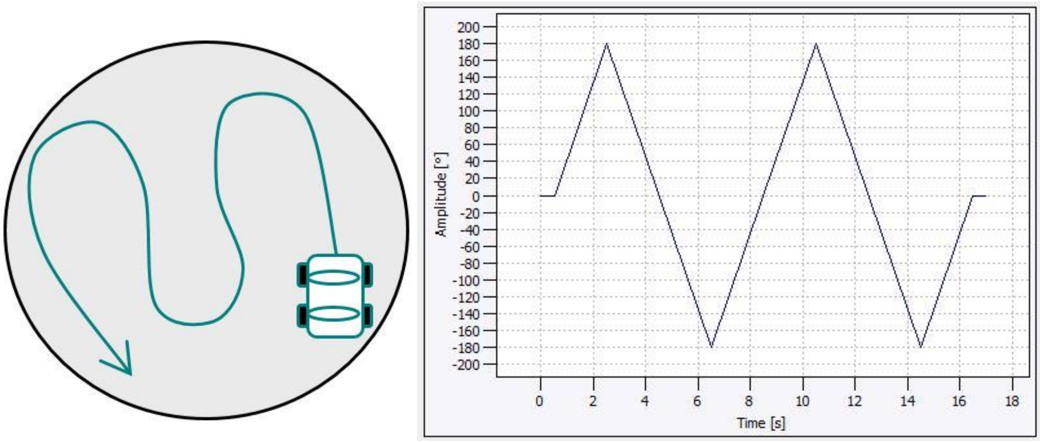

Figure 2.2 Parking Effort Vehicle Path and SWA Input.

2.4.2 OC – On Centre

On centre tests main objective is to determine characteristics in steering at a constant sine shaped line with low SWA velocity and medium levels of Ay. The test is repeated in 5 different constant Vx, from low to high speed. The test starts with a certain SWA frequency at an amplitude that responds to the target Ay of the given test.

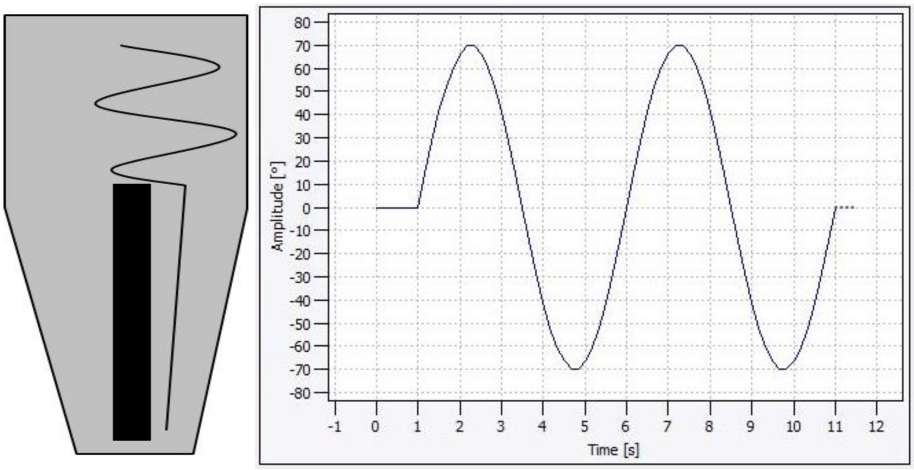

Figure 2.3 On Centre Vehicle Path and SWA Input.

2.4.3 LSS – Low G Swept Steer

Low G swept steer is used to determine characteristics in steering within a vehicle around the straight ahead trim state. This correspond to highway situations like small direction adjustments such as passes and long corners with low g-forces. The test starts by driving in a straight line at two different Vx, then change the SWA at a rate so that the jerk level reaches a certain value and continues until the target Ay is reached. Each set includes 5 runs of each Vx and turn direction.

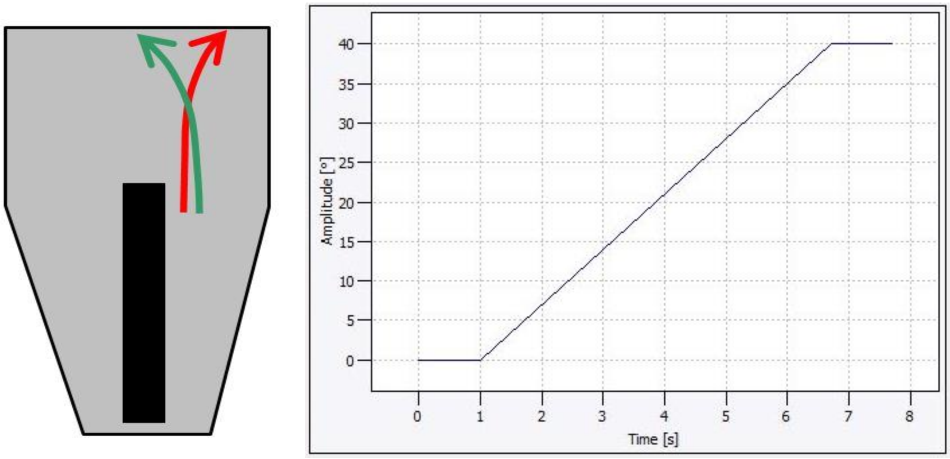

Figure 2.4 Low G Swept Steer Vehicle Path and SWA Input.

2.4.4 HSS – High G Swept Steer

High G swept steer has the main objective to determine the vehicles steady-state turning performance in long corners with high g-forces. It characterizes directional and roll dynamics for the complete driving spectrum, from normal turning to limit road holding capability. The test is performed at a certain Vx. Then a change in SWA is applied that responds to a certain jerk level until the target Ay is reached. Each set includes 5 runs of each turn direction.

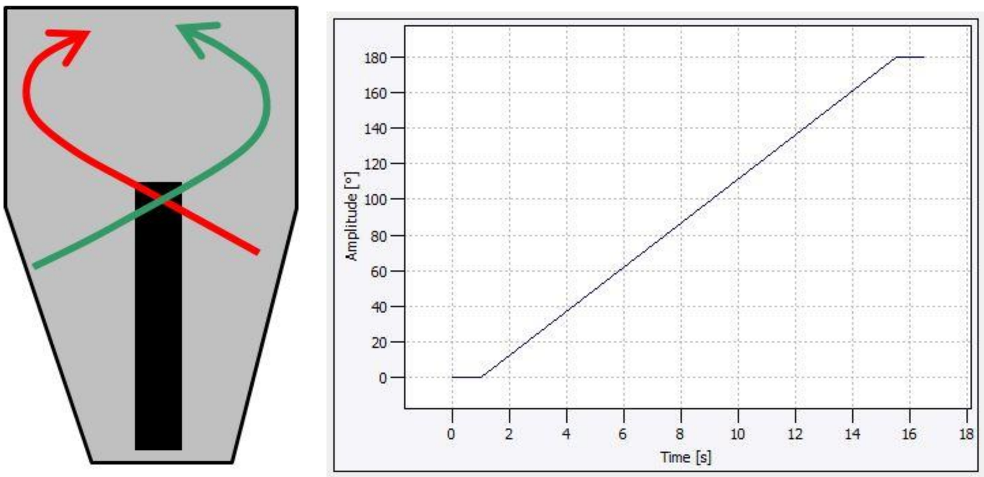

Figure 2.5 High G Swept Steer Vehicle Path and SWA Input.

2.4.5 FR – Frequency Response

Frequency Response has the main objective to determine the dynamic equilibrium of the vehicle, or steady-state. This correspond to the transient and steady state turning performance in the linear driving domain. The linear driving domain is what the normal customer commonly use while driving and includes manoeuvres at a low level of Ay. The test starts with a sine wave SWA with an amplitude responding to a certain Ay. An ideal input signal starts with a higher frequency that is ramped down to low frequency. The test is performed in two different Vx.

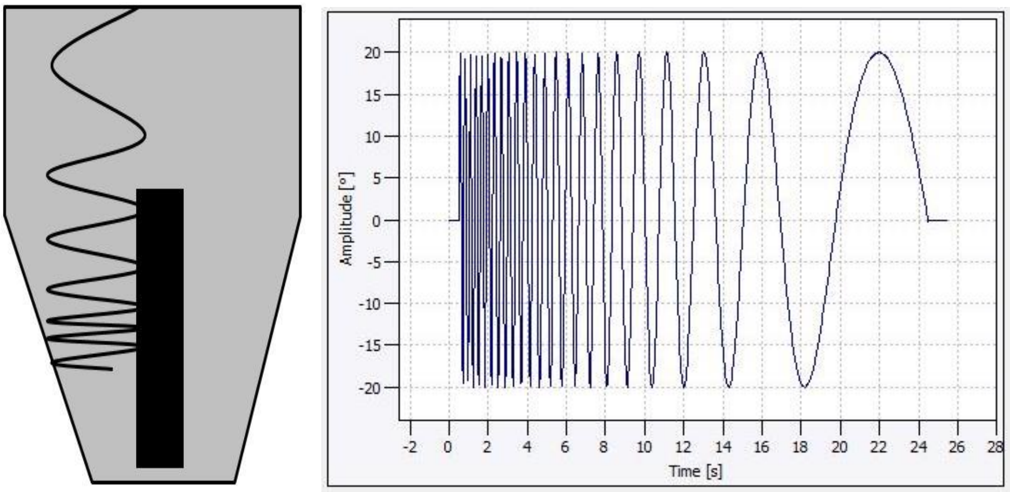

Figure 2.6 Frequency Response Vehicle Path and SWA Input.

2.4.6 SWD – Sine With Dwell Steer

Sine with dwell steer has the main objective to determine the vehicle's transient response behaviour; yaw stability and response. The test is intended to be similar to lane change manoeuvres in real traffic. The test is performed at a constant Vx and consists of a single sine manoeuvre with a short dwell at the second SWA peak. The SWA amplitude should be such that the vehicle achieves the target Ay, and the SWA is increased for each run until slip occur. Each set includes one test of each direction in each SWA amplitude.

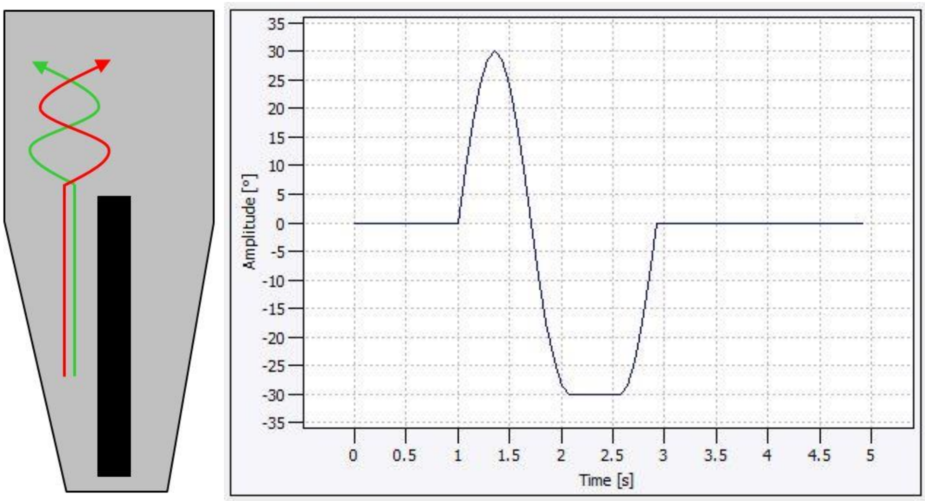

Figure 2.7 Sine with Dwell Steer Vehicle Path and SWA Input.

2.5 Gage R&R, Repeatability and Reproducibility

In an article (Dr McNeese, 2015) repeatability is described as the variation within the measurements created by one operator, measuring the same item repeatedly during similar conditions. In the same article Dr McNeese also describes the reproducibility as the difference in how different operators, or different occasions obtain a variance in measurements. In simpler terms:

Repeatability is the ability to repeat a test on the same occasion by the same operator.
Reproducibility is the ability to recreate a test on a different occasion and if needed, a different operator.

According to (Martz & Smith, 2014), Gage R&R is the most common measurement system analysis and it assesses the sources of variation and the amount of variation within the measurements.

The Gage R&R method is applied in this context by analysing the variation in a measurement during the same occasion and then by the variation between different occasions. The method is appropriate when analysing a test procedure with unknown affecting factors.

2.6 ANOVA – Analysis of Variance

ANOVA is used to analyse variation of data divided into groups. By dividing the data into different groups, it is possible to quickly evaluate the spread of the data both within each group and also to see the variation in data between groups. This opens up the possibility of using the same sets of data in different analysis, by dividing the data in groups depending on the point of interest in each analysis. For instance, divided by operator, occasion, weather etc. (Andersson, 2012).

2.6.1 p-value

The p-value is an abbreviation of probability value and is commonly used in statistical analysis to determine if the results is caused by a coincidence or a known factor. According to (Andersson, 2012), the p-value is described as “the probability of obtaining data that are at least as extreme as the ones in the sample, assuming that the null hypothesis is correct”. The higher the p-value is, the better. A p-value of 5% or higher is considered good.

Andersson also describes the p-value as a measurement effect in relation to the uncertainty in the data. It means that a large sample will give higher certainty and even a small effect will become statistically significant. A small sample requires the effect to be greater to stand out from the noise. In simpler terms: The sample size needs to be large to be able to detect a small difference. This means that the p-value says more about the precision in the data than about the actual effect. "A high p-value does not say that the effect is inexistent. It says that the experiment is too insensitive to detect it if it exists". The size of the samples in this study is a border line case, therefore the p-value will be used as an indication rather than an actual conclusion.

2.6.2 Linear Regression

Linear regression is a method to evaluate if a factor is affecting a result, and if so, how much. In other words if there is a correlation between two variables. The method is based on how you can fit a linear curve optimally to a scatter of data in two variables in a xy-coordinate system. Mathematically, the result of the linear regression is the linear equation on general form, describing the relation between a result (y-axis) and a possible affecting factor (x- axis), see equation 2.1.

$$Metric = k * factor + Amplitude$$

Equation 2.1 Linear regression mathematical model.

The result is interpreted by the size of the k-value. The higher k-value, the more influence from the factor.

3 Test Plan

The first step of the test plan was to perform three full series of tests to find out which sub tests and which metrics that needed to be evaluated. These three complete tests were performed during equal weather conditions and with different operators, to be able to find differences between both operators and occasions.

3.1 Test Selection

According to VCC CAE engineering division, a test result is never ideal even though the evaluation may appear so. There is next to infinite possibilities in result analysis in terms of how specific the analysis is performed. Their recommendation was that the thest plan should be limitatded to 2-3 sub tests that appear as "the worst", to be able to collect more data on each analysed test.

By creating a new test series with the specified subtest, more data could be collected during the same period of time that a full test series require. That allowed the possibilities of categorizing data into more categories. It makes the ANOVA analysis more efficient and opens up the possibility of performing several one-way ANOVA analyses with data collected in a short period of time. The analysis of categorized result spreads will be evaluated graphically with interval plots with a 95% confidence level.

3.1.1 VCC Confidence Grade

Today, the test result spread is evaluated with Volvo Confidence Grade, which basically is a method that evaluates the result spread window in relation to the target window. The method is useful in terms of how much the result is allowed to differ, because a test which allows a wide target window does not require a narrow window in result spread. However, the method is not ideal in the aspect of a general test evaluation, due to the fact that the target window varies between different platforms/chassis applications. To make the evaluation independent of the target window, p-value from ANOVA is applicable, but only in the tests that have several measurement values within each test. The tests that only have one measurement in each test, for instance an average over time, cannot be evaluated with ANOVA. The Confidence Grade is calculated with equation 3.1 and table 3.1.

$$Relative\ Spread = \frac{Spread\ Window}{Target\ Window}$$

Equation 3.1 - VCC Confidence Grade.

The VCC Confidence is graded according to the following table, where confidence grades less than 2 are results that needs to be evaluated:

Table 3.1 Definition of Confidence Grade level.

VCC Confidence Grade	Relative Spread
2	> 50%
3	30% - 50%
4	10% - 30%
5	< 10%

3.2 Selected Test Plan

The confidence grades and the p-values from the first three test series can be found in Appendix A. There are tests that should be evaluated regarding to the confidence grade and the p-value, but with guidance from the CAE division, the decision was made to focus on tests that provide the most data relative to the level of effort required.

After the process of test selection had been made, the selected tests were the following:

- On Centre in 50 km/h at 0.4g and 80 km/h at 0.4 g.
- High G Swept Steer
- Sine with Dwell Steer

The three tests were performed in 8 sets of tests, 4 by each operator. The sets were performed as following and generated the following amount of runs each:

Table 3.2 Number of runs in each selected test set.

Test	Number of runs in each set
OC, 50 km/h, 0.4g	5
OC, 80 km/h, 0.4g	5
HSS	5 Left and 5 Right
SWD	3 Left-Right and 3 Right-Left

One operator drove every other set so that both operators generate data at every test day and during similar conditions so that the data can be separated into condition and operator without depending on each other.

3.2.1 Metrics of Interest

To define the steering characteristic a series of calculations and post-processings are made. For the analysis, the results from these calculations are referred to as metrics. A full test series includes a lot of metrics and the calculations behind them are sometimes both complicated to understand and to describe. The metrics of interest, after the test selection process was done, are the ones that are presented and further described below:

- **OC 50 0.4g -** The "*Torsional Rate"* [Nm/100 deg] can be described as the change of SWT vs SWA or the amount of torque needed to turn the steering wheel 100 [deg].
- **OC 80 0.4g -** The *"Hysteresis at 0.3g"* [Nm] is the difference in SWT between right and left turn during the sine period. The Ay level over time follows a complete sine period, the difference between SWT at 0.3g and – 0.3g is the hysteresis.
- **HSS -** The *"Torque gradient 0.3 - 0.5g"* [Nm/(m/s^2)] is calculated as the slope between the SWT value at 0.5g and 0.3g. *"Torque at 0.3 g"* [Nm] is calculated as the SWT value at 0.3g Ay. The mean value from all runs is used.
- **SWD -** The metric "*Ay @ Max Yaw gain"* [m/s^2] can be described as at which Ay the increase of the Yaw reaches its maximum value. "*Ay - SWA time lag @ 4m/s2"* [ms] is the time delay between the SWA input and the reaction in the car. "*Ay - Yaw time lag @ 4m/s2"* [ms] can be described in the same way, but instead of looking at how the change in SWA affects the Ay, the Yaw is regarded. In simpler terms: When the SWA changes, the Yaw changes and that will cause a reaction in the car that can be visualised as Ay.

3.2.2 Possible Affecting Factors

Possible affecting factors that will be measured and evaluated during the study have been selected in cooperation with VCC project supervisor.

The selection of factors to log and evaluate are:

- Tire condition – Contact patch temperature and tire pressure
- Weather – Tarmac temperature and wind conditions.
- Operator – The data was grouped by operator

If any further weather conditions are affecting the results, it will affect the data if divided into different test occasions.

The tire condition will be measured before each test, in each test set, but not each run. The temperature is measured with an IR-thermometer and the pressure is measured with a certified barometer.

4 Results

The analysis started with ANOVA by dividing each test metric into the categories: test set number, operator and if metric allows, turning direction. Each Analysis gives an interval plot, describing the spread within groups and the groups magnitude in relation to each other. All interval plots contain respective p-value.

A scatterplot with a linear regression will present the correlation between the results and external factors. Only the wind velocity will be observed in the wind condition analysis, hence the wind direction only varied 3 [deg] between all test days.

4.1 On Centre, 50 km/h

The analysis procedure started by dividing the data into test set number, which can be seen in figure 4.1.

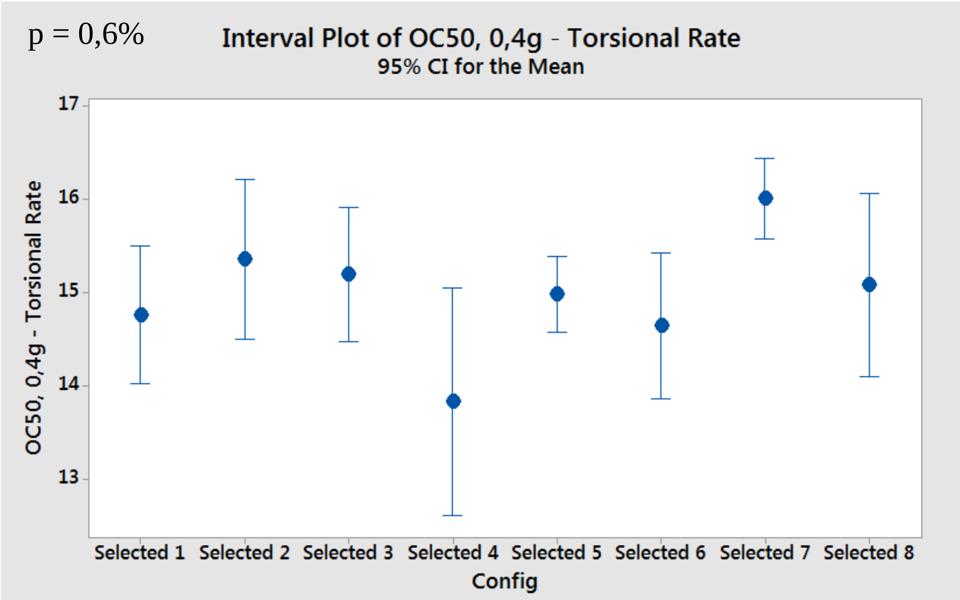

Figure 4.1 Interval plot of Torsional Rate [Nm/100°], grouped by test set number.

No obvious trend can be spotted. Surprisingly, both mean value and magnitude of spread differ between test set numbers.

The data was grouped by operator, which can be seen in figure 4.2.

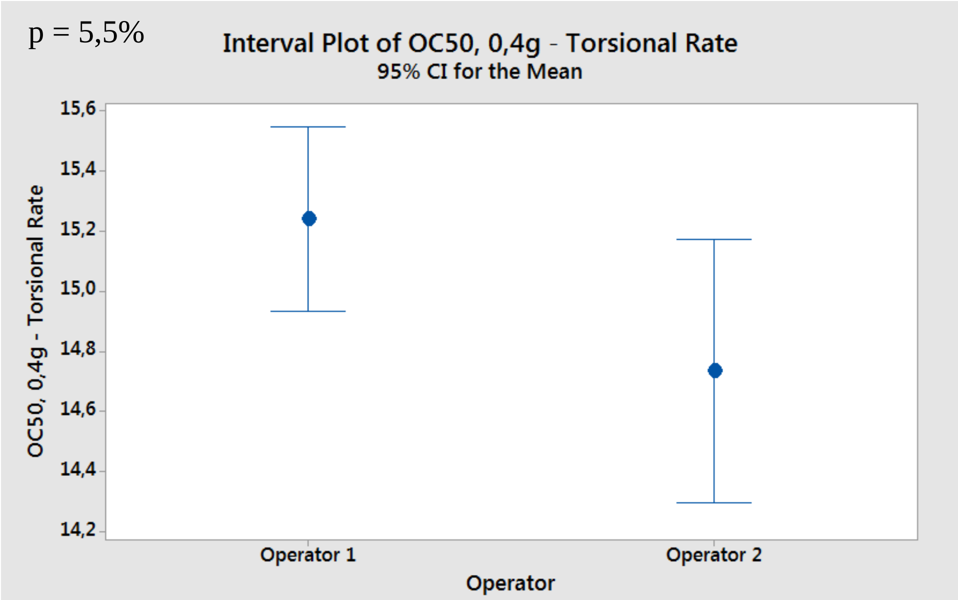

Figure 4.2 Interval plot of Torsional Rate [Nm/100°], grouped by operator.

A difference between operators can be seen in figure 4.2. The separation between operators is in this case significant and cannot be overlooked. This is hard to explain due to the fact that the test is amongst the tests with the least operator effort. The inrun path is GPS controlled and the input value during the test is the same each time. The only parameter that has an obvious difference between test sets is the homing of the robot. It is obtained in the study that the operators perform the zero-steer homing in different ways, which would describe the difference between operators. In the test note protocol (Appendix B), a certain trend can be seen in terms of zero-steer error. In test sets "Selected 1-3", all zero-steer errors were observed to be around 4 [deg] to the right. In test set "Selected 4" the zero-steer error was noted to be slightly to the left. This implies that the homing has a certain influence on the data results, which was unexpected.

The data needed to be further investigated to determine whether the tire conditions influence the data. The correlation can be seen in figure 4.3.

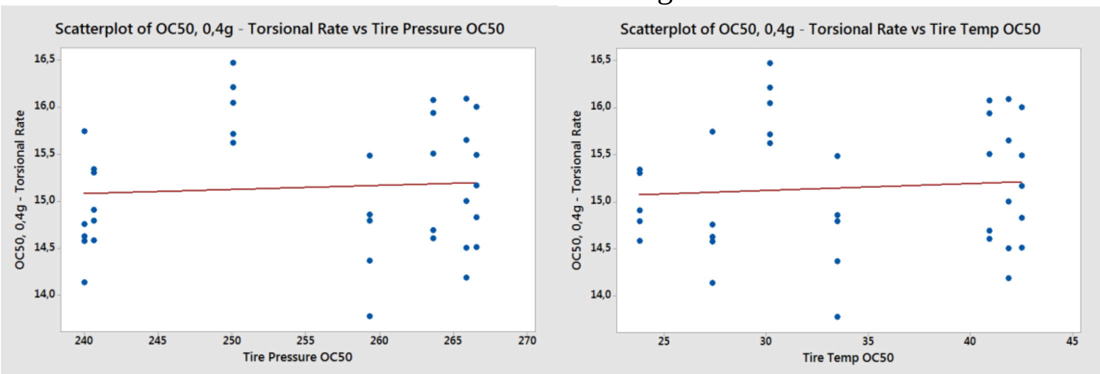

Figure 4.3 Scatterplot with linear regression between Torsional Rate [Nm/100°] and tire condition [kPa] and [°C].

The slope order of magnitude is 1/100, which implies that the tire condition does not affect the results.

A regression between torsional rate and wind velocity was created and can be seen in figure 4.4.

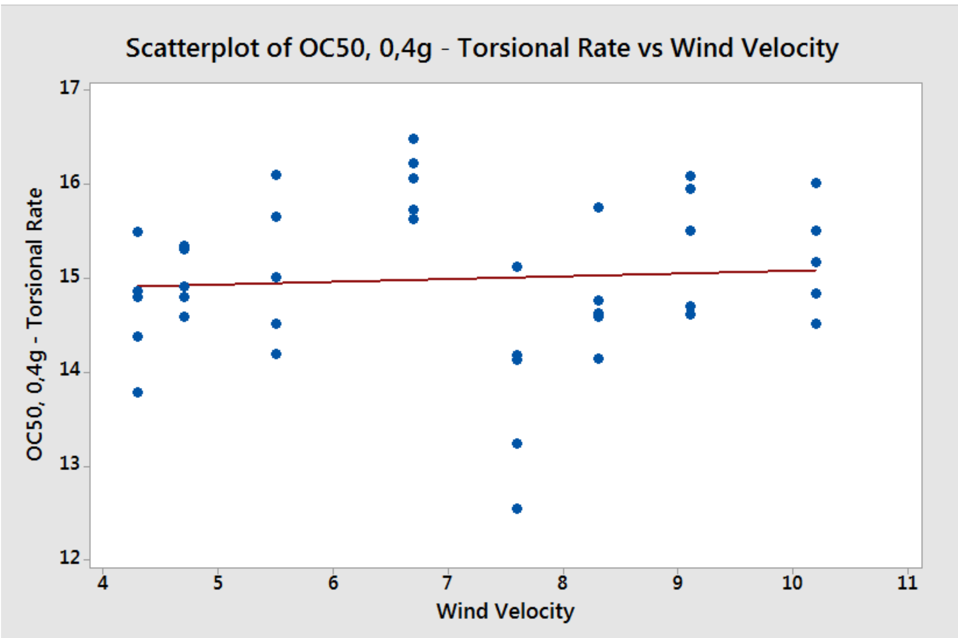

Figure 4.4 Scatterplot with linear regression between Torsional Rate [Nm/100°] and wind velocity [m/s].

With the slope's order of magnitude less than 1/1000, the conclusion is that the torsional rate is not affected by the wind velocity.

4.2 On Centre, 80 km/h

The data grouped by test set number can be seen in figure 4.5.

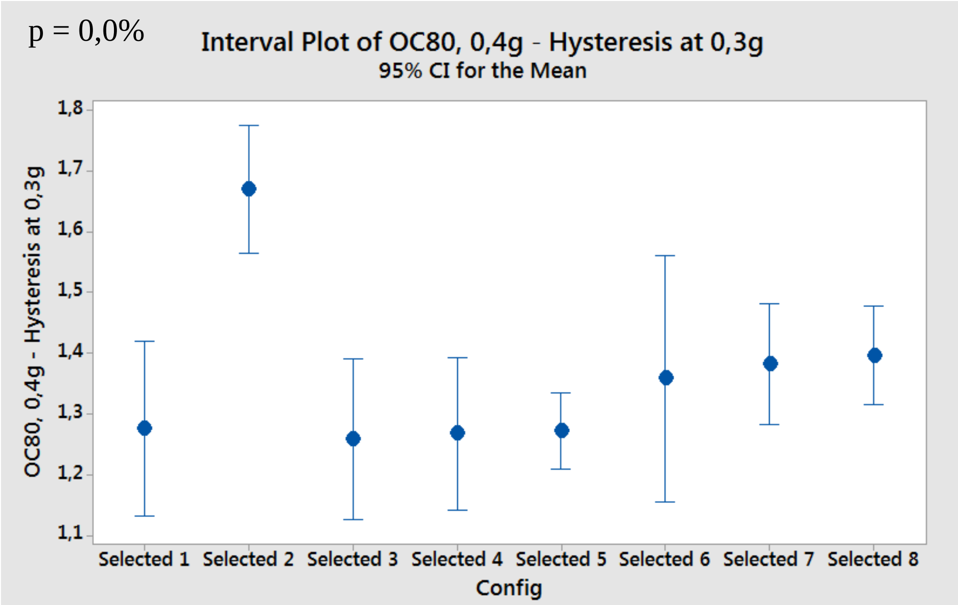

Figure 4.5 Hysteresis at 0.3g [Nm], grouped by test set number.

The results are pretty constant in terms of mean values but vary a bit in spread magnitude. Test set "Selection 2" is abnormal without any obvious explanation. All runs in "Selection 2" follows the same trend in SWT as the other runs, but peaks at 1 [Nm] higher. No explanation has been found.

The data was grouped by operator, which can be seen in figure 4.6.

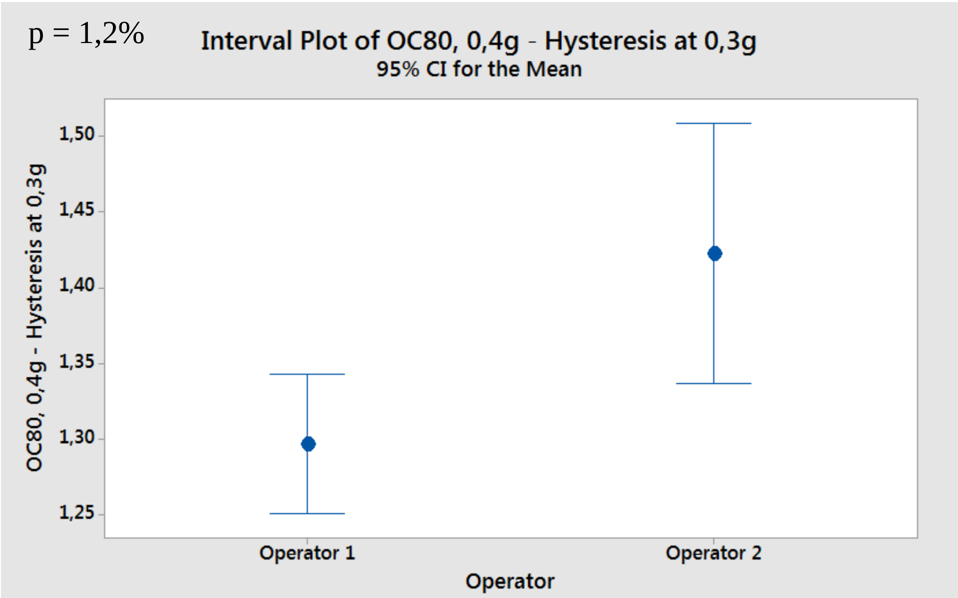

Figure 4.6 Interval plot of Hysteresis [Nm], grouped by operator.

The difference between operators is big, but how much does the abnormal result in "Selected 2" affect the difference? The data was grouped by operator and "Selected 2" was excluded and can be seen in figure 4.7.

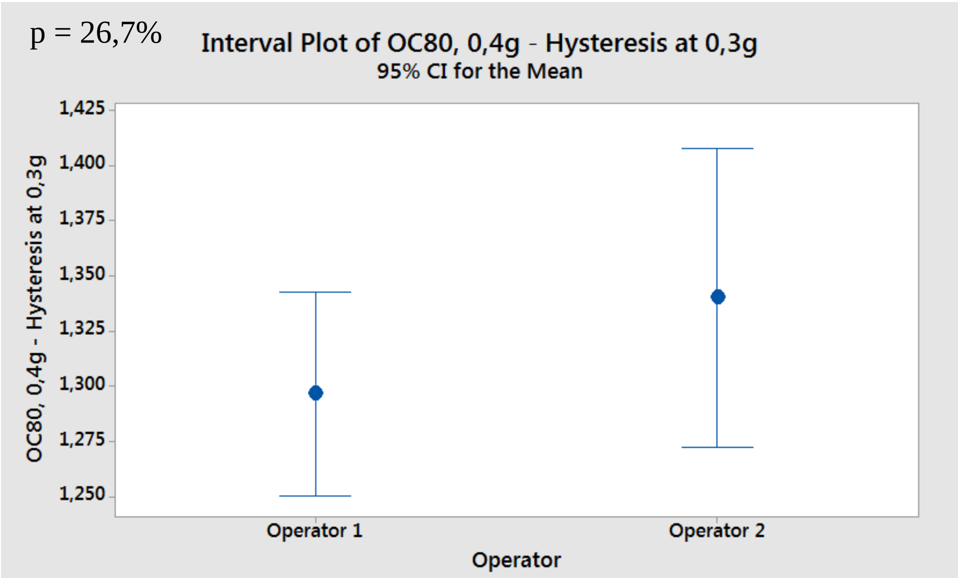

Figure 4.7 Interval plot of Hysteresis [Nm], grouped by operator, "Selected 2" excluded.

The difference between the mean values is only 0,03 Nm when "Selected 2" is excluded. This explains the big difference between operators due to the abnormal "Selected 2".

Further investigation in correlation between tire condition and hysteresis can be seen in figure 4.8.

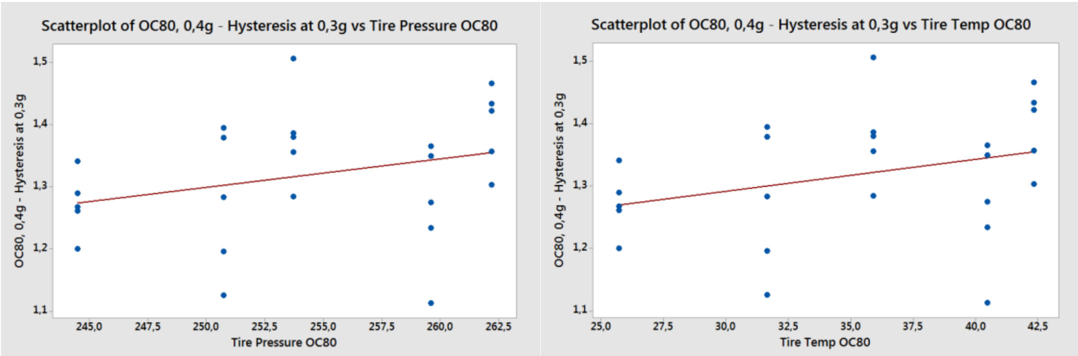

Figure 4.8 Scatterplot with linear regression between Hysteresis [Nm] and tire condition [kPa] and [˚C].

At first sight, a slope can be seen in the linear regression. But the slope is small and much smaller in magnitude than the spread window, which implies that the regression is random rather than affecting.

A regression between Hysteresis at Ay 0.3g and wind velocity was created and can be seen in figure 4.9.

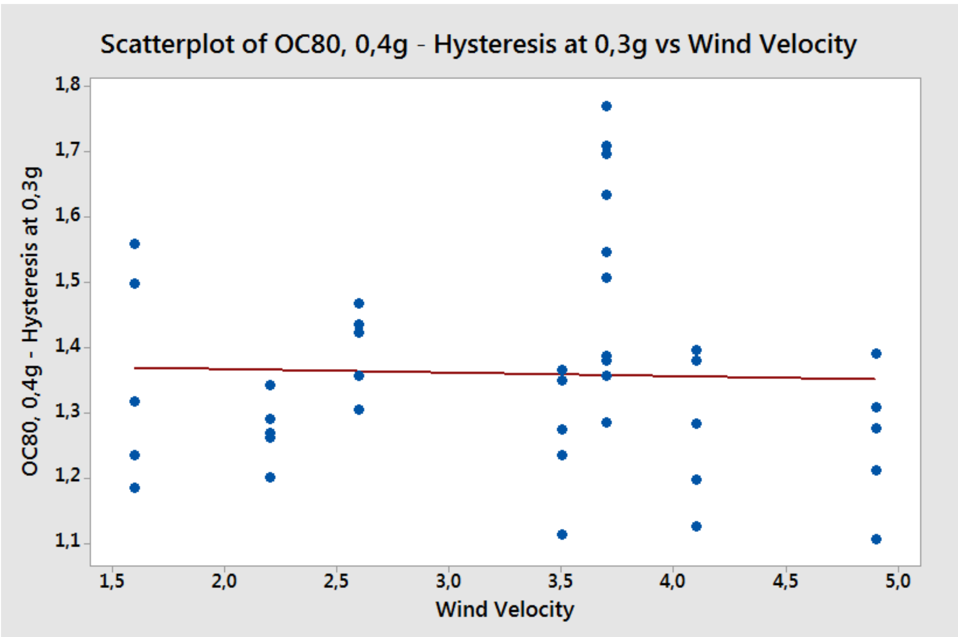

Figure 4.9 Scatterplot with linear regression between Hysteresis at 0,3g [Nm] and wind velocity [m/s].

With the slope's order of magnitude approximately equal to 0, the hysteresis is not affected by the wind velocity.

4.3 HSS – High G Swept Steer

Starting by dividing the data by test set number, figure 4.10 and figure 4.11 were achieved.

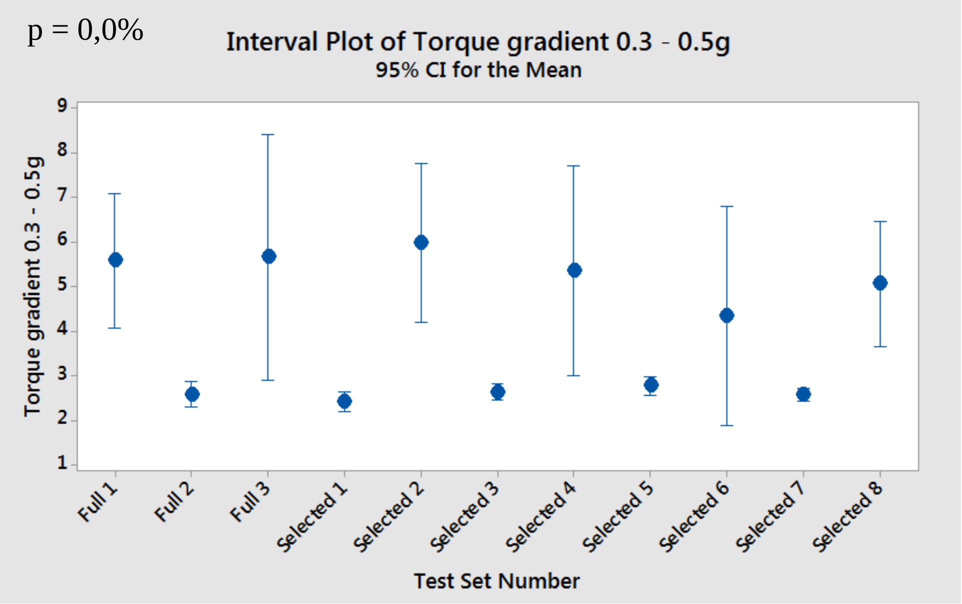

Figure 4.10 Interval Plot of Torque gradient from 0.3g to 0.5g [Nm/(m/s²)], grouped by test set number.

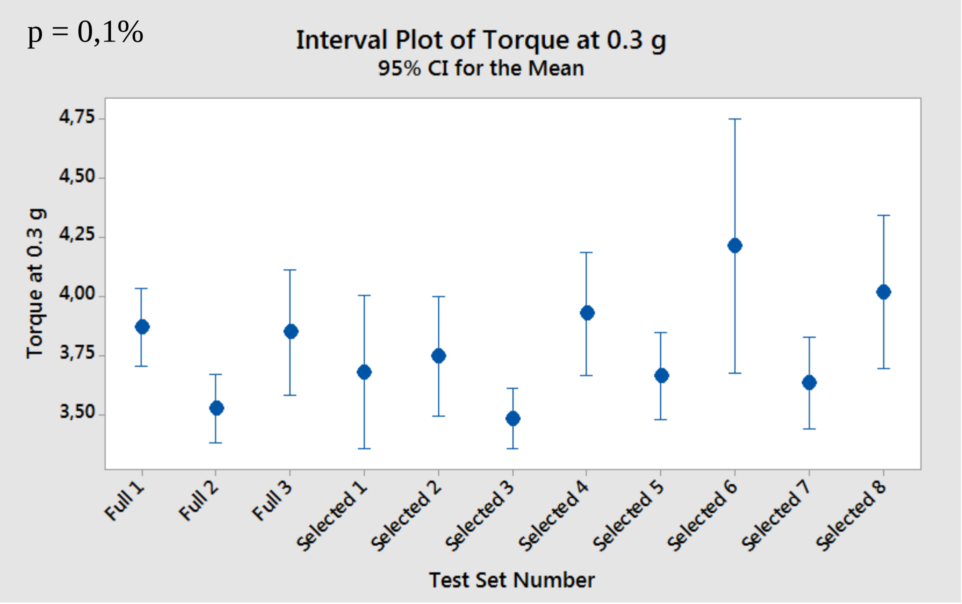

Figure 4.11 Interval Plot of Torque at 0.3g [Nm], grouped by test set number.

The spread between test set numbers was larger than expected, but a certain trend can easily be spotted with every other set higher than the other. The cause of this trend can be seen in figure 4.12 and figure 4.13, when divided by operator

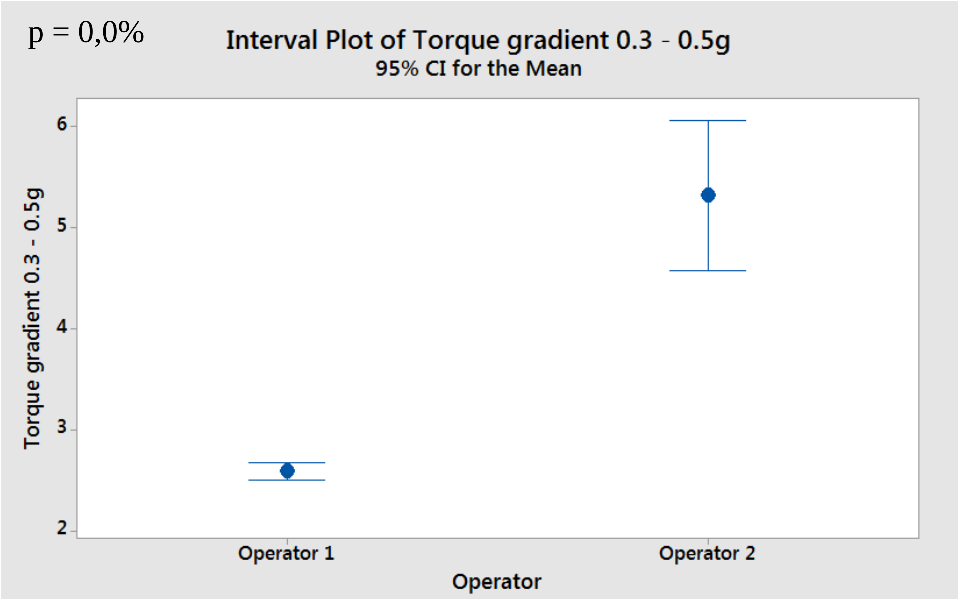

Figure 4.12 Interval Plot of Torque gradient from 0.3g to 0.5g [Nm/(m/s²)], grouped by operator.

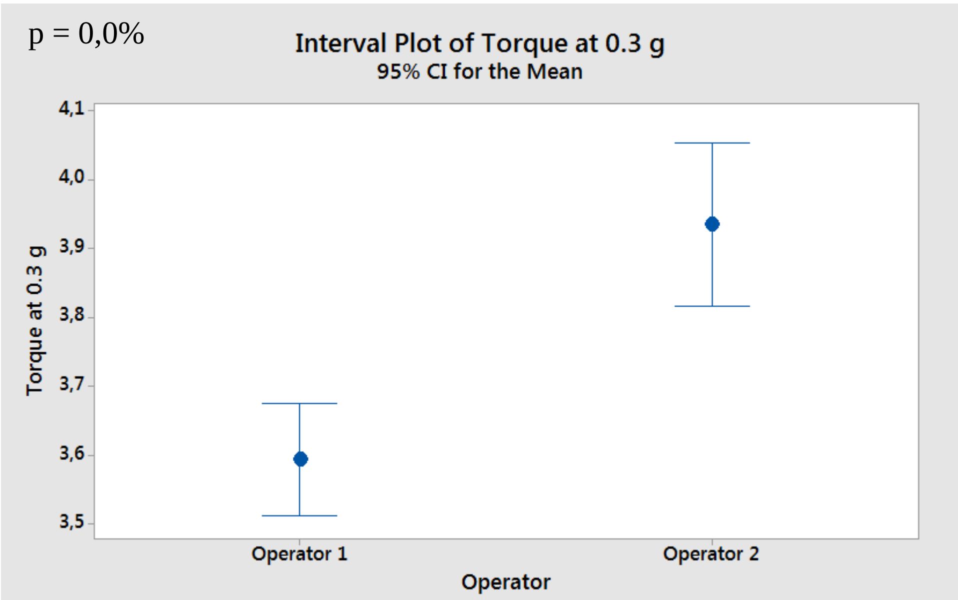

Figure 4.13 Interval Plot of Torque at 0.3g [Nm], grouped by operator.

It is clear that operator 2 achieves both 100% higher values and a bigger spread, which theoretically should not be the case. This indicates that operator 2 is doing something wrong when performing the test.

To analyse the difference between the operators, respective SWT vs. Ay plot was put next to each other and can be seen in figure 4.14.

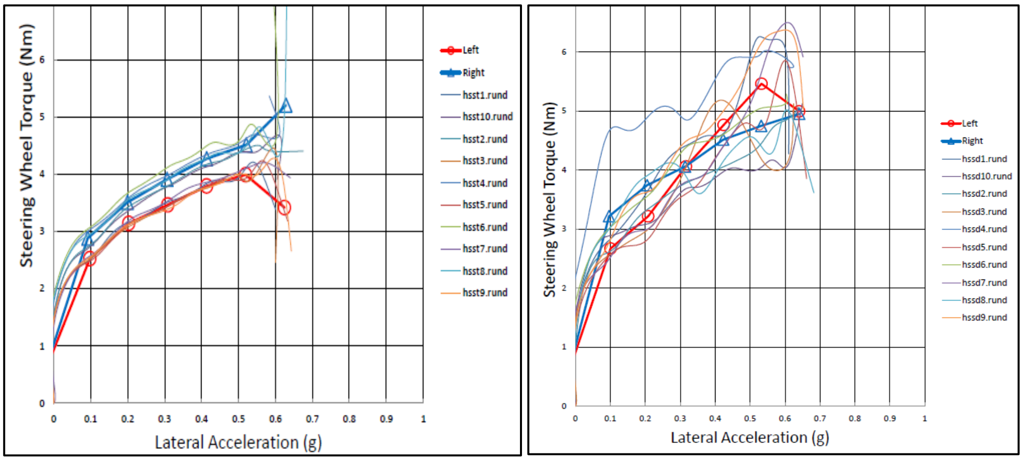

Figure 4.14 SWT vs. Ay plot, Operator 1 to the left, Operator 2 to the right.

There is a big noise in operator 2's results. After an analysis in how operator 2 performs the HSS test, it was observed that the operator accidently touches the steering robot which the force sensors are mounted to. To verify this conclusion, another HSS test was performed by operator 2 in the end of the project. In this test the operator was focusing on not to touch any equipment. In figure 4.15, an old SWT vs. Ay plot was compared to a new one.

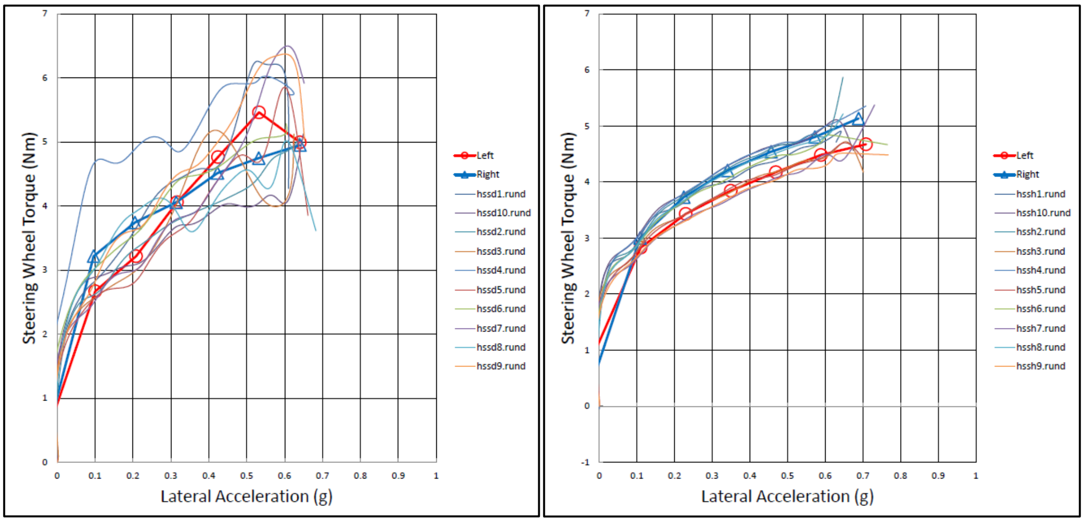

Figure 4.15 SWT vs. Ay plot, Old test to the left, New test to the right.

This verifies the conclusion of operator 2 touching the steering robot.

Because of the inconsistency, Operator 2's data results were excluded in further analysis of HSS. The analysis dividing the data into test set number can be seen in figure 4.16 and figure 4.17.

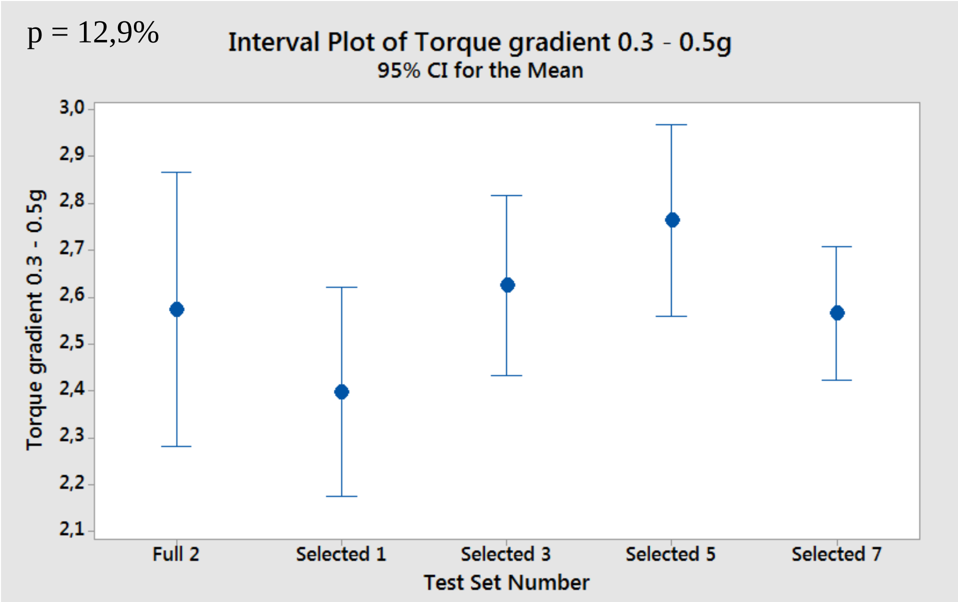

Figure 4.16 Interval Plot of Torque gradient from 0.3g to 0.5g [Nm/(m/s²)], grouped by test set number, Operator 2 excluded.

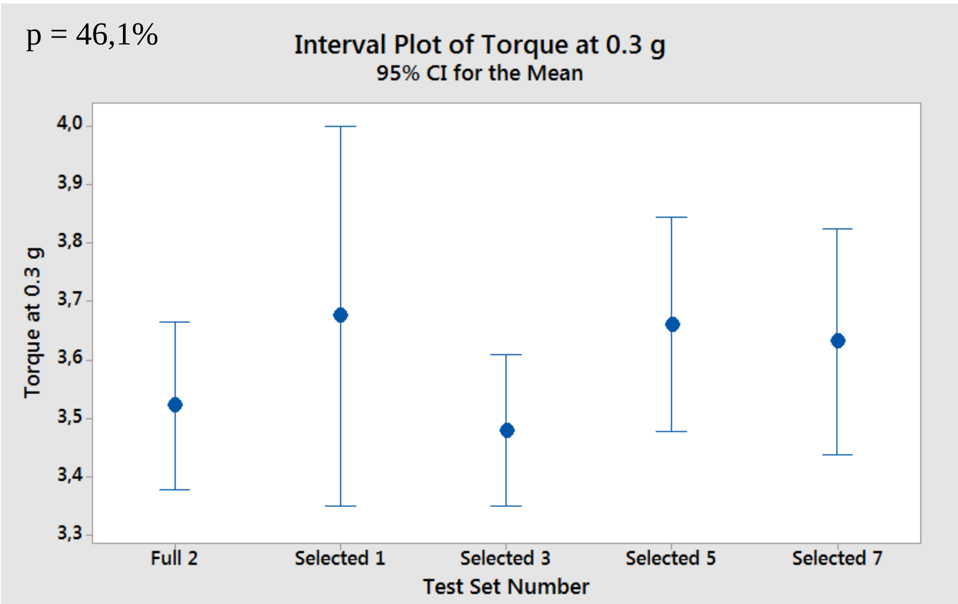

Figure 4.17 Interval Plot of Torque at 0.3g [Nm], grouped by test set number Operator 2 excluded.

The spread is by far smaller, it is only a few percent with operator 2 excluded. Somehow the direction and magnitude of the spread varies between test sets.

To determine the correlation between data and external factors, a linear regression was fitted to the data. The regression model between data and tire conditions can be seen in figure 4.18 and figure 4.19.

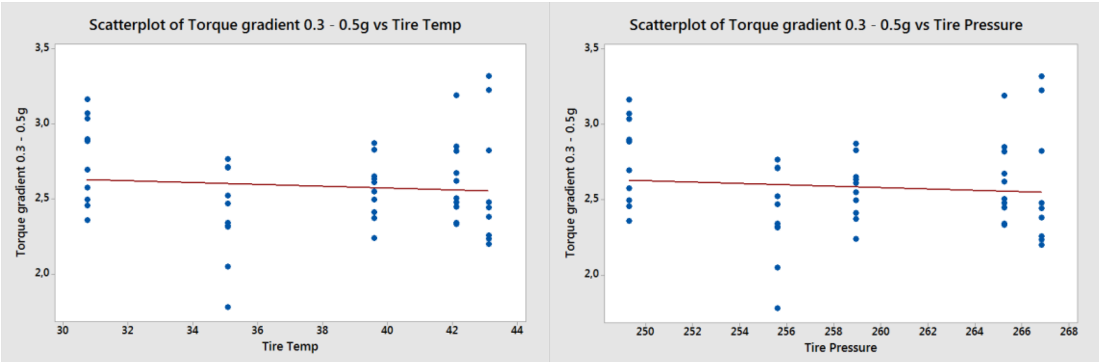

Figure 4.18 Scatterplot with linear regression between Torque gradient [Nm/(m/s²)] and tire condition [°C] and [kPa].

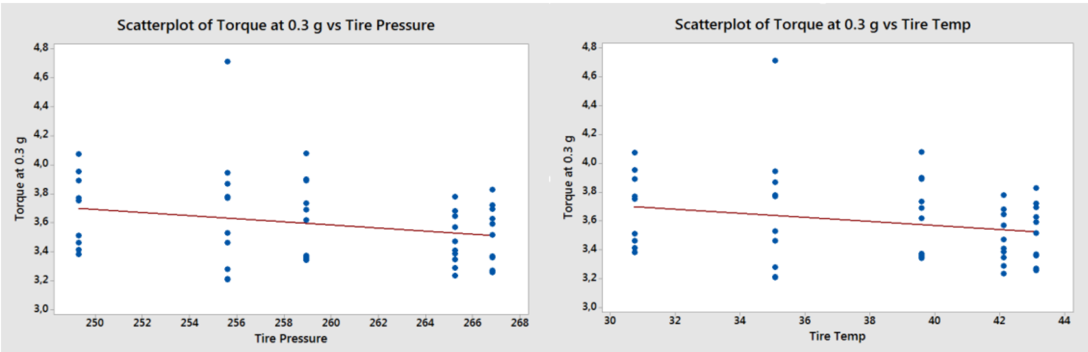

Figure 4.19 Scatterplot with linear regression between torque at 0.3g [Nm] and tire condition [kPa] and [°C].

With the slope order of magnitude 1/1000, none of the HSS data results is considered to be affected by the tire condition.

Both torque gradient and torque at 0.3g were divided into turning direction and can be seen in figure 4.20.

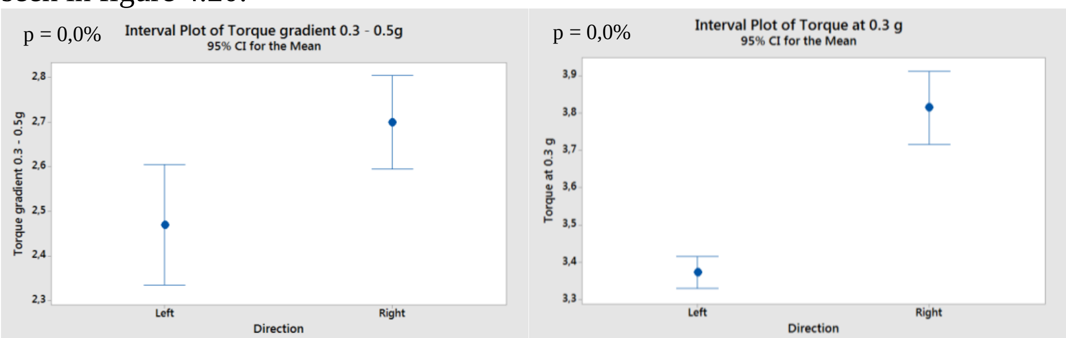

Figure 4.20 HSS metrics [Nm/(m/s²)] and [Nm] grouped by turning direction.

There is a difference between left and right sequences. The spread window does not differ much between left and right in the torque gradient, but in torque at 0.3g the window is much smaller in left turn than right.

A regression between HSS data results and wind velocity was created and can be seen in figure 4.21.

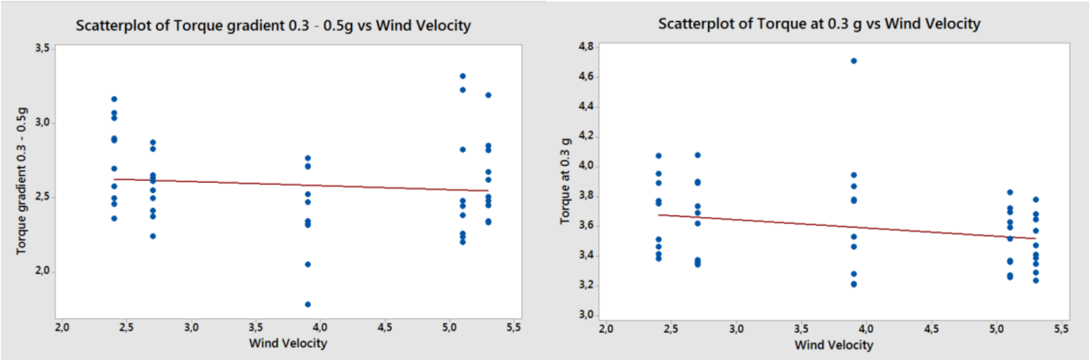

Figure 4.21 Scatterplot with linear regression between HSS metrics, [Nm/(m/s²)] and [Nm], and wind velocity [m/s].

With slopes order of magnitude less than 1/100, the conclusion is that neither of the metrics of interest in HSS is affected by the wind velocity.

4.4 Sine with Dwell Steer

Ay at maximum yaw gain data grouped by test set number can be seen in figure 4.22.

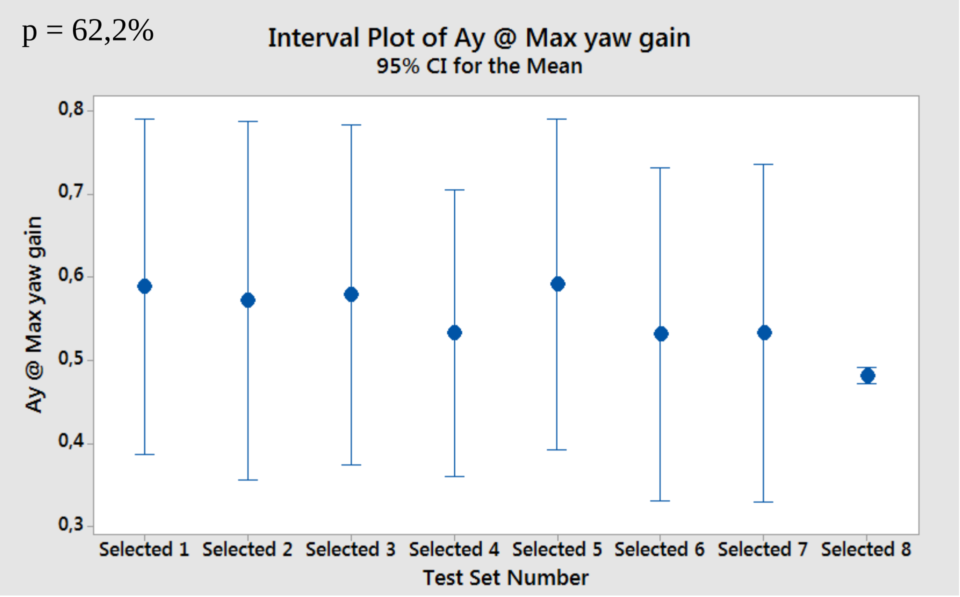

Figure 4.22 Interval plot of Ay at maximum yaw gain [m/s²], grouped by test set number.

Both direction and magnitude of the Ay at maximum yaw gain data spread is rather constant in all test sets and the data obtains a large p-value, which implies that the test is good. The data grouped by operator can be seen in figure 4.23.

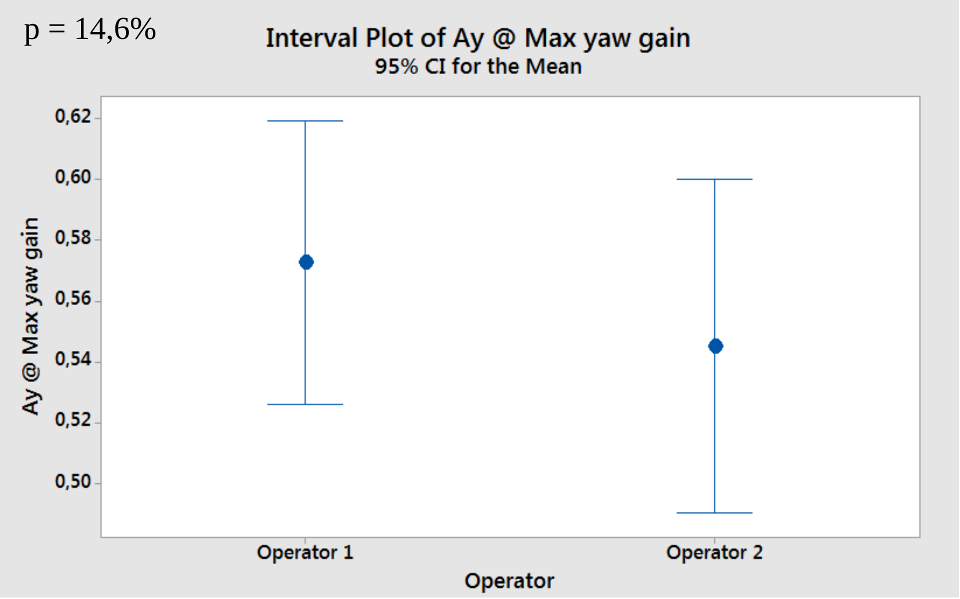

Figure 4.23 Interval plot of Ay at maximum yaw gain [m/s²], grouped by operator.

The difference between operator is relatively small, with only a few percent difference in mean value and spread window.

A linear regression was fitted between the results and tire condition and can be seen in figure 4.24.

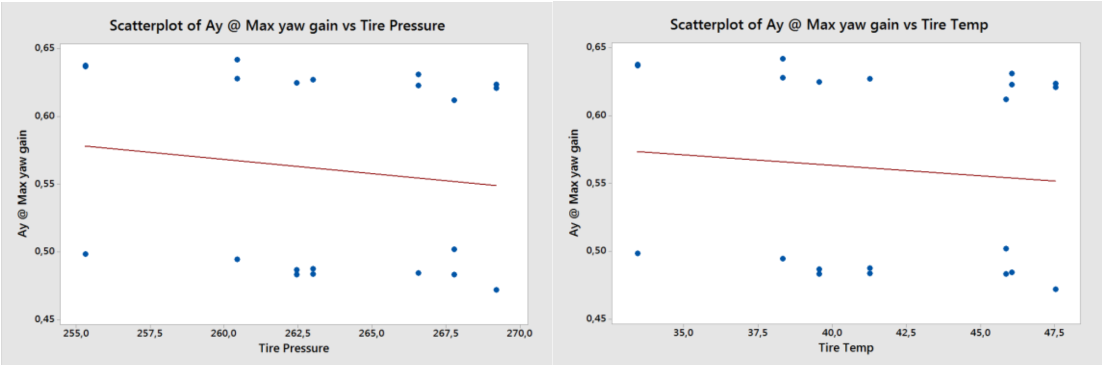

Figure 4.24 Scatter plot with regression between Ay at maximum yaw gain [m/s²] and tire condition [kPa] and [˚C].

The slope's magnitude is small, which implies that ther is no correlation between Ay at maximum Yaw gain and tire condition.

A regression between Ay at maximum Yaw gain and wind velocity was created and can be seen in figure 4.25.

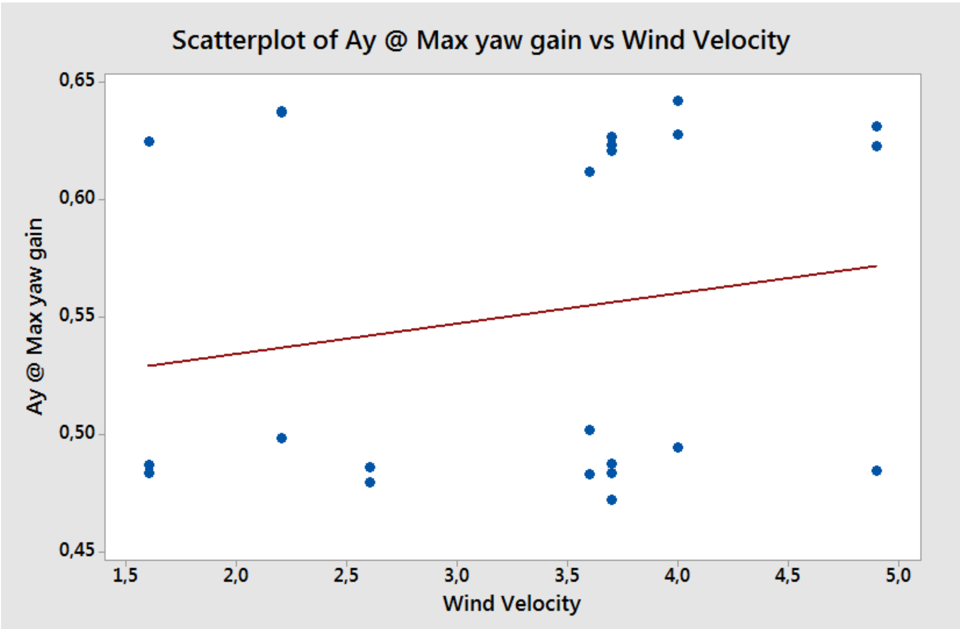

Figure 4.25 Scatterplot with linear regression between Ay at max Yaw gain [m/s²] and wind velocity [m/s].

With the slope's order of magnitude less than 1/100, the conclusion is that the hysteresis is not affected by the wind velocity.

The Ay to SWA time lag data was grouped by test set number and can be seen in figure 4.26.

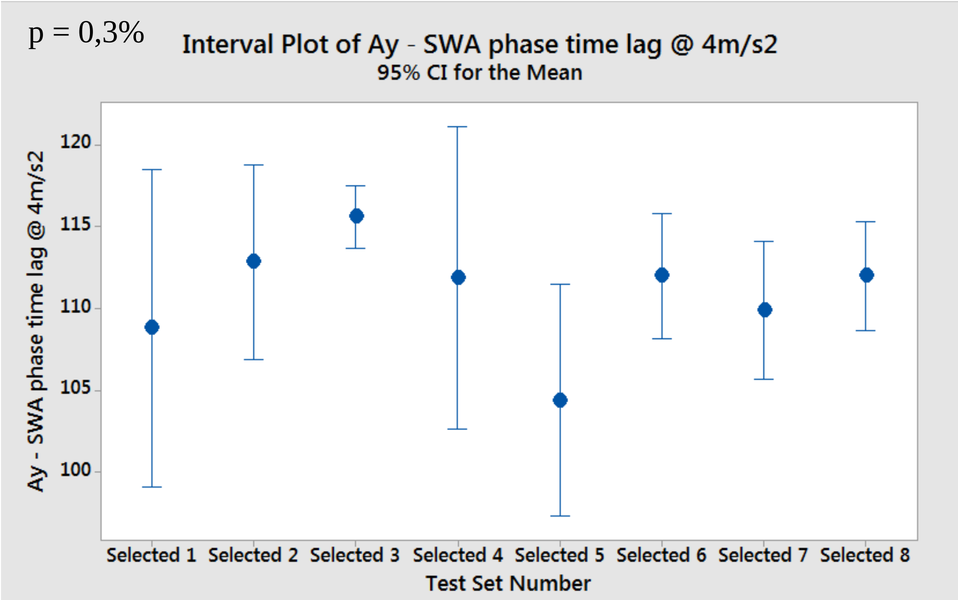

Figure 4.26 Interval plot of Ay to SWA time lag [ms], grouped by test set number.

In the Ay to SWA time lag data, direction and magnitude of the data spread differs a lot between test sets. The data grouped by operator can be seen in figure 4.27.

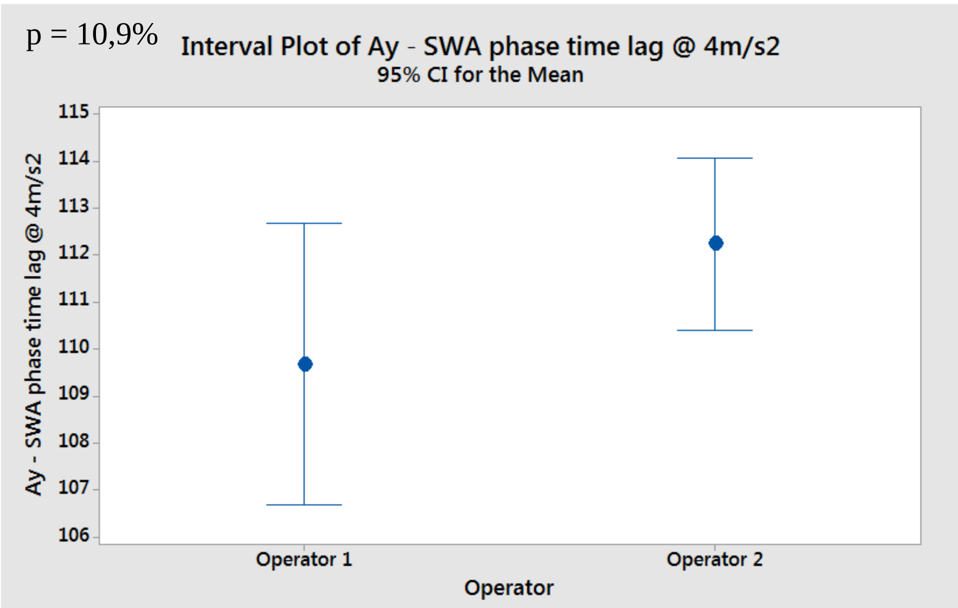

Figure 4.27 Interval plot of Ay to SWA time lag [ms], grouped by operator.

In this case, an obvious difference between operators can be seen. It is possible that the homing of the zero-steer can have some effect to this as well. But, even though the time lag is a metric depending on the SWA, the SWA amplitude is determined at an Ay of 0.4g of each run instead of a certain value for each run. This implies that the zero-steer should not have that big of influence.

The data was fitted with a regression to tire condition, seen in figure 4.28.

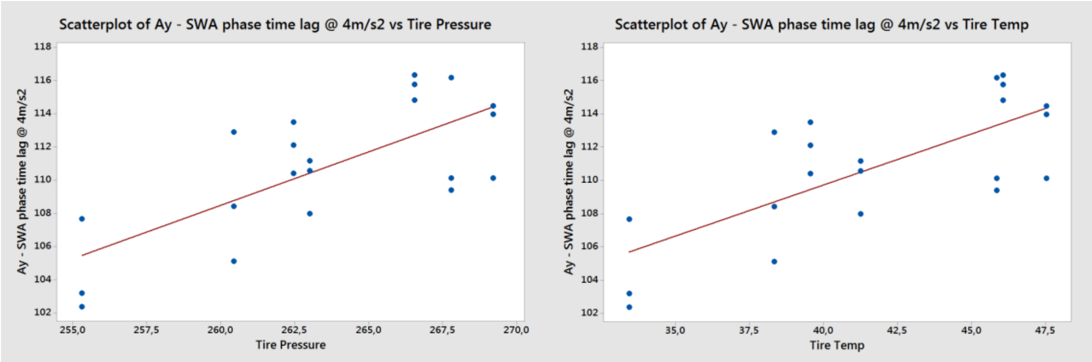

Figure 4.28 Scatter plot with regression between Ay to SWA time lag [ms] and tire condition [kPa] and [˚C].

The regression in figure 4.28, shows that there is a certain correlation with tire conditions. Both tire pressure and tire temperature are affecting the results of Ay to SWA time lag. Increased tire pressure and tire temperature causes increased time lag.

To check if this also can be the reason of the difference between operators, the scatterplot was separated between operators and can be seen in figure 4.29.

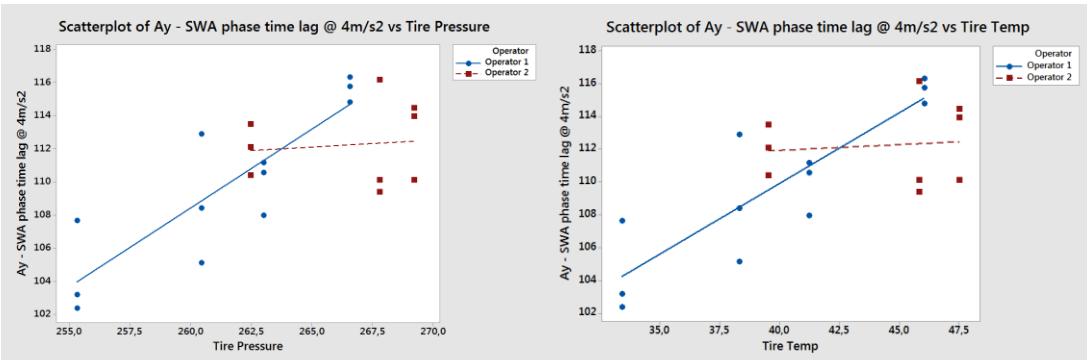

Figure 4.29 Scatter plot with regression between Ay to SWA time lag [ms] and tire condition [kPa] and [˚C], grouped by operator.

Because operator 1 perform the tests first, the operator holds some test results with colder tire than operator 2. This explains the difference between operator in figure 4.27.

A regression between Ay to SWA time lag and wind velocity was created and can be seen in figure 4.30.

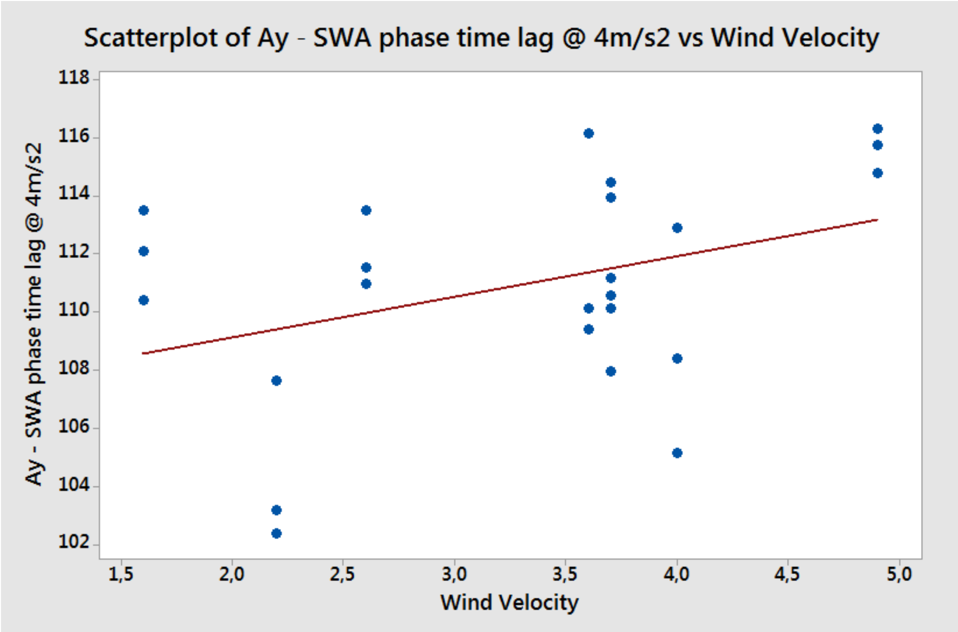

Figure 4.30 Scatterplot with linear regression between Ay to SWA time lag [ms] and wind velocity [m/s].

With a slope magnitude of 1.4, the regression model implies that the wind velocity is affecting the Ay to SWA time lag. But the spread window is big and it is uncertain if there is a correlation or a random effect. A bigger sample is needed to verify this.

The Ay to Yaw time lag data was grouped by test set number and can be seen in figure 4.31.

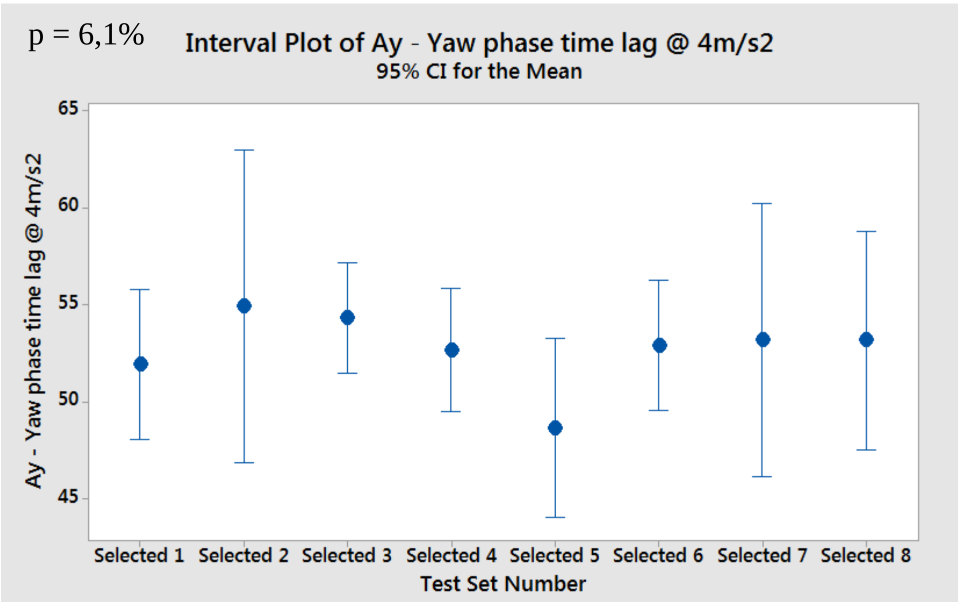

Figure 4.31 Interval plot of Ay to Yaw time lag [ms], grouped by test set number.

The Ay to Yaw time lag data differs a lot between test sets in both direction and magnitude of the data spread. The data grouped by operator can be seen in figure 4.32.

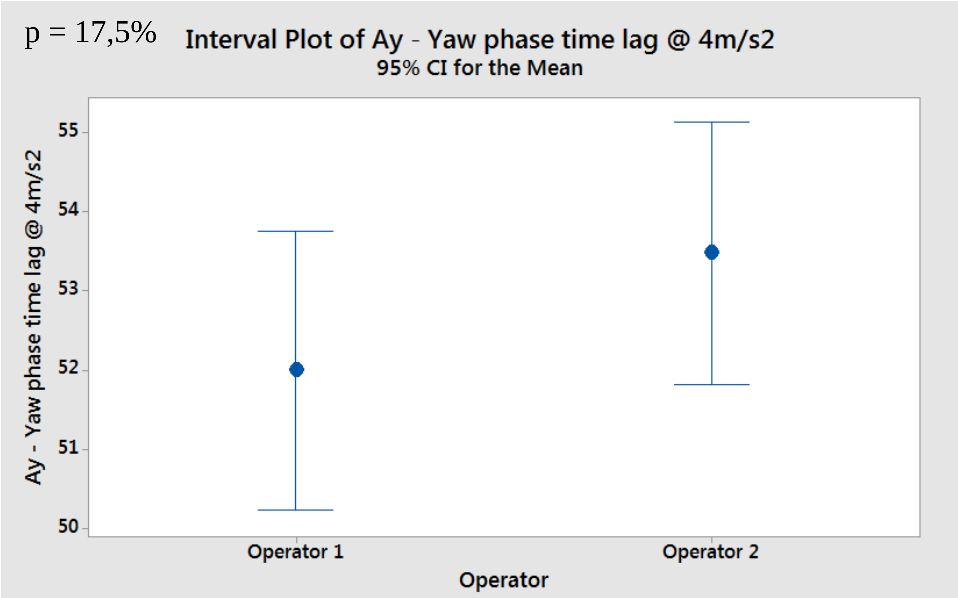

Figure 4.32 Interval plot of Ay to Yaw time lag [ms], grouped by operator.

With similar tendency as in the Ay to SWA time lag, but with smaller spread, it is possible that the reason of difference between operators is the same as previously. Starting with the data without dividing into operator groups and fit a regression between Ay to Yaw time lag and tire condition, figure 4.33 was obtained.

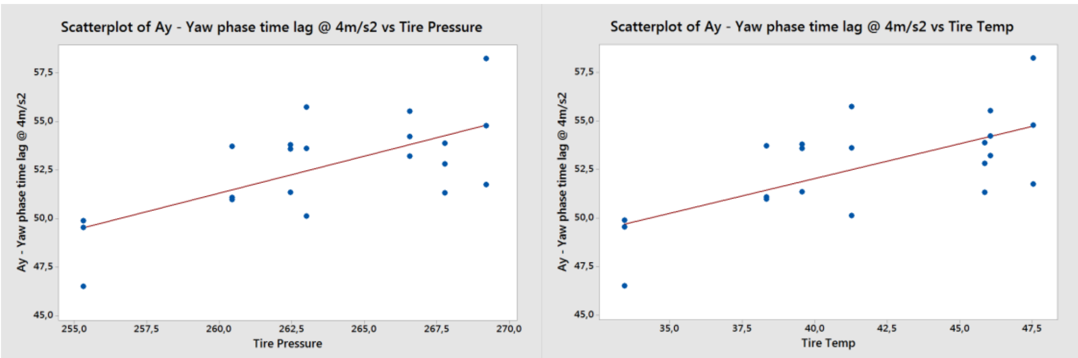

Figure 4.33 Scatter plot with regression between Ay to Yaw time lag [ms] and tire condition [kPa] and [˚C].

As well as Ay-SWA ime lag, increased tire pressure and tire temperature results in an increased time lag in Ay to Yaw.

The scatterplots, grouped by operator can be seen in figure 4.34.

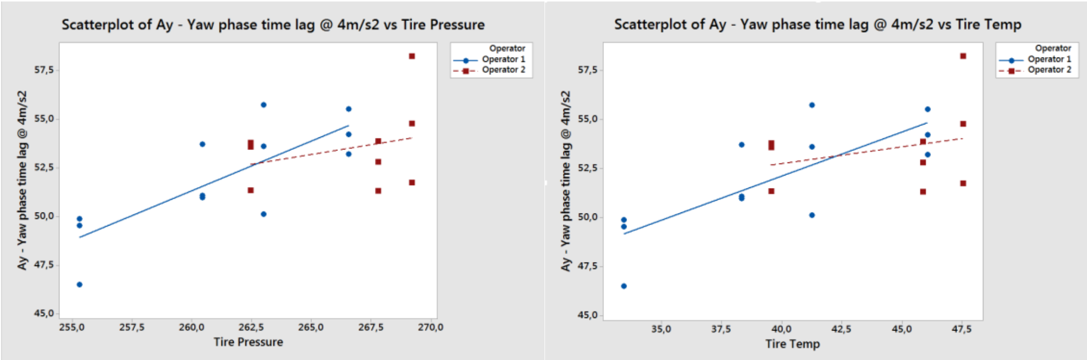

Figure 4.34 Scatter plot with regression between Ay to Yaw time lag [ms] and tire condition [kPa] and [˚C], grouped by operator.

Once again, there is a certain explanation that the different tire condition also causes the difference in time lag between operators.

A regression between Ay to Yaw time lag and wind velocity was created and can be seen in figure 4.35.

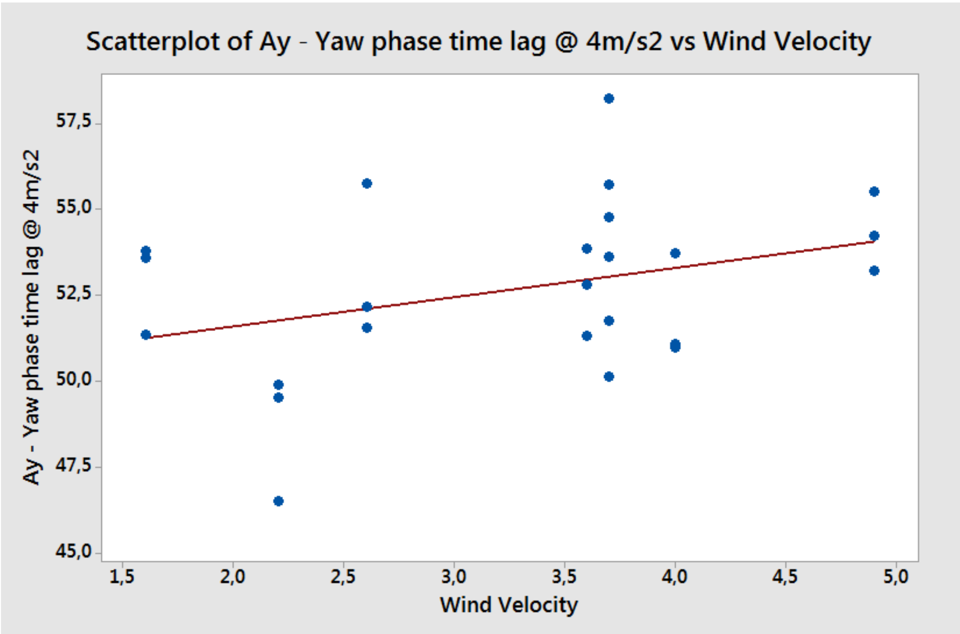

Figure 4.35 Scatterplot with linear regression between Ay to Yaw time lag [ms] and wind velocity [m/s].

With a slope magnitude of 0.86, the regression implies that there could be a correlation between the Ay to Yaw time lag and wind velocity. But once again, a bigger sample size is needed to be able to verify because of the spread window.

5 Conclusions and Future work

The conclusion of the study is that there is not only one certain factor causing spread in the results. There are multiple factors of significance in different tests. It is not possible to determine a certain factor that should be taken into account for the entire test series.

The only metrics affected by external factors were the time lag metrics. The time lag is measured in [ms], which means a small change causes big numeric difference. All scatterplots hold big spread windows from the respective linear regression model, bigger test sample would be a good way to verify the tendencies discovered in this study.

The difference between operators is in general not that big, if difference between tire conditions and the incorrect performed HSS tests are taken into account. There are other factors affecting results more, such as the zero-steer homing and the tire conditions. The operator needs to be experienced and have knowledge about how to avoid affecting any equipment. The operator also needs to have a solid method when homing the steering robot, because the homing is a crucial part when performing the test. It is hard to verify if the homing is acceptable. In development purposes, the homing could possibly be performed by letting the robot identify the zero-steer by following a straight GPS path, instead of letting the operator carry the responsabillity of the calibration.

Another thing that was noticed when studying the SDNA test series, was that in the HSS test the minimum target of Ay was set to 0.5g. The torque gradient is measured between 0.3g and 0.5g, so with runs ended too soon the gradient was in some cases negative. Because of this, the minimum limit was changed to 0.6g to eliminate this issue, and a recommendation is to consider doing this in the test code as well.

In further investigation to verify the noticed tendencies of difference in results depending on the zero-steer homing, a suggestion would be to:

- Compare test result data when having manipulated homing, for instance 5 degrees to the right and 5 degrees to the left.
- Comparing test result data between a homing performed manually by operator and a homing performed with GPS path.

Regarding how the tire conditions are affecting the results, further investigations are recommended:

- Evaluate if there are more tests affected by the tire condition other than the time lag metrics
- Evaluate if it is possible to achieve more constant tire conditions between test sets.

Another interesting analysis would be the surface of the brake and handling area at Hällered. For instance, comparing test results between Hällered Proving Ground and Asta Zero, which is another test facility located next to Hällered with a better brake and handling area. Both to evaluate the difference between camber offsets and surface smoothness. It has during the study been noticed that there are some bumps at Hällered's brake and handling area and there are also some patches with different tarmac that could be causing spread in results depending on where the path is throughout each test.

The investigation achieved several good and important conclusions in what is tending to cause the spread in the results, but there is a lot more to investigate. There are close to infinite possibilities in further investigation on the subject, in everything from finding more external factors to analysing the post-processing methods.

The most important advice in further investigation is to not analyse too many factors at a time. It is better to specify what to analyse and narrow down the limitations to be able to dig deeper into each analysis.

6 References

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Appendix A

Test selection sheet.

Some metrics is missing the p-value due to the fact that the p-value require more than one measurement value.

Metric	Test	Relative Spread	p-value
SWA at 0.05 g	Low G Swept Steer	31%	60,9%
Avg On Center Yaw Gain	On Centre 0.2 g	26%	-
Sensitivity Ratio	Low G Swept Steer	36%	11,6%
Yaw/SWA 45 deg Phase Lag Time	Frequency Response	3%	-
TRollR/AyCG Gradient @ 1 Hz	Frequency Response	7%	-
SWA at 1.3 Nm	Low G Swept Steer	44%	35,8%
Torsional Rate	Low G Swept Steer	70%	9%
Torque At 0 g	On Centre 0.2 g	40%	-
Off Center Yaw Gain	On Centre 0.4 g	26%	-
Understeer Gradient	High G Swept Steer	16%	-
Yaw Linearity	On Centre 0.4 g	8%	-
Total Roll Gradient	High G Swept Steer	22%	-
Torsional Rate	Low G swept Steer	41%	19,6%
Torque gradient 0.3 - 0.5g	High G Swept Steer	123%	1,7%
Deadband in degrees	On Centre 0.4 g	11%	-
Hysteresis At 0.3 g	On Centre 0.4 g	58%	-
Torque at 0.3 g	High G Swept Steer	57%	1,6%
Avg On Center Yaw Gain	On Centre 0.4 g	7%	-
Torsional Rate	On Centre 0.4 g	104%	-
Torque Near Center Average	Parking Effort	23%	-
Torque Just Off Center Average	Parking Effort	77%	0,2%
Overall steering sensitivity	On Centre 0.2g	21%	-
Overall steering sensitivity	On Centre 0.2g	9%	-
Lat acc. @ Max yaw gain	Sine With Dwell	150%	-
Yaw gain@max lat acc/max yaw gain	Sine With Dwell	0%	-
Yaw - SWA phase time lag @ 4m/s2	Sine With Dwell	22%	-
Ay - SWA phase time lag @ 4m/s2	Sine With Dwell	85%	-
Ay - Yaw phase time lag @ 4m/s2	Sine With Dwell	111%	-

Appendix B

Test Note Protocol

Notes taken during testing.

Test	LF		LR		RR		RF		Ground	Day/Date	Friday 18-04-20
	T	P	T	P	T	P	T	P	T	cfg	E
OC	29,7	-	24,1	-	23,8	-	26,6	-	20,1	Test	Full Serie #1
LSS	31,8	256,3	36,0	250,7	29,8	252,9	34,9	259,1	-	Operator	PE: 1
HSS	38,7	267,3	36,3	260,6	36,0	261,9	41,6	270,6	24,8		OC: 2
End	36,4	263,7	33,9	257,7	35,9	259,7	40,6	266,7	-		LSS: 2
Lunch											HSS: 1
FR80	31,9	255,1	29,8	247,3	32,9	254,3	35,4	263,2	29,9		FR: 2
FR120	38,3	261,4	36,5	255,8	36,7	257,1	42,7	264,6	28,7		SWD: 1
SWD	37,9	265,7	36,1	259,8	38,4	260,5	43,3	268,2	29,6	Start Time	09:45
End	39,6	266,9	37,8	260,6	40,2	262,1	44,7	271,1	29,9	Lunch Break	11:30-12:30
										End Time	13:40
										Weather	-
										Comments:	Different operators.

Test	LF		LR		RR		RF		Ground	Day/Date	Monday 18-05-07
	T	P	T	P	T	P	T	P	T	cfg	F
Lunch										Test	Full Serie #2
OC50	33,5	253,6	30,4	247,6	30,7	247,5	36,3	258,0	33,3	Operator	1
LSS80	39,2	259,4	38,3	255,0	37,1	255,5	42,1	263,8	35,5	Start Time	10:30
LSS120	41,2	263,1	37,8	260,0	38,8	260,5	44,4	269,3	34,8	Lunch Break	11:45-13:00
HSS	43,0	267,0	40,8	263,7	42,2	264,1	46,4	272,5	34,7	End Time	15:30
FR80	42,7	265,8	40,8	261,3	42,4	263,4	45,2	270,6	36,2	Weather	-
FR120	41,9	263,5	39,3	259,7	40,7	259,8	44,3	267,3	36,1	Comments:	Reperformed from OC.
SWD	44,1	264,9	39,6	260,4	40,2	259,6	44,2	270,1	36,2		
End	-	-	-	-	-	-	-	-	-		

Test	LF		LR		RR		RF		Ground	Day/Date	Tuesday 18-05-08
	T	P	T	P	T	P	T	P	T	cfg	G
OC	-	-	-	-	-	-	-	-	-	Test	Full Serie #3
LSS80	36,8	255,0	34,5	253,3	35,3	253,7	42,9	260,2	20,4	Operator	2
LSS120	37,2	259,0	36,1	256,7	36,1	255,9	38,6	263,2	21,3	Start Time	08:21
HSS	40,2	264,1	37,3	259,4	37,1	259,2	41,8	269,4	24,8	End Time	11:15
FR80	38,6	262,1	37,2	258,8	38,4	259,6	38,7	267,3	26,4	Weather	-
FR120	39,3	258,9	37,8	256,1	38,2	256,1	39,6	262,6	28,1	Comments:	-
SWD	40,8	260,5	39,0	257,1	38,8	257,0	40,5	264,8	29,2		
End	-	-	-	-	-	-	-	-	-		

Test	LF		LR		RR		RF		Ground	Day/Date	Wednesday 18-05-09
	T	P	T	P	T	P	T	P	T	cfg	H+I+J
OC50	27,9	-	27,1	-	27,8	-	26,7	-	21,9	Test	Selected #1
OC80	31,7	250,4	31,7	249,6	30,3	250,0	32,9	252,9	22,7	Operator	1
HSS	35,4	256,2	35,0	254,2	34,2	253,9	35,7	258,1	24,0	Start Time	09:30
SWD	37,2	260,3	38,6	258,4	36,9	258,5	40,6	264,5	26,6	End Time	10:35 (+11:30-12:00)
End	38,8	264,5	36,6	258,0	36,0	259,0	41,5	268,8	27,2	Weather	Sunny
										Comments:	Homing 4,1 deg wrong.
											(HE - "Blåser möe idag")

Test	LF		LR		RR		RF		Ground	Day/Date	Wednesday 18-05-09
	T	P	T	P	T	P	T	P	T	cfg	K+L+M
OC50	42,1	266,5	36,1	258,2	38,8	259,4	46,6	270,4	36,4	Test	Selected #2
OC80	-	-	-	-	-	-	-	-	-	Operator	2
HSS	45,7	267,0	42,4	262,0	44,2	262,6	47,4	270,6	38,0	Start Time	13:15
SWD	47,8	270,5	45,2	265,8	47,2	266,1	49,9	274,4	37,8	End Time	14:30
End	40,8	266,9	39,6	262,1	40,6	264,2	49,0	273,0	37,8	Weather	Strålande sol
										Comments:	OC80 Run 2: Different line.
											HSS Run 3: Tuched the wheel.
											Forgot to fill up gas.

Test	LF		LR		RR		RF		Ground	Day/Date	Wednesday 18-05-09
	T	P	T	P	T	P	T	P	T	cfg	N+O+P
OC50	40,8	266,9	39,6	262,1	40,6	264,2	49,0	273,0	37,8	Test	Selected #3
OC80	-	-	-	-	-	-	-	-	-	Operator	1
HSS	42,8	266,1	39,7	263,5	40,8	262,2	45,1	269,2	37,4	Start Time	15:00
SWD	46,8	267,3	43,4	264,7	42,6	263,4	51,4	270,8	37,7	End Time	16:00
End	43,2	271,7	42,2	267,5	45,3	267,2	51,2	279,0	37,2	Weather	Strålande sol
										Comments:	OC80 Run 4: Different line.

Test	LF		LR		RR		RF		Ground	Day/Date	Wednesday 18-05-09
	T	P	T	P	T	P	T	P	T	cfg	Q+R+S
OC50	-	-	-	-	-	-	-	-	-	Test	Selected #4
OC80	43,1	262,2	40,4	258,1	37,4	254,7	40,9	263,4	34,7	Operator	2
HSS	43,1	263,9	41,3	260,6	39,8	257,5	44,3	266,9	33,8	Start Time	17:15
SWD	46,1	268,4	43,9	265,3	44,7	263,9	48,7	273,5	33,1	End Time	18:10
End	46,9	271,6	45,1	266,9	43,0	265,2	48,6	276,7	34,3	Weather	Sunny. Little wet.
										Comments:	Homing from other direction.
											Ground temp damped 26,7 deg.

Test	LF		LR		RR		RF		Ground	Day/Date	Friday 18-05-11
	T	P	T	P	T	P	T	P	T	cfg	T+U+V
OC50	24,4	240,3	23,5	240,4	23,2	240,2	24,1	241,7	20,6	Test	Selected #5
OC80	26,2	243,7	25,4	243,5	24,7	243,5	26,6	247,3	20,1	Operator	1
HSS	30,7	248,6	27,8	247,4	28,6	247,5	35,9	253,7	20,9	Start Time	09:45
SWD	34,3	255,0	32,2	252,7	32,3	252,7	34,9	260,8	21,3	End Time	10:45
End	34,1	261,5	30,6	253,4	32,2	255,0	37,0	267,4	21,7	Weather	Cloudy, around 15 deg
										Comments:	Forgot to fill upp gas. (3/4 left)
											New Homing

Test	LF		LR		RR		RF		Ground	Day/Date	Friday 18-05-11
	T	P	T	P	T	P	T	P	T	cfg	W+X+Y
OC50	34,1	261,5	30,6	253,4	32,2	255,0	37,0	267,4	21,7	Test	Selected #6
OC80	-	-	-	-	-	-	-	-	-	Operator	2
HSS	38,0	261,4	37,9	255,6	37,9	257,5	40,6	267,8	25,7	Start Time	10:55
SWD	40,3	263,0	36,8	258,3	38,7	259,8	42,4	268,7	29,2	End Time	11:56
End	39,6	265,1	36,8	258,7	38,8	262,3	43,8	273,6	31,6	Weather	Cloudy, sunny in the end.
										Comments:	Homing from prev. test.

Test	LF		LR		RR		RF		Ground	Day/Date	Friday 18-05-11
	T	P	T	P	T	P	T	P	T	cfg	A+B+C
OC50	33,0	250,8	28,1	244,6	29,2	246,9	30,4	258,0	32,9	Test	Selected #7
OC80	37,2	254,3	32,3	249,0	33,3	251,1	40,8	260,5	34,2	Operator	1
HSS	41,1	259,2	36,2	254,0	37,3	255,9	43,7	266,7	36,1	Start Time	13:15
SWD	42,7	264,0	39,4	258,1	38,7	259,9	44,2	270,0	33,3	End Time	14:20
End	40,7	266,0	37,0	259,6	40,9	262,3	48,8	275,5	35,5	Weather	partly cloudy ,around 20 deg
										Comments:	New Homing.

Test	LF		LR		RR		RF		Ground	Day/Date	Friday 18-05-11
	T	P	T	P	T	P	T	P	T	cfg	D+E+F
OC50	40,7	266,0	37,0	259,6	40,9	262,3	48,8	275,5	35,5	Test	Selected #8
OC80	43,2	263,7	41,3	256,3	40,3	258,2	44,5	270,5	37,8	Operator	2
HSS	44,8	264,4	41,9	258,3	40,8	259,8	46,1	271,3	37,3	Start Time	14:30
SWD	-	-	-	-	-	-	-	-	-	End Time	15:38
End	40,1	268,1	37,5	261,6	37,8	264,6	41,6	276,6	37,8	Weather	Partly cloudy, around 25 deg
										Comments:	Homing from prev. test.

Appendix C

Weather Log

Weather log data provided by HPG Trafic control.

DataRWIS.Date	Config	Luft temp	Yttemp	Vindriktning	Vindriktning 10	Vindhastighet 30	Vindhastighet max
Apr 20 2018 9:30AM	Full 1	15.1	10.5	188	186	4.5	7.1
Apr 20 2018 10:00AM	Full 1	16.1	10.9	193	198	4.6	8.1
Apr 20 2018 10:30AM	Full 1	17	11.4	191	194	5.3	8.4
Apr 20 2018 11:00AM	Full 1	18.2	11.9	178	191	5.3	7.9
Apr 20 2018 11:30AM	Full 1	18.9	12.3	193	188	5.2	8.9
Apr 20 2018 12:30PM	Full 1	20.6	13.4	204	202	5.2	9.5
Apr 20 2018 1:00PM	Full 1	21.4	14	195	201	5.9	11.4
Apr 20 2018 1:30PM	Full 1	21.6	14.6	195	205	6.1	10.4
Apr 20 2018 2:00PM	Full 1	22.3	15.3	189	194	6	10.8
May 7 2018 10:30AM	Full 2	18.3	13.3	217	212	4.5	7.7
May 7 2018 11:00AM	Full 2	19	12.9	172	198	3.8	7.6
May 7 2018 11:30AM	Full 2	20.1	13.1	211	200	5	8.7
May 7 2018 12:00PM	Full 2	20.2	13.4	217	201	5.4	8.8
May 7 2018 1:00PM	Full 2	21.4	14	197	205	5.1	9.9
May 7 2018 1:30PM	Full 2	21.9	14.3	200	217	4.5	10.4
May 7 2018 2:00PM	Full 2	22.2	14.8	188	201	5.4	9.2
May 7 2018 2:30PM	Full 2	22.1	15.1	244	222	5	9.4
May 7 2018 3:00PM	Full 2	23.1	15.3	228	222	4.1	10.4
May 7 2018 3:30PM	Full 2	22.6	15.5	215	214	4.4	8.9
May 8 2018 8:00AM	Full 3	16.1	10	171	226	1.8	3.8
May 8 2018 8:30AM	Full 3	17	10.6	175	226	2.2	4.5
May 8 2018 9:00AM	Full 3	18	11.4	164	226	2.7	5.3
May 8 2018 9:30AM	Full 3	19.5	15.1	168	226	2.6	5
May 8 2018 10:00AM	Full 3	19.8	15.8	198	226	4	6.7
May 8 2018 10:30AM	Full 3	20.3	14.9	183	226	3.7	6.6
May 8 2018 11:00AM	Full 3	21.1	14.6	153	226	3.9	7.6
May 8 2018 11:30AM	Full 3	22	14.6	146	226	3.7	7.6
May 9 2018 9:30AM	Selected 1	18.3	16.2	171	226	3.3	7.7
May 9 2018 10:00AM	Selected 1	19.4	17.2	150	226	3.9	10.1
May 9 2018 11:30AM	Selected 1	21.9	15.6	125	226	4.1	8.1
May 9 2018 12:00PM	Selected 1	22.5	15.9	149	226	4	8.3
May 9 2018 1:00PM	Selected 2	23.9	16.4	180	226	4.1	8.3
May 9 2018 1:30PM	Selected 2	24.5	16.7	155	226	3.7	8.4
May 9 2018 2:00PM	Selected 2	24.5	17	128	226	3.7	9.1
May 9 2018 2:30PM	Selected 2	24.8	17.5	173	226	4.4	11
May 9 2018 3:00PM	Selected 3	24.8	17.9	184	226	5.7	10.8
May 9 2018 3:30PM	Selected 3	25.3	18.4	139	226	5.3	11.5
May 9 2018 4:00PM	Selected 3	25.1	18.6	142	226	4.9	10.2
May 9 2018 5:00PM	Selected 4	25.3	18.8	179	226	4.1	8.4
May 9 2018 5:30PM	Selected 4	24.6	18.8	146	226	4.4	9.5
May 9 2018 6:00PM	Selected 4	24.8	18.6	138	226	3.5	7.6
May 9 2018 6:30PM	Selected 4	24.2	18.4	140	226	3.6	8.8
May 11 2018 9:30AM	Selected 5	13.3	15.8	219	226	2.1	4.7
May 11 2018 10:00AM	Selected 5	12.8	15.8	265	226	2.4	5
May 11 2018 10:30AM	Selected 5	13.1	16	191	226	2.2	4.7
May 11 2018 11:00AM	Selected 5-6	15.4	16.4	202	226	1.9	3.6
May 11 2018 11:30AM	Selected 6	16.4	16.4	254	226	1.9	4.3
May 11 2018 12:00PM	Selected 6	17.6	16.1	128	226	1.6	4.3
May 11 2018 1:00PM	Selected 7	17.9	17.4	229	226	2.7	5.2
May 11 2018 1:30PM	Selected 7	19	18.3	211	226	2.7	7
May 11 2018 2:00PM	Selected 7	18.7	18.8	210	226	3.7	6.7
May 11 2018 2:30PM	Selected 7-8	19.8	18.6	311	226	2.4	5.5
May 11 2018 3:00PM	Selected 8	20.2	18.3	213	226	2.3	5.5
May 11 2018 3:30PM	Selected 8	19.3	18.3	308	226	2.6	5.5
May 11 2018 4:00PM	Selected 8	19.4	18.3	299	226	2.6	7.8