Steer-by-wire variable ratio

A study about speed & position dependent ratios

Bachelor`s thesis in Electrical engineering

FILIP BRINK

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DEMARTEMNT OF
MECHANICS AND MARITIME SCIENCES

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
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Cover: The test vehicle

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Abstract

This thesis aims to explore the field of Steer-By-Wire and rationalise how a steering ratio can vary depending on the speed of the vehicle and the position of the steering wheel while providing a good combination of mobility and stability. The thesis also investigates how a phase delay, which occurs between the input and output signal, affects the vehicles steerability. To answer these questions, a test bench and a test vehicle had to be set up where various experiment could be done.

The tests done on the bench and in the vehicle involved researching different function and how they affect the steerability. The experimental process is separated into two parts in this report, where one part is for a speed dependent solution and the other part is for a vehicle speed and angular position dependent ratio with a fixed end lock. It is worth noting that the speed dependent ratio is based on the speed of the vehicle, while a speed and position dependent ratio is based on the vehicle speed and the steering angle. There were two main speed dependent functions that were tested, one exponential and one quadratic. There was only one function tested for the speed and position dependent ratio. The testing process for these functions involved changing different parameter values until a satisfying result was obtained. When a parameter was changed, the system was tested on a designated testing track to observe how it affects the vehicle.

It was observed after conducting these tests that the factor with the biggest impact on the speed dependent function was the maximum steer ratio and when the minimum ratio was reached. However, the factor with the most impact for the vehicle speed and angular position dependent ratio was the position of the end lock. The result of these tests showed that a smaller end lock angle made the vehicle more unstable at higher speed but provided high mobility while a bigger end lock angle made the vehicle more stable, but a decrease of mobility was noted. It was observed that when a more direct ratio was used it increased the phase delay between the steering wheel and the power steering system. This happens because a more direct ratio creates a greater difference between the input signal, the requested value and output signal, the actual value, which causes problems with the rack regulator. This made the vehicle difficult to control around corners and the signal had magnitude losses when rapid movements were done with the steering wheel. However, this delay can be reduced significantly by replacing the hardware with a more precise power steering system that can handle more rapid movements.

Acknowledgments

Firstly, we would like to thank our supervisor Matthijs Klomp for all the guidance throughout the project, always being available to discuss ideas and how different solutions will affect vehicle performance. We are also grateful for all the resources we were given and the opportunity to hear about and test other exciting projects. We really appreciate the opportunity to work with Steer-by-wire at Volvo Cars. Secondly, we would like to thank Fredrik Bruzelius for providing good inputs along the way, not only when working on this project but also with the writing of this report.

Filip Brink & Linnea Wennberg, Gothenburg, May 2023

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1. INTRODUCTION

The car industry is an everchanging industry where each year new and exciting changes are implemented, and new models are released to the public to try and buy. Steering on the other hand has not been in the spotlight for a while. The electrification of cars has been more of a focus and therefore steering has not seen as much of a change except the change from hydraulic actuator to electrical ones. But ever since the focus shifted to autonomous vehicles, new and innovative ways to control the vehicle are developed, and Steer-By-Wire is one concept that is of interest. The concept of Steer-By-Wire (hereinafter SbW) is that there is no mechanical link between the steering wheel and the wheels. Instead, the steering column is replaced with an electrical connection between the steering wheel and the steering axle and electric motors at each end. The concept of SbW has been present in the vehicle industry since 2013 when Infiniti launched their first SbW vehicle to the market, the Q50 model [1]. The use of this technology in commercial cars was initially limited due to safety regulations. However, since the passing of the UN regulation No 79, it is now possible to include SbW into the production of vehicles with appropriate fault prevention measures [2].

Since then, Steer-By-Wire has improved, and new ways to utilize the technology have emerged. There are endless ways to use SbW in the vehicle industry. One use of SbW is the ability to have a variable ratio between the steering wheel and steering axle, depending on speed and driving situation. This may enable less turning of the steering wheel when driving at lower speeds and more turning when driving at high speeds. It may also increase the vehicle's mobility at a lower speed and minimizes the need to change the grip on the steering wheel, while also increasing stability when driving at high speeds. Car manufacturers have also used SbW to create a speed- and position variable ratio. This ratio is controlled by the speed combined with the relation between the steering wheel angle and the roadwheel angle. The speed dependent part of this solutions has a maximum and a minimum ratio which changes depending on the speed of the vehicle. However, the position dependent part, the relation between the steering wheel and the rack, changes depending on the angle of the steering wheel. This makes it possible to have a physical end lock, similarly to the stop provided by a steering column, instead of a simulated one. The question one might ask is, which one of these two variants provides the best stability for the vehicle and the most comfort for the driver?

1.1 Purpose

The purpose of this project is to create and evaluate different vehicle speed- and angular position variable ratios that variates in different driving scenarios. The intention is to create a ratio that varies depending on the vehicle speed and a ratio that varies with vehicle speed and angular position that has safe driving potential and feels comfortable to drive. To evaluate these implementations, tests on a test track will be made to evaluate the stability and mobility of the vehicle and from that different potential improvements can be presented. The term stability in this report serves as a reference of how sensitive the vehicle becomes at higher speeds and how difficult it is to keep the vehicle in a steady course. Mobility on the other hand is a reference of how effortlessly it is to manoeuvre the vehicle in different driving situations.

An analysis of the requested and actual steering output will also be presented in the report to see how fast the response is between the input and output signal. This is relevant since a delay between input and output creates an unfair outcome where the test subject may focus more on the delay rather than the variable ratio.

1.2 Questions

The following bullet points create a baseline for what will be covered in the report and what questions should be investigated.

- How to design a variable steering ratio dependent on vehicle speed and angular position?
- What is a good compromise between stability and mobility when it comes to a variable steering ratio?
- How much phase delay is there between the steering input and output and is it acceptable?

1.3 Limitations

This project is done during a period of six months at half speed. Because of the short time for the project there are some limitations, which are the following:

- The ratio between steering wheel and steering axle during reversing, it will be the same as driving forward. No adjustments will be done for reverse driving.
- How the feedback and torque is designed in the steering wheel will not be considered. The focus is only on the functionality of the steering ratio and how the driver experiences the feeling in the steering wheel in minor details.
- The focus for this thesis will only be on vehicle speed variable ratio and vehicle speed and angular position variable ratio.

2. BACKGROUND

The background section is describing how the steering ratio in cars without SbW function and the possibilities with SbW. This section also involves theory explaining relevant background to understand why some tests were made to come up with the final implementations.

One of the key functions of an automobile`s stability and safety is the steering system. Two commonly used steering systems in cars today are rack and pinion system which is the most common, and recirculating ball steering system. The rack and pinion system consist of a linear gear, the rack and a circular gear, the pinion. The pinion is placed on the top of the rack and attached to a shaft that is connected to the steering wheel. When the steering wheel moves, the shaft moves with it and this also moves the pinion. The wheel hub is connected to the steering arm which is connected to the tie rods that are placed after the rack. When the steering wheel rotates, the rack moves linearly and then the tie rod moves. The tie rod then causes the wheel to turn [3]. Figure 2.1 shows a steering linkage.

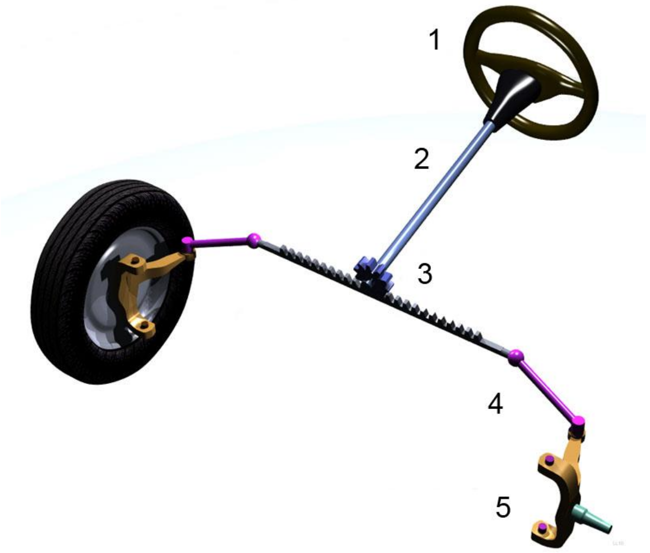

Figure 2.1. Simplified steering column. 1-steering wheel, 2-steering column, 3- rack and pinion, 4- steering arm, 5- steering knuckle. From [4] CC BY-SA.

The steering ratio in passenger cars is usually between 12:1 and 20:1 [5] and can be calculated with the following equations below [6].

$$a_y = \frac{v^2}{R} \qquad (1)$$

Where a_y is the lateral acceleration, v is vehicle speed and R is radius of curvature.

$$\dot{\psi} = \frac{v}{R} \qquad (2)$$

$\dot{\psi}$ is the yaw rate and by combining equation (1) and (2) it results in equation (3).

$$a_y = v \cdot \dot{\psi} \quad (3)$$

$$R_{WA} = \frac{L}{R} = \frac{L \cdot \dot{\psi}}{v} \qquad (4)$$

In equation (4), L is the length of the wheelbase and R_{WA} is the wheel angle of the tires.

$$n = \frac{S_{WA}}{R_{WA}} \qquad (5)$$

The steering ratio, n in cars can be calculated from steering wheel angle, S_{WA} divided by steering wheel angle of the tires, R_{WA}. To get this variable a slow speed cornering driving test can be performed. Where the vehicle drives at a minimum speed and the steering wheel is at end lock while collecting data.

When using SbW the possibilities for designing the steering ratio are infinite. SbW also has other advantages, for example placement of the steering wheel. Since the steering column is removed it makes it possible to freely move the steering wheel to any position in the vehicle. The steering wheel is no longer required to be on one side of the vehicle but instead it could be placed in the middle. More possible design choices can be made when designing the interior and the placement of mechanical parts in the vehicle [7]. This also makes it possible to have a different shape of the steering wheel, because with SbW the need for changing the grip position in low speed is no longer needed to the same extent. For example, an ellipse shaped steering wheel can be used which will give more leg space and better view of the road. When it comes to safety, SbW has the potential to have more safety functions and improved driver assistance. One source [7] also claims that SbW can decrease the impact risk on the driver in case of a car crash, because of the lack of a steering column.

There are endless ways to create and configure a steer-by-wire system. One big advantage with SbW is the possibility to personalize a configuration depending on what kind of driver the consumer is. However, the focus for this report is to analyse two different configurations. The first configuration is based on a speed dependent ratio, which increases or decreases depending on what speed the vehicle is traveling. It is worth noting that whenever ratio is mentioned for the vehicle speed dependent configuration, it acts as a factor that is multiplied with the position of the steering wheel. Whenever this factor is greater than one, it corresponds to a case with smaller steering wheel angles for the same road wheel angle. It is also worth noting that when a ratio of 1:1 is mentioned, it corresponds to the vehicle's standard ratio, which is 16:1 while if a ratio of 2:1 is mentioned, it corresponds to a vehicle ratio of 8:1. It continues with the same relation between the ratio created and the standard vehicle ratio. The resulting product of the multiplication becomes the required steering angle for the vehicle, which is then sent to the power steering system. However, this configuration changes the end lock depending on the speed if the intention is to use the whole road wheel angle span.

The second configuration is a ratio based on the vehicle speed and the steering wheel angle. This ratio is built after the fact that the maximum road wheel angle should always be reachable and have a fixed end lock. There are two variables that control the characteristics of the function. These variables are the speed of the vehicle and the angular position of the steering wheel. Both variables are multiplied with the position of the steering wheel and the sum of the multiplication becomes the required steering angle, and not a factor like the speed dependent solution. The goal with this configuration is to enable a fixed end lock, and not a variable one like the speed dependent configuration, as mentioned before. Toyota has created a similar solution where the steering wheel has a fixed end lock at 150° [8]. This fixed end lock acts as a starting point for this report's experiments.

The system used in report showed a notable delay between the steering wheel and the power steering system. This delay affects the feeling of the system since it affects the responsiveness of the vehicle. An investigation of the frequency response in form of a bode plot can be made to see how the system handles different frequencies. It is worth noting that this delay is only present since this is an early prototype and does not represent the final product. This can be presented in a bode magnitude plot and a bode phase plot. The phase plot shows the delay between the input and output signal, and the magnitude plot shows the difference in amplitude between the input and output.

3. EXPERIMENTAL SETUP

The experimental setup section describes the testbench, test vehicle used, the main equipment and the programs utilized for this project. The equipment used are an integrated servomotor, a VN8911 interface from Vector that also is used as a real time controller when testing, the software CANoe (also developed by Vector) and a DASH4PRO display from Race Technology. These components are used to create the Steer-By-Wire system for the testbench and test vehicle.

3.1 Testbench

Since the project required tests to be performed in real vehicles, a testbench was constructed where simulations could be performed before testing in a real environment. The testbench has a steering wheel with a servomotor connected to the steering wheel shaft, the VN8911 interface, two power supplies, a high voltage protection unit to protect the motor and a desktop computer where CANoe was installed.

The connection between the integrated motor, the power steering system and the VN8911 were done with split CAN cables. The servomotor and the power steering system was connected directly to the VN8911's channels. Not all values were measured since it required real sensors from the test vehicle. Instead, these where simulated. The two power supplies were connected to the motor on the steering wheel and the power steering system for the wheels. The voltage supplied to the motor was set to 14 V while the other one provided a voltage of approximately 30 V. The high voltage protection unit was placed between the 14 V power supply and the motor. Figure 3.1 shows the setup used.

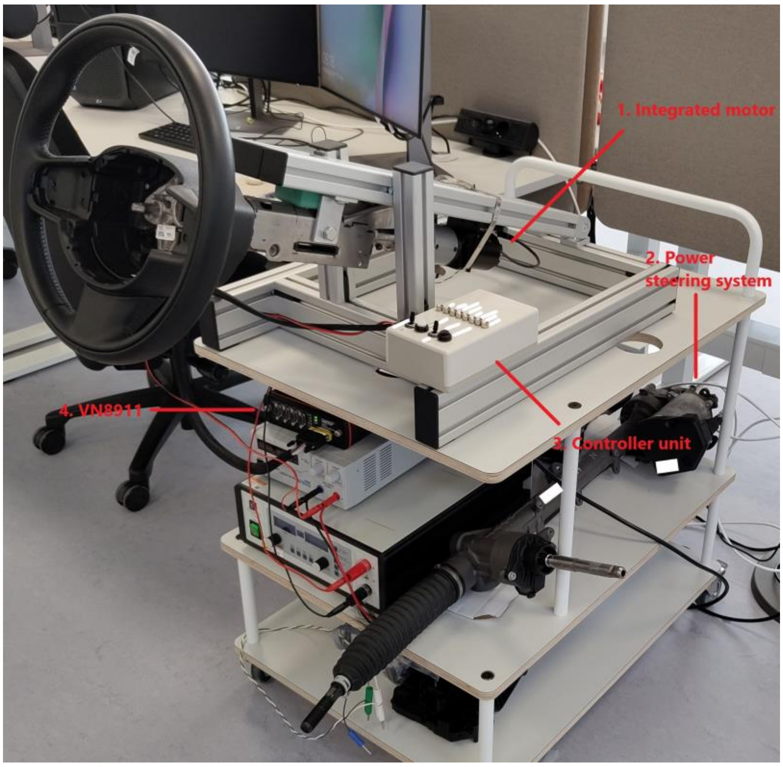

Figure 3.1. The testbench used. It is installed with an integrated servomotor, power steering system, controller unit and a VN8911 interface.

There is also a controller unit which is a part of the testbench. The unit is programmable, and it is used to turn the system on and off and switch between different configurations. Figure 3.2 shows the controller unit used.

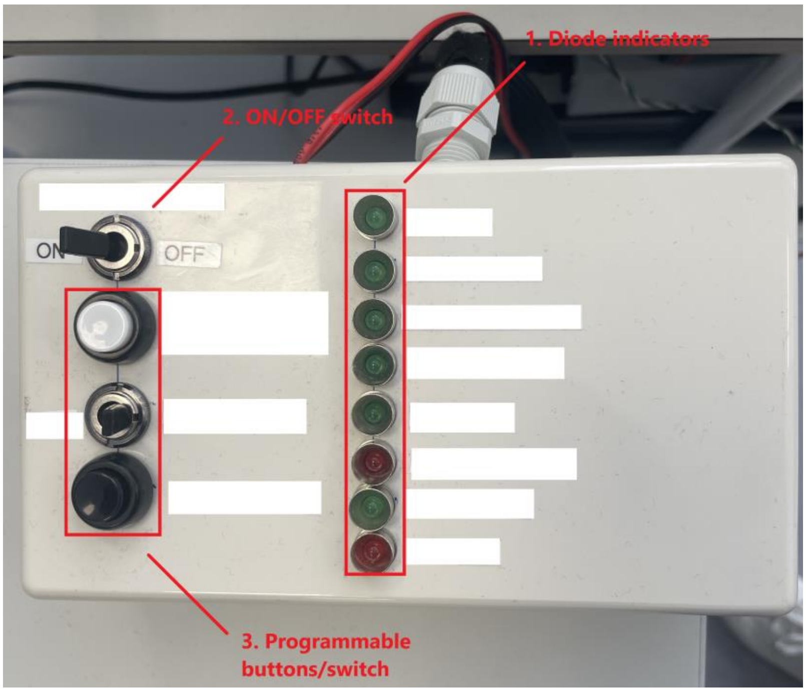

Figure 3.2. The control unit used to control which config used and to turn on and off the SbW system.

3.1.1 Integrated Servomotor

The integrated servomotor is a small motor installed with a PID regulator and an encoder. It can be connected to a computer through USB and configured using a software installed on a computer. The motor communicates via twisted CAN cables, sending information from the motor to a designated computer or interface. Its main purpose is to send signals containing the position of the steering wheel to the steering rack.

3.1.2 Vectors VN8911 interface

The VN8911 interface is designed to be a part of a system in different kinds of vehicles. It is used to take information from measurements done within a vehicle and make it readable and workable for the user. The interface has a total of four inputs which CAN cables can be connected. Each input has two channels. The cables can be connected directly to a channel on the interface or to a split cable can be used to utilize both channels. This results in a total of eight channels that can be used. The interface supports standard CAN and FlexRay on its channels [9].

3.1.3 Vector CANoe

CANoe is a program used for the VN8911 interface to set up simulations, databases, analyse information and make real-time changes to the system connected to a vehicle. CANoe has features such as logging, displaying graphs in real-time, tracing data and generating signals. CANoe also has a built-in debugger which is called CAPL browser. The CAPL language is based on C programming and is an event-based language [10]. The language is specifically used for CANoe.

3.2 Test vehicle

The test vehicle is a modified passenger vehicle. The vehicle still has a steering wheel with a mechanical link on the driver side and the SbW steering wheel is placed in front of the passenger seat. There is a switch between the seats to switch the SbW system on and off, that is connected to the Vector interface, the same type of interface used for the test bench. The Vector interface is also used as a real time controller for this project. Both driver – and passenger side in the vehicle have gas-and braking pedals, so the vehicle has double command. For safety reason, a driver on the driver's side had to be seated in the car when driving the SbW system in case the system stopped working. Figure 3.3 presents the test vehicle.

Figure 3.3. The test vehicle used where two steering wheels are installed. One with SbW and one with a steering column. A controller unit is also included between the seats.

3.2.1 DASH4PRO display

A display was installed in the test vehicle. The display was first programmed using the race technology application to select which data to present on the display. The steering ratio was added to be able to see the exact ratio while driving. The display was connected to the vehicle's 12 V auxiliary power outlet and placed above the right steering wheel in the car to have a clear sight of the ratio all the time.

The DASH4PRO display is a piece of equipment used to show measurements in real time during tests in the vehicle. The LCD display can be programmed using Race Technology's own analysis software where specified signals and variables can be selected to be displayed.

4. IMPLEMENTATION

The implementation chapter explains how the thesis work was conducted and how hypotheses were tested. It is divided into sub-chapters, with each part being explained in detail and its importance for the project. It is worth noting that the tests and experiments presented in this chapter were first carried out on a testbench to ensure that the system work as intended. When tested in a real vehicle, the testing was performed on a designated test track.

4.1 Slow-speed cornering test

To calculate the steering ratio in the test vehicle a slow-speed cornering driving test was performed. This was done by driving on max left steering, driving in a circle at minimum speed. At the same time data of the yaw rate, vehicle speed and steering wheel angle was collected by CANoe via Vector interface. When all the data was gathered the calculations were done in Matlab using the mean values from the measurement to establish the steering ratio. The wheelbase was collected from the technical data of the vehicle.

4.2 Fixed steering ratio

To implement a speed variable steer ratio, a configuration with a fixed steering ratio was first created for a reference. The purpose of the fixed steering ratio was to test multiple ratios at different speeds to observe how the vehicle behaves and to get a better understanding of how the ratio impacts the stability of the vehicle. The test results also serve as a reference to determine the parameters of a speed-dependent steer ratio system.

For implementing fixed steering ratios, the controller on the testbench, which is the same model as the one used in the vehicle were programmed using CANoe. A switch was programmed to set the ratio to either 1:1 or 2:1, while the black button was used to set the ratio to either 3:1 or 4:1. Figure 3.2 shows the controller used on the testbench. These ratios were tested in the vehicle at different speeds to determine which ratio should be used at what speed. This was done to ensure the best stability and mobility. Two additional ratios, 5:1 and 6:1, were tested in a similar way, where the stability of the vehicle was tested at various speeds.

4.3 Vehicle speed dependent ratio

With the information gathered from the tests with a fixed steering ratio, a ratio depending on speed could be done. The results from the fixed ratio test acted as a base from which different ratios could be determined for different speeds. With the information gathered, a configuration where the ratio is dependent on speed could be created. The variable ratio, similarly, to the fixed ratio, was programmed using CANoe.

The experimental process involved testing two primary functions, a quadratic function, and an exponential one. The selection of parameter values was crucial to obtain a favourable trade-off between vehicle mobility and stability. The first tests involved an exponential function, which was shifted with the variable n_{min} on the x-axis to avoid the issue of the function approaching zero. If the function value becomes zero it would lead to non-steerable vehicle conditions. Different combinations of the constants a and b were tested. The constant a determined the maximum steer ratio, while b determined the slope value. The variable v is the speed of the vehicle, n_{steer} is the steering ratio and n_{min} is the minimum ratio. Equation (6) represents the function created.

$$n_{steer} = (a \cdot e^{b \cdot v}) + n_{min} \quad (6)$$

The next stage in the process of developing the speed variable ratio was to replace the exponential function with a quadratic function. A similar testing procedure was followed, where different parameter values were tested to tune the quadratic function. Specifically, the maximum and minimum steering ratios as well as the threshold speed at which the minimum ratio is reached were varied. Both a function to the power of two and four were tested to see which one provided the most comfort and stability when driving. Only the function to the power of four is presented but the other function was equally tested. The function used is presented in equation (7) and the k value of the function is presented in equation (8). The variable v is the speed of the vehicle, $v_{threshold}$ is the threshold speed where the minimum ratio is reached while n_{min} and n_{max} is the maximum and minimum steering ratio. The experimental process was repeated numerous times until a good combination between stability and mobility was obtained.

$$n_{steer} = k(v - v_{threshold})^4 + n_{min} \quad (7)$$

$$k = (n_{max} - n_{min})/({v_{threshold}}^4) \quad (8)$$

4.4 Vehicle speed and angular position dependent ratio

The next step was to create a steering function that combined the steering wheel angle and roadwheel angle with a speed-dependent factor. This approach allows for a fixed end lock instead of a variable end lock that comes with a speed dependent ratio solution. The function used for this solution is presented in equation (9) where $r_{wheel-steer-ang}$ is the required steering angle.

$$r_{wheel-steer-ang} = (n_{steer} \cdot p_{motor}) + (n_{motor} \cdot {p_{motor}}^3) \quad (9)$$

The speed dependent factor, n_{steer}, is the same as the speed variable solution, equation (7), where a maximum and minimum ratio was set as well as a threshold where the minimum ratio is reached. But for this solution, the maximum ratio is calculated using equation (10) where $A_{Str-ang}$ is the maximum steering angle while $A_{Str-whl-ang}$ is the maximum steering wheel angle.

$$n_{steer} = \frac{A_{Str-ang}}{A_{Str-whl-ang}} \quad (10)$$

On the other hand, the speed dependent factor is multiplied with the position of the motor p_{motor}. The other part of the function, the relation between steering wheel angle and roadwheel angle, is controlled by the variable n_{motor}, which is the steering wheel ratio. n_{motor} is represented by equation (11).

$$n_{motor} = \frac{n_{wheel-steer} - n_{steer} \cdot p_{motor}}{p_{motor}^3} \quad (11)$$

To tune the function in question, a testing procedure like the previous ones was done. This procedure involved testing of various parameters until a wanted result was obtained. The parameters that were altered were the same as the speed dependent function but also adjustments to the angle at which the end lock was reached. Specifically, the end lock angle varied between 90° and 150° to identify an optimal angle that maximizes vehicle stability and mobility.

4.5 Phase delay between steering input and output

An investigation of the frequency response was made to compare the steering input and output. This was done by driving the test vehicle and rotating the steering wheel at different rates to establish data on the requested steering angle and the actual steering angle. The intention was to gather as many different frequencies as possible to be able to plot the bode magnitude and the bode phase diagram and then analyse these. The data was collected by CANoe via Vector interface during the test. The results were then implemented in Matlab. The functions used were tfestimate (), phase () and abs (). These functions were used to plot a phase bode plot and a magnitude bode plot with the collected data.

5. RESULTS

This chapter presents the results for the various tests that were conducted. This chapter is divided into similar sub-chapters as the method part of this report.

5.1 Slow-speed cornering

The result of the mean values from the slow-speed cornering driving test is presented in table I and the test conducted is plotted in figure 5.1. The wheelbase of the test vehicle is $L = 2.872\ m$.

TABLE I
THE RESULT VALUES FROM THE SLOW-SPEED CORNERING
DRIVING TEST

Variable	Result
Yaw rate	0.2940 deg/s
Vehicle speed	1.5139 m/s
Steering wheel angle	8.9248 rad

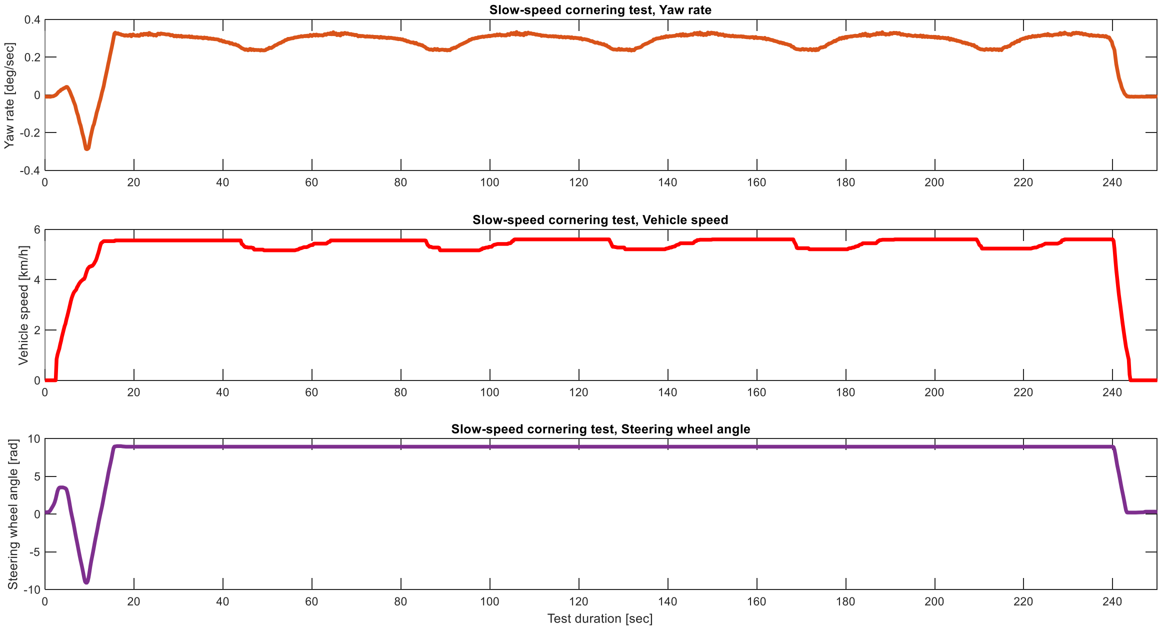

Figure 5.1. The results from the slow-speed cornering test plotted in three different graphs. The x-axis is the duration of the test done, while the y-axis shows what has been measured.

Equation (4) was used to obtain the road wheel angle and then equation (5) was used to get the vehicle´s steer ratio. This resulted in a steering ratio of 16 as seen below. This represents the vehicle´s steering ratio for the mechanical steering system.

$$R_{WA} = \frac{L * \dot{\psi}}{v} = \frac{2.872 * 0.2940}{1.51139} = 0.56\ rad$$

$$n = \frac{S_{WA}}{R_{WA}} = \frac{8.9248}{0.5577} = 16$$

5.2 Fixed steering ratio

When testing the different ratios, it was observed that a 4:1 ratio gave the vehicle stability up to 15 km/h, while a 3:1 ratio was stable up to 30 km/h. The 2:1 ratio was observed to be easy to control for speeds up to 60 km/h while the 1:1 ratio was stable for speeds above 60 km/h. The last tests involved observing the stability and mobility of a 6:1 and 5:1 ratio for lower and higher speeds. Both ratios were observed to make the vehicle easy to manoeuvre around corners but made the vehicle more difficult to control at speeds above 10 km/h. The results of the experiments are presented in table II.

TABLE II
OPTIMAL STEER RATIO VALUES IN RELATION
TO THE SPEED

Fixed steer ratio	Observed speeds where vehicle was stable
6:1	0-10 km/h
5:1	0-15 km/h
4:1	0-15 km/h
3:1	15-30 km/h
2:1	30-60 km/h
1:1	60 – km/h

5.3 Vehicle speed dependent ratio – Exponential function

The exponential function was the first one to be tested. After testing various combinations of the maximum steering ratio and slope value, which was based on the values obtained from table II, a function with an appropriate combination of stability and mobility was reached. The function had a max steering ratio of 5:1 and a slope value of -0.036. The values obtained are used in equation (6) which is gives the following equation:

$$n_{steer} = (4 * e^{-0.036*x}) + 1$$

This function made it possible to manoeuvre the vehicle easily around corners and made parking less demanding while also providing good stability while driving on higher speeds. The function is plotted in figure 5.2.

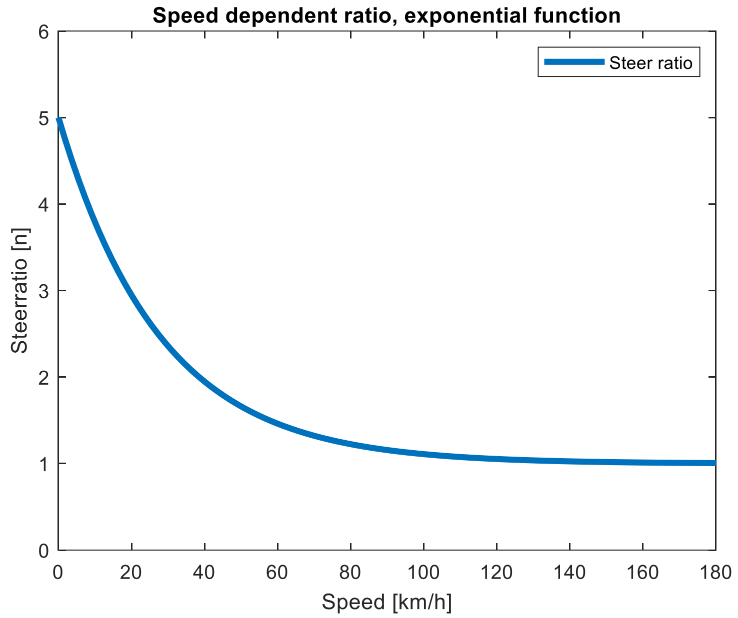

Fig. 5.2. The exponential speed ratio, presented in a plot where speed is on the x-axis and the steer ratio on the y-axis.

5.4 Vehicle speed dependent ratio – Quadratic function

The approach while testing the function involved changing one parameter in equation (7) and equation (8) at the time while documenting the process. The initial parameters, which served as a baseline for the experimental process, were defined by the values presented in table III. N_{max} is the maximum ratio, N_{min} is the minimum ratio and $N_{threshold}$ is the speed at which the minimum ratio is reached.

TABLE III
STARTING PARAMETER VALUES FOR
THE QUADRATIC FUNTION

Variable	Value
N_{max}	5
N_{min}	1
$N_{threshold}$	43 km/h

The vehicle was observed to be highly manoeuvred at lower speeds, while maintaining stability at higher speeds. However, it was observed that while driving at speeds between 40 km/h and 60 km/h, a more direct ratio could be used to ensure more mobility. Figure 5.3 represents the graph that was tested. The blue line represents the function to the power of two, and the orange line represents the function to the power of four. This is the case for all the figures with a blue and orange line.

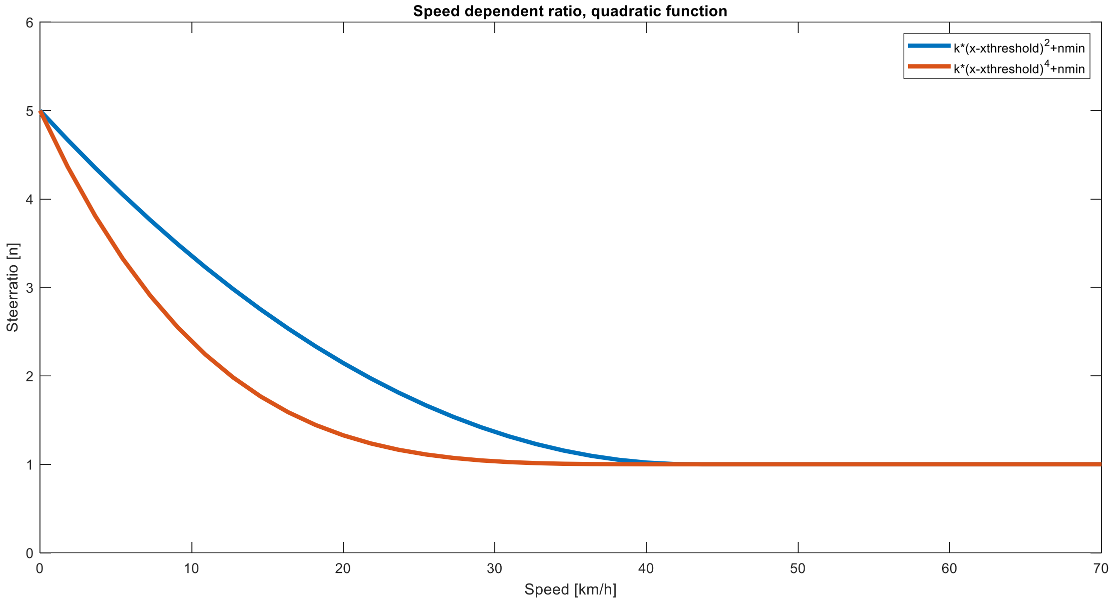

Fig. 5.3. The first configuration tested of the speed dependent ratio. The configuration has a maximum ratio of 5:1 and a minimum of 1:1. The speed threshold is at 43 km/h, which is the speed where the minimum ratio is reached.

Another test was conducted where the maximum ratio of the function was changed to 6:1 and the minimum ratio to 0.8:1 while also moving the threshold further up on the x-axis to 100 km/h. This solution provides more mobility while driving at speeds between 40 km/h and 60 km/h than the previous attempt. On the other hand, since the ratio is less than one, the vehicle was observed to be more difficult to manoeuvre at higher speeds, more exactly speeds above 80 km/h. When the function is to the power of four it provides more stability rather than mobility compared to when the function is to the power of two. When driving at speeds above 80 km/h, the vehicle was less responsive, and the driver was required to turn the steering wheel more than what was wanted. This effect was most noticeable whenever the driver needed to do a sharp turn. Figure 5.4 represents the function tested. However, when moving the threshold further up the x-axis it provided more mobility at higher speeds. Although the vehicle acquired more mobility at higher speeds, it also decreases the stability at midrange speeds.

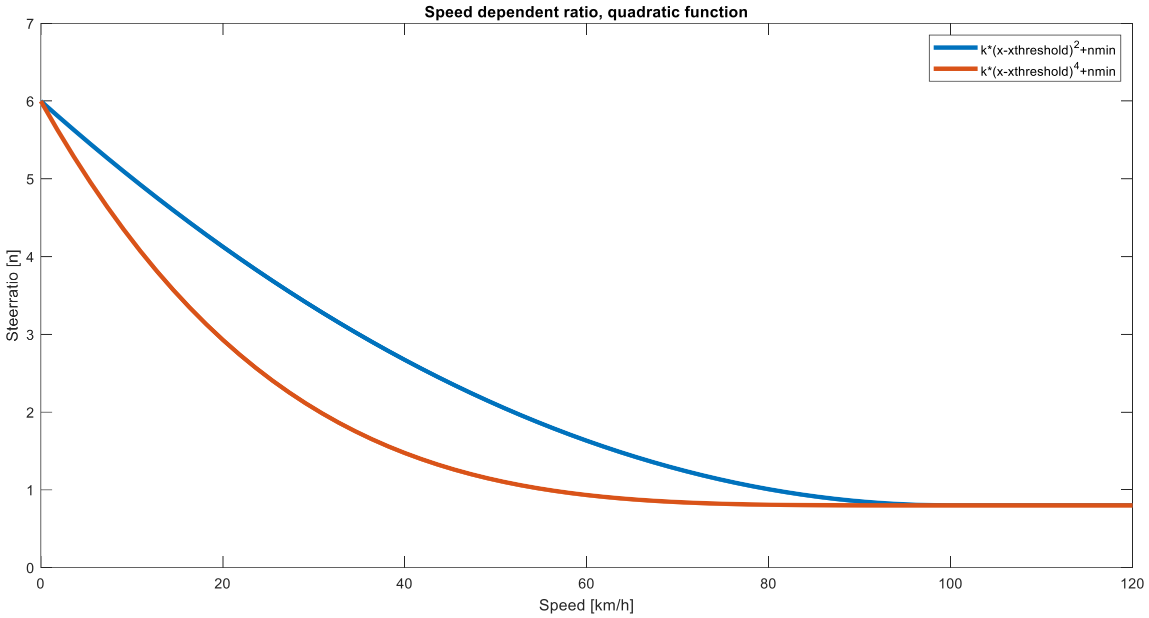

Fig. 5.4. The second configuration tested. The configuration has a maximum ratio of 6:1 and a minimum of 0.8:1. The speed threshold is at 100 km/h.

An additional test was conducted where the maximum ratio factor was set to 4:1 and minimum to 1:1. This combination of maximum and minimum ratios was observed to give the vehicle stability for midrange speeds as well as higher speeds. This was the case for the function to the power two and to the power of four. Although the vehicle was stable at higher and midrange speeds, it did not provide enough mobility at lower speeds. The vehicle was observed to be more difficult to manoeuvre compared to a maximum ratio of five or six. The mobility was increased by moving the threshold, but this only affects the mobility and stability at higher speeds. Figure 5.5 represents the function used.

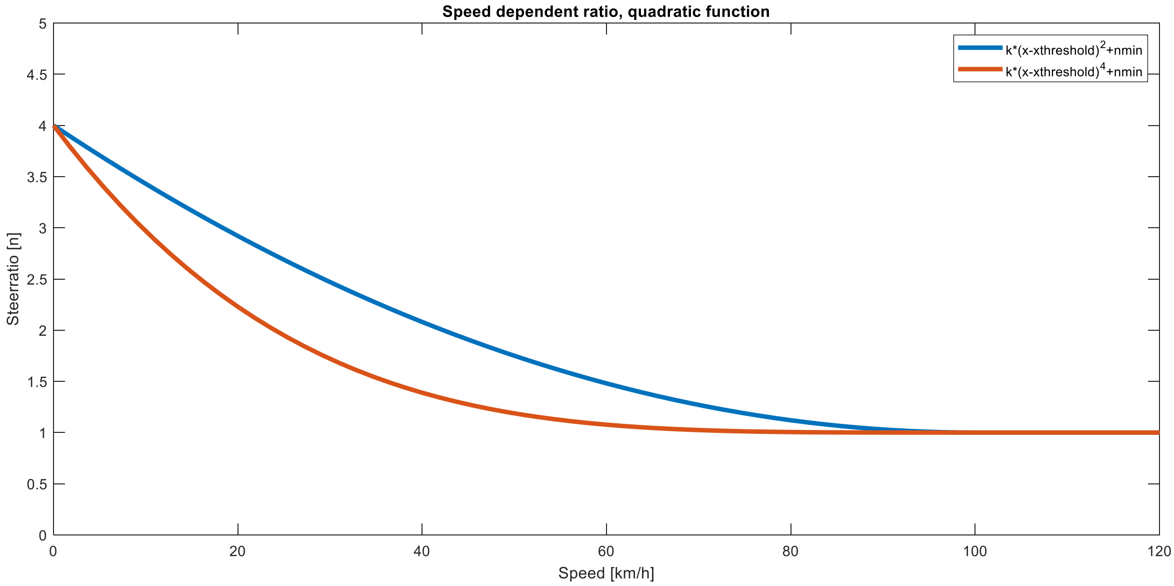

Fig. 5.5. The third configuration tested. The configuration has a maximum ratio of 4:1 and a minimum of 1:1. The speed threshold is at 100 km/h as well.

The parameters were changed once more for an additional experiment. It was notable that a maximum steer ratio of 5:1 and a minimum ratio of 1:1 provided a good combination of stability and mobility compared to the 6:1 and 0.8:1 ratio or the 4:1 and 1:1 ratio. With the information gathered, a new set of parameters were tested. Table IV shows the parameters tested.

TABLE IV
FINAL PARAMETER VALUES FOR
THE QUADRATIC FUNTION

Variable	Value
N_{max}	5
N_{min}	1
$N_{threshold}$	100 km/h

This combination of a maximum steering ratio of 5:1 and a minimum of 1:1 gave the vehicle enough mobility at lower speeds while maintaining good stability even at higher speeds. The threshold was moved between 150 km/h and 50 km/h, and it was observed that a threshold at 150 km/h made the vehicle slightly unstable at higher speeds while a threshold at 50 km/h forced the driver to turn the steering wheel more than wanted. It was also observed that the function to the power of four was more versatile because the change in ratio while accelerating were more natural compared to when the function was to the power of two. Figure 5.6 shows the finalized function.

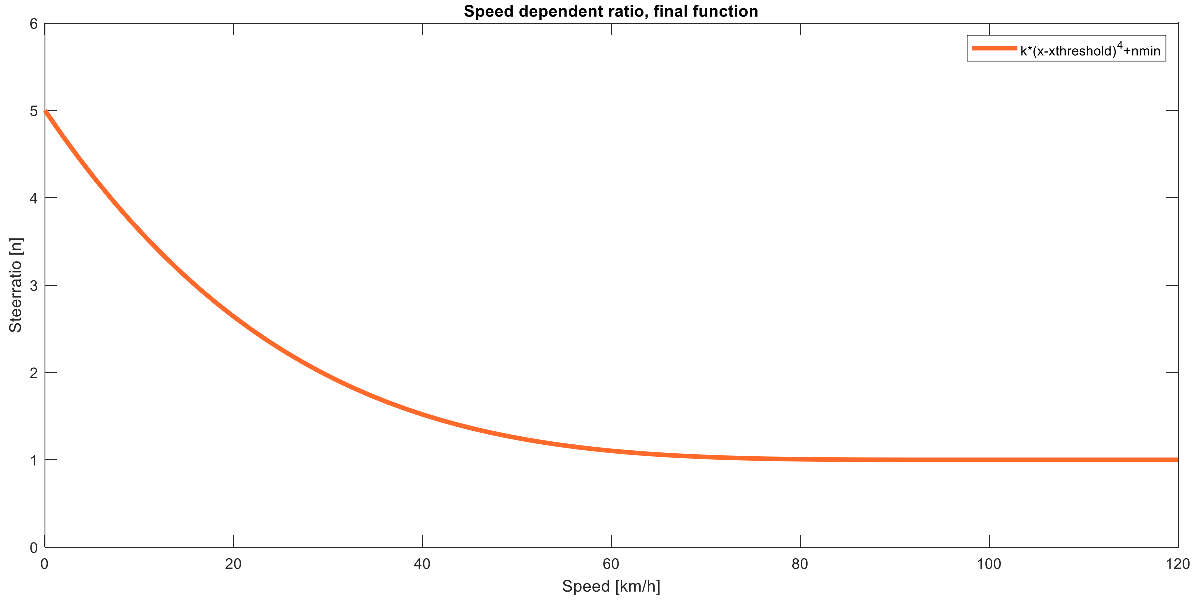

Fig. 5.6. The final configuration. The configuration has a maximum ratio of 5:1, a minimum ratio of 1:1 and a threshold at 100 km/h.

An experiment with this configuration was conducted where the vehicle was tested on a bigger testing track. Figure 5.7 shows the steering ratio compared to the speed of the vehicle where the blue line is the ratio while the orange one is the speed.

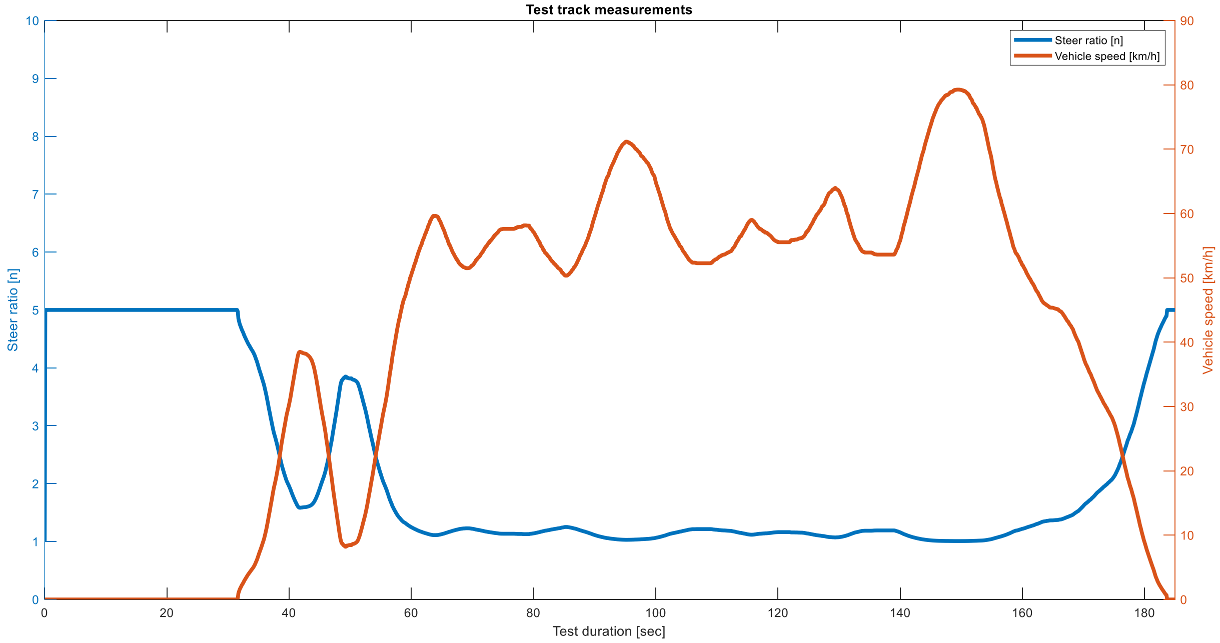

Fig. 5.7. A plot that shows the steer ratio in relation to the speed of the test vehicle when driving on a designated test track.

5.5 Vehicle speed and angular position dependent ratio

Various tests were conducted where both the speed dependent part and steering wheel dependent part were changed. Various end locks between 70° and 150° were tested while also changing the threshold speed for which the function reaches the minimum ratio. It was observed that the factor that made the biggest change is the position of the end lock. Whenever a smaller angle for the end lock was used, it made the vehicle more easily to maneuver and less turning was needed for the driver. However, this made the vehicle unstable at higher speeds since it lowers the required steering angle for the driver to reach the end lock. If the threshold was moved, then the vehicle became more stable but not enough. An end lock at 90° on the other hand provided more stability while maintaining a high mobility. Various settings were tested for this end lock where the maximum and minimum ratio were changed.

A 150° end lock was then tested. This end lock provided a better combination of stability and mobility than the end locks tested before. The configuration was then tuned by changing the threshold to 100 km/h. Multiple thresholds were tested for this end lock and it was observed that a threshold at 100 km/h provided enough stability and mobility at higher speeds. However, it was observed that the changing of the threshold did not have as much of an impact on the vehicle's performance compared to the speed dependent solution. Figure 5.8 shows a representation of the function used. The orange line is when the vehicle is standing still, while the blue line represents the vehicle moving at a higher speed.

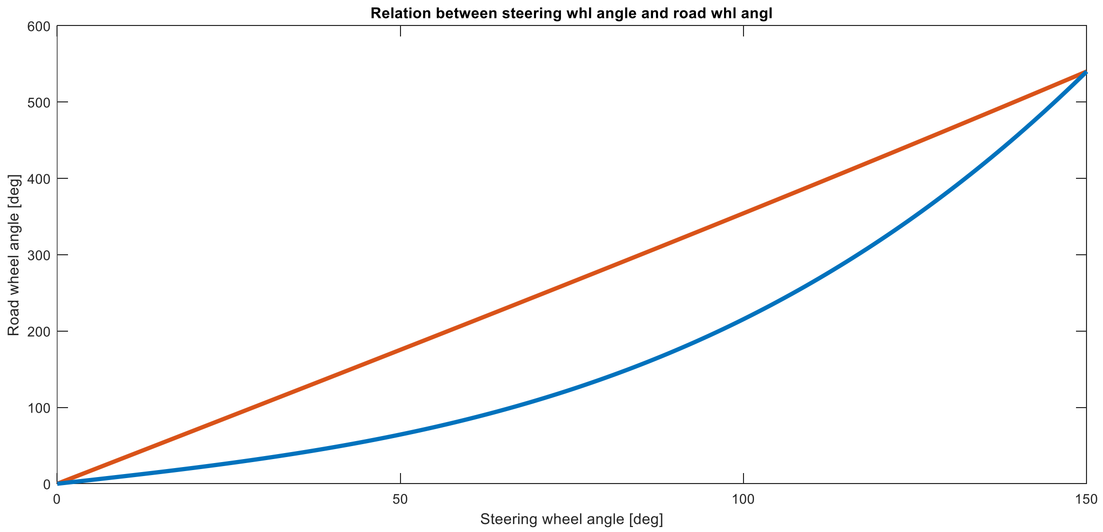

Fig. 5.8. A plot of the vehicle speed and angular position dependent ratio. The orange line is how the relation between steering wheel angle and road wheel angle when standing still while the blue line is when the vehicle is traveling at higher speeds.

Table V represents the variables values used for the final configuration that was implemented.

TABLE V
THE FINAL CONFIGURATION VALUES FOR THE
VEHICLE SPEED AND ANGULAR POSITION DEPENDENT RATIO

Variable	Value
N_{max}	3.6:1
N_{min}	1:1
$N_{threshold}$	100 km/h
End lock	150°

5.6 Phase delay between steering input and output

After collecting data from the test that was conducted, a bode plot of the magnitude diagram was created. This plot is presented in figure 5.9. The figure shows that the vehicle has relatively good response between 0-2 rad/s, after that the steering output does not reach the same value as the steering input. It can still be observed from the figure that even in low frequencies there is a delay.

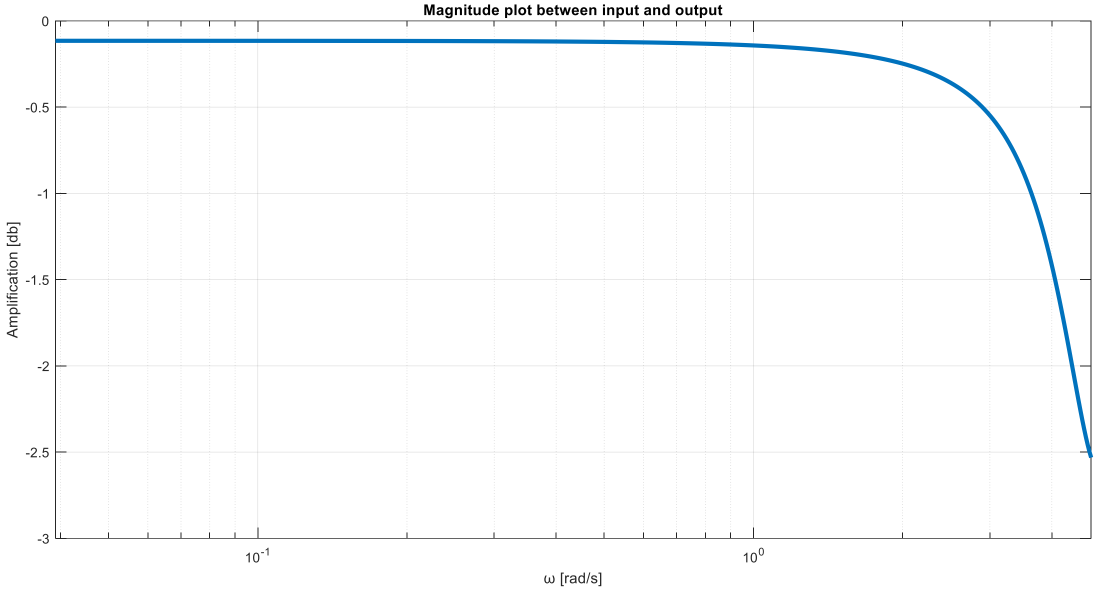

Fig. 5.9. A bode magnitude plot which measures the difference between the input signal, steering wheel, and the output, power steering system

In figure 5.10, the bode phase diagram shows the phase difference between the input and output signal. It was observed that there is notable phase difference even at lower frequencies such as 2 rad/s. The phase difference in corelation with the frequency was observed to be close to linear.

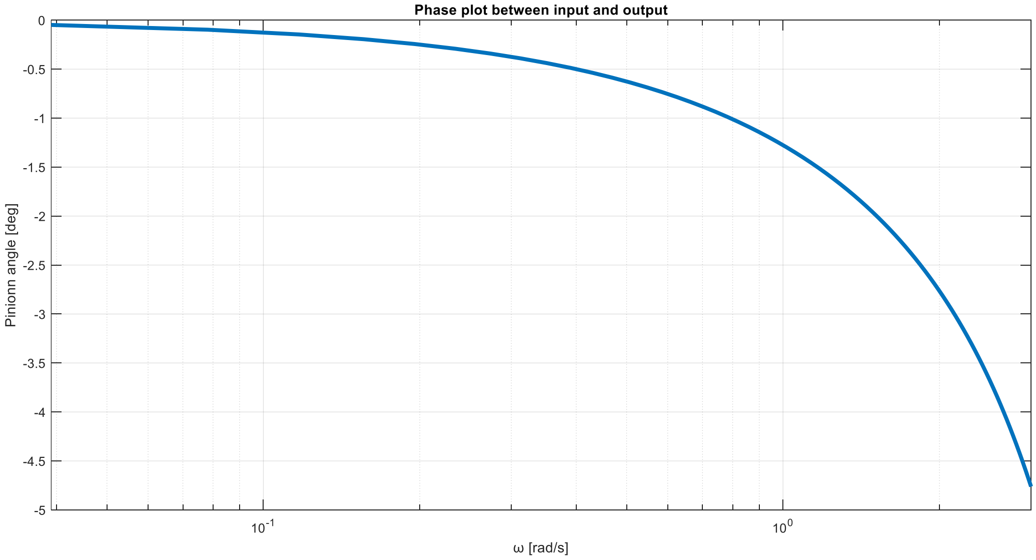

Fig. 5.10. A bode phase plot which measures the phase difference between the input signal, steering wheel angle, and the output, road wheel angle.

This delay was observed for both configurations, the vehicle speed dependent one and the vehicle speed and angular position dependent one. It was also observed that the magnitude losses and phase differences were more notable whenever a more direct ratio was used. It was also easier to reach the state where the power steering system could not keep up with the turning of the steering wheel, which resulted in the system shutting down. Figure 5.11 shows an experiment where the driver rotated the steering wheel with different frequencies until a disconnection between the steering wheel and power steering system was detected. The red line is the pinion angle, output, while the blue line is the steering wheel angle, input.

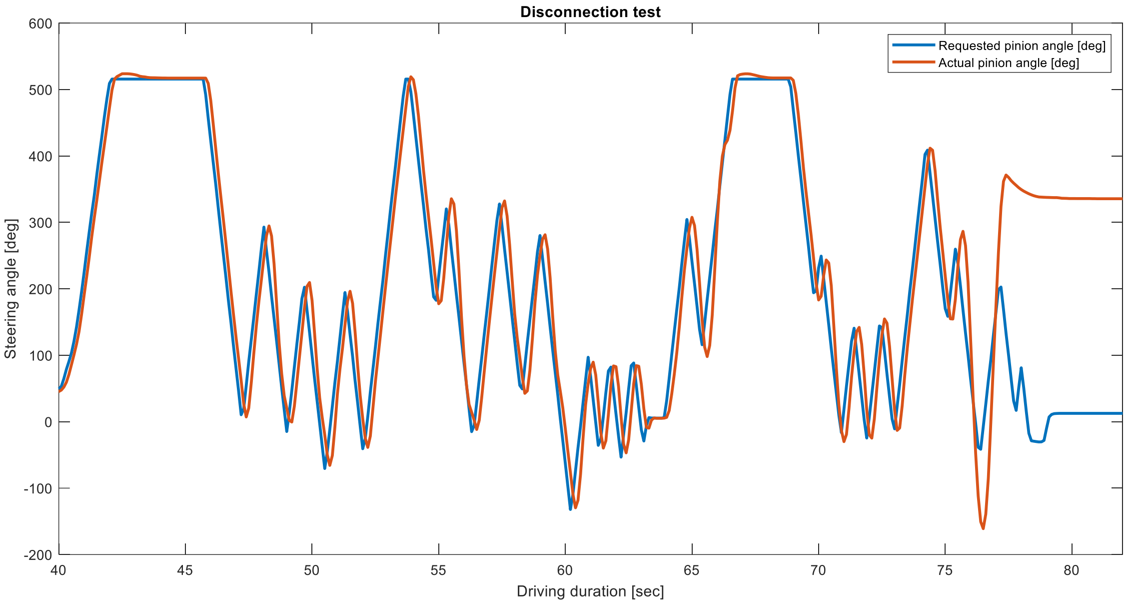

Fig. 5.11. The plot of the input and output signal get out of phase. The orange line is the actual angle of the pinion while the blue line is the requested angle. It also shows when the power steering system disconnects due to the high frequency.

It is notable through figure 5.11 that it does not require a lot from the driver to rotate the steering wheel fast enough to get a detectable phase delay. This delay made it exceptionally difficult to manoeuvre the vehicle around smaller areas and sharper corners.

6. DISCUSSION

There are endless ways to implement a speed variable ratio for SbW and only a few has been tested for this project, but from the tests that has been performed some conclusions and possible improvements can be presented which will be discussed in this chapter.

6.1 Vehicle speed dependent ratio

The focus has been on a vehicle speed dependent ratio with a quadratic function and a vehicle speed and angular position variable ratio. The speed variable ratio with an exponential function was tested but with that solution it was more complicated to get exact values for different speeds, meanwhile the quadratic function was more flexible, so it became natural to focus more on the quadratic function as the speed dependent one.

Both the final vehicle speed dependent and the final vehicle speed and angular position dependent solutions are quite similar. An inexperienced driver might not notice a difference between the two solutions because both start at about the same ratio and ends up at ratio 1:1 when the speed is 100 km/h. However, as seen in figure 5.6 compared to 5.8 there is a difference in high speed, because in the vehicle speed and angular position dependent implementation, figure 5.8, there is a steeper slope at the end of the curve, that is because it must reach the end lock. This might be a problem and maybe also unsafe, if a driver drastically turns the steering wheel at high speed, then the wheels will rotate more than the driver probably intended.

One might ask, how important is it to be able to reach the rack end lock at high speeds? This is a question that people feel different about. Some do not want to limit the steering in any situations, and some do not feel the need to be able to steer to end lock at high speed. It is quite uncommon for a passenger car to steer close to end lock at high speed if driving on roads. One situation it might be needed is if the vehicle swerving and loses the grip of the road, then the driver might want to compensate by steering the opposite direction and use the wheel´s full range. A test like this was not made so it is difficult to evaluate, but while driving on the test track in high speed and rounding a bend it did still feel stable.

Both final solutions had good stability and mobility during test drive on a bigger track, where the speed varies from 0-100 km/h. The implementations worked well in both parking situations and on country road, at least what the result from the drive at the test track could say. The solutions showed good stability in higher speeds because the ratio goes down quite fast. So, it feels more like driving a car with a mechanical link in higher speeds. Then the solution has kind of high ratio at 0 km/h to make parking easy with less turning of the steering wheel. One disadvantage may be that the driver can lose the precision while parking because it is difficult to get an exact angle on the wheels with high ratio.

6.2 Phase delay

Since there is a phase delay between the input signal, the steering wheel, and the output signal, the power steering system, it is difficult to test the different configurations when the delay gives a false representation of how it feels to drive the vehicle. It is hard to separate the feeling in the steering wheel with the implemented speed dependent steer ratio. Both aspects change how the driver perceives the steerability which makes it difficult for third parties to test the vehicle.

How much of a delay should the consumer expect and what is acceptable when it comes to a vital component such as the steerability? A consumer would most likely want a vehicle that is reliable and easy to control, which is not the case with this kind of system with those noticeable delays. There will always be some sort of delay when it comes to circuitry and electrical connections, it is inventible. However, the delay that was precent made it too difficult to manoeuvre the vehicle around corners and when trying to make fast steering adjustments. One factor that may cause the delay to be as notable as it is, could be the fact that the factor that is multiplied with the steering wheel angle is too high. When multiplying the input angle with five or four, it makes the output more aggressive and responsive which then requires hardware that can handle that kind of change. The solution to this is to lower the maximum ratio, but then the vehicle loses its mobility and that is of the key purposes of using SbW. It is important to note that the delay is planned to be minimal and not noticeable for future projects, it is present since this is a first prototype of the vehicle.

6.3 Improvements

Since there are endless ways to create and tune a system with SbW, there are a lot that can be done to improve the results from this report. One aspect of the system that can be changed is the fact that it now uses one function and not one for low speeds and one for high speeds. One solution could be to implement a function with a more aggressive characteristic when driving on lower speeds while implement a linear function for higher speeds. This would allow the vehicle to be highly manoeuvrable at lower speeds while still provide assistance at higher speeds. The linear function would provide a less aggressive change of ratio while still helping the driver, instead of having a function that quickly sets the ratio to 1:1 like the one created in this report. Another improvement that could be done is to install a mechanical end lock for the vehicle speed and angular position dependent solution. This would give the driver a familiar feeling to the already existing end lock. It is an easier process to install a mechanical end lock instead of a motor-based end lock which would be the other alternative.

When it comes to the phase delay, it needs to be investigated further to figure out exactly what causes the delays in the system. One contributing factor can be the hardware that is limiting the system, newer and improved hardware may improve the system. For example, a better power steering system could be used that can handle more rapid changes without shutting down. There could also be a limit in the regulation loops that causes the delay. To be sure more tests could be done, to find out what causes the delay and then improve the faults.

6.4 Future work

The next step with this reports results would be to combine the variables steer ratio with a tuned steering wheel. The steering wheel would simulate the feeling of a steering wheel with a mechanical link to the pinion. This will make a fairer experience of the implementations because it is difficult to try to only review the functionality of the variable ratio when the feeling in the steering wheel is not developed. It would also be necessary to do more testing, for example on different road conditions, drive further distances and drive in traffic. Then maybe small changes must be made in the functions so they can adapt to all kinds of driving situations.

7. CONCLUSION

During the time this thesis was conducted, various aspects of how a speed dependent ratio could be created and implemented in a real vehicle has been examined. There are endless ways to create a variable steering ratio for Steer-by-Wire and only a few has been tested for this project. But from the tests that have been conducted some conclusions can been drawn. Both the final vehicle speed variable ratio and the vehicle speed and angular position variable ratio has good stability and mobility with a maximum ratio of around 5:1 at 0 km/h and a ratio of 1:1 at 100 km/h. These functions have only been tested on test tracks, to be able to evaluate the implementations in all kinds of driving situations more tests must be done.

When it comes to the phase delay, it was discovered that there is a quit large phase delay between steering input, requested value and output, actual value. This made the vehicle difficult to manoeuvre fast around corners at low speeds, because a high ratio creates a greater difference between the input signal and output signal, which causes problems with the rack regulator. To improve this more test must be done to figure out exactly what causes the delay. Changing the hardware and especially the power steering system could be needed to make this delay more acceptable. This is a change that will be present in future instalments of the vehicle, and the delay is planned to be minimized and not noticeable for the driver.

Steer-by-Wire has the potential to improve the car industry and make vehicle more stable and easily manoeuvred in all kinds of driving situations because it is possible to implement different configurations for different driving situations. There are multiple advantages with this new technology, not least it will be safer for the driver in case of a car crash since the steering column will be removed which is a significant improvement when it comes to safety.

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