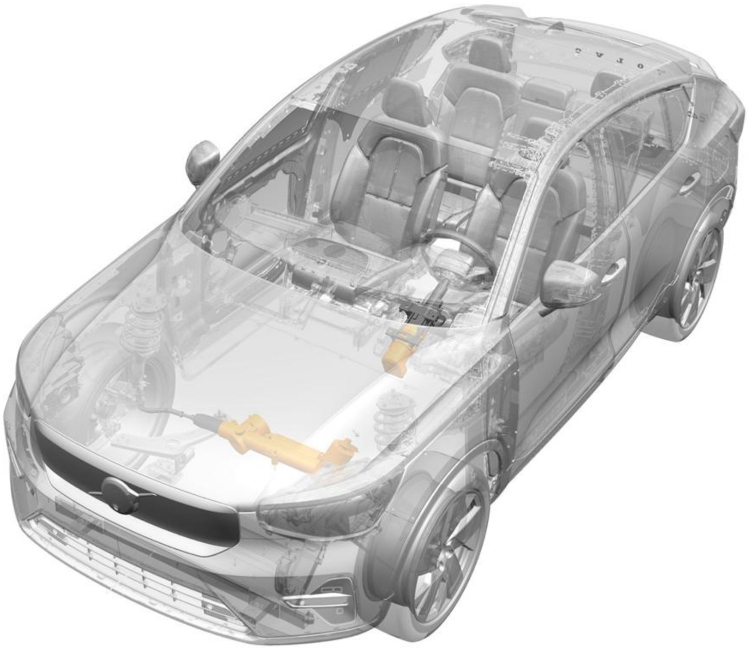


Design and Development of a Steer-By-Wire Hand-Wheel Actuator

Bachelor’s Thesis in Mechanical Engineering

Leo Ekström, Loke Lindblad

DEPARTMENT OF INDUSTRIAL- AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

Examiner: Erik Hulthén, Industrial- and Materials Science
Supervisor: Matthijs Klomp, Department of Deceleration and Steering

Bachelor's Thesis 2025, *15 HP*
Department of Industrial- and Materials science
Course: IMSX20
Chalmers University of Technology
SE-412 96 Gothenburg

Abstract

This bachelor's thesis, conducted at Chalmers University of Technology in collaboration with Volvo Cars, explores the development of a Steer-By-Wire steering column, a system designed to replace traditional mechanical steering connections with an electrically actuated alternative. The study investigates the challenges of integrating a torque feedback device into the steering column while juggling several requirements and wishes, ensuring compatibility with existing vehicle cabin constraints. Through an extensive patent and market investigation, multiple design solutions were generated and systematically evaluated using elimination by several matrixes. The final concepts were developed in CAD and underwent testing to ensure compliance with the requirement specification. This thesis contributes insights into the optimization of steer-by-wire systems, offering potential improvements in driver comfort, maneuverability, and space efficiency. The study shows that the implementation of a steer-by-wire hand-wheel actuator is possible in the current Volvo 40-series with only minor modifications. However, additional design changes may be required for integration into other vehicles.

Detta examensarbete genomfört vid Chalmers tekniska högskola i samarbete med Volvo Cars, undersöker utvecklingen av en Steer-By-Wire styrkolonn. Detta är ett system som är utformat för att ersätta den traditionella mekaniska styrkopplingen med en elektrisk förbindelse. Studien undersöker utmaningarna med att integrera en momentåterkopplingsenhet i styrkolonnen, samtidigt som flera krav och önskemål balanseras för att säkerställa kompatibilitet med befintliga förarmiljöer. Genom en omfattande patent- och marknadsundersökning genererades flera koncept, vilket i sin tur systematiskt utvärderades med hjälp av eliminerings- och urvalsmatriser. De slutgiltiga koncepten utvecklades i CAD och genomgick ett flertal tester för att bedöma dess förmåga att uppfylla kraven i kravspeifikationen. Denna uppsats ger insikter i optimeringen av steer-by-wire-system, med potentiella förbättringar inom förarkomfort, manövrerbarhet och platseffektivisering. Studien visar att en steer-by-wire hand-wheel actuator kan implementeras i den nuvarande Volvo 40-serien med endast mindre modifikationer, men större förändringar kan behövas för implementationen i andra modeller.

Acknowledgements

We would like to express our gratitude to Volvo Cars for their support and assistance throughout this bachelor's thesis. Their generous offerings of resources, expertise and guidance have been instrumental in the successful completion of this project.

We are particularly grateful to Matthijs Klomp and the members of the Steering Column Team for their support and feedback. Their openness to sharing their knowledge and experience has greatly enhanced our research and learning experience.

This thesis would not have been possible without the collaboration and encouragement from Volvo Cars, and we are thankful for the opportunity to work with such a distinguished organization.

Additionally, we are deeply appreciative of Chalmers University of Technology and our examiner Erik Hulthén for providing us with the academic environment and assistance to pursue our research.

List of Acronyms

Below is a list of acronyms that have been used throughout this thesis listed in alphabetic order.

CAD	Computer-Aided Design
CMA	Compact Modular Architecture (Vehicle platform)
CVT	Continually Variable Transmission
ECU	Electronic Control Unit
EMB	Electro Magnetic Brake
FEM	Finite Element Method
HVAC	Heating, Ventilation, and Air Conditioning
HWA	Hand-wheel Actuator
LHD	Left Hand Drive
RHD	Right Hand Drive

Table of Contents

1 INTRODUCTION 1

1.1 BACKGROUND 1

1.1.1 Volvo Cars 1

1.1.2 Steering Column 2

1.1.3 Steer-By-Wire 2

1.1.4 The drivers of Steer-By-Wire 2

1.2 PROBLEM 3

1.3 AIM 4

1.4 RESEARCH QUESTIONS 4

1.5 ETHICS 4

1.6 LIMITATIONS 5

2 METHODOLOGY 6

2.1 RESEARCH METHODOLOGY AND INVESTIGATION 6

2.1.1 Patent and Market Investigation 6

2.1.2 Requirement Specification 6

2.2 IDEATION OF CONCEPTS 7

2.3 SCREENING OF CONCEPTS 7

3 ANALYSIS OF KNOWN CONCEPTS 8

3.1 EVALUATION OF CURRENT STEERING COLUMN 8

3.1.1 Main function 8

3.1.2 Adjustment 9

3.1.3 Energy Absorption 10

3.1.4 Size and size limitations 11

3.1.5 Steering lock 11

3.2 PATENT INVESTIGATION 11

3.2.1 Patent 1 – Direct drive 12

3.2.2 Patent 2 – Direct drive with telescopic shaft 13

3.2.3 Patent 3 – Direct drive with telescopic shaft 14

3.2.4 Patent 4 – Parallel torque feedback device 16

3.2.5 Patent 5 – Torque feedback device connected via a worm gear 17

3.2.6 Patent 6 - Torque feedback device connected via a worm gear 18

3.3 MARKET INVESTIGATION 19

3.3.1 Automotive Sector 19

3.3.1.1 Tesla Cybertruck 19
3.3.2 Maritime Sector 20
3.3.3 Other Sectors 21
3.4 Assessment of sub-solutions 22

4 REQUIREMENTS SPECIFICATION 23

5 CONCEPT GENERATION AND SCREENING 26

5.1 Brainstorming and Mind map 27
5.1.1 Feedback and Connection 27
5.1.2 Adjustment and Collapse zone 28
5.1.3 Steering Angle Limiter 29
5.2 Elimination of Weak Links (Mind map) 30
5.2.1 Feedback and Connection 30
5.2.2 Adjustment and Collapse 31
5.2.3 Steering Angle Limiter 32
5.2.4 Streamlined Mind Map 33
5.3 Feedback and Connection Concepts 33
5.3.1 Morphological Matrix 33
5.3.2 Elimination Matrix 34
5.3.3 Pugh Matrix 34
5.4 Adjustment and Collapse Concepts 35
5.5 Steering Angle Limiter Concepts 36
5.5.1 Morphological Matrix 36
5.5.2 Elimination Matrix 36
5.5.3 Pugh Matrix 37
5.5.4 Assessment of Concepts 38
5.6 Complete System Concepts 39
5.6.1 Concepts 39
5.6.1.1 Concept 1 – Direct Drive 39
5.6.1.2 Concept 2 – Belt Drive 40
5.6.1.3 Concept 3 – Gear Drive 40
5.6.1.4 Concept 4 – Worm Gear 41
5.6.1.5 Concept 5 – Bevel Gear 41
5.6.1.6 Concept 6 – Direct Drive + EMB 41
5.6.1.7 Concept 11 – Belt Drive + EMB 41
5.6.2 Kesselring 42
5.6.3 Analysis 42

6 DESIGN OF COMPONENTS 44

6.1 CONCEPT 2 - BELT DRIVE 44
6.1.1 Motor Size 44
6.1.2 Gearing and resulting output 44
6.1.3 Design 45
6.1.4 Drawbacks 45
6.2 CONCEPT 3 - GEAR DRIVE 46
6.2.1 Motor Size 47
6.2.2 Gearing and resulting output 48
6.2.3 Design 48
6.2.4 Drawbacks 49
6.3 STEERING ANGLE LIMITER 49
6.3.1 Design 49
6.3.2 Dimensioning 50
6.3.3 Fitment in the steering column 50
6.4 INCREASED AXIAL ADJUSTMENT 52
6.4.1 Modifications 52

7 TEST OF CONCEPTS 53

7.1 MEASUREMENTS 53
7.2 ADJUSTABILITY 56
7.3 CRASH SAFETY 57
7.4 FUNCTIONALITY 57

8 DISCUSSION 60

8.1 SOCIAL, ETHICAL AND ECOLOGICAL ASPECTS 60
8.2 MATRIXES 61
8.3 FURTHER DEVELOPMENT 61
8.3.1 Possible improvements to concept 2 61
8.3.2 Possible improvements of concept 3 62
8.3.3 Prototype **Fel! Bokmärket är inte definierat.**
8.3.4 Double telescopic adjustment 62
8.3.5 Electrical adjustment 63
8.4 TRANSGRESSIONS 63

9 CONCLUSION 65

10 BIBLIOGRAPHY 66

1 Introduction

The introduction gives a brief explanation of the relevant background information needed to understand the aim and limitations described.

1.1 Background

Traditionally, there is a physical connection between the steering wheel in a car and its steering rack. Volvo Cars is one of the companies that are evaluating the possible implementation and execution of a steer-by-wire system in an automotive setting. Steer-by-wire replaces the physical connection with an electrical connection. Steer-by-wire offers multiple advantages over mechanical steering. It enables continuously variable gearing and eliminates any need for a physical steering shaft, which in turn removes constraints on the placement of the hand-wheel actuator (HWA), allowing for greater flexibility.

To achieve this, components such as a motor used for force feedback are added. This creates the challenge of adding components without adding to the overall length or infringing on any other critical dimension. The total length of the HWA is especially important as it is directly connected to the maximum cabin volume achievable with any given chassis.

1.1.1 Volvo Cars

Volvo Cars has manufactured vehicles for nearly one century. The company's first model, the Volvo ÖV4 marked the beginning of a legacy focused on production excellence, safety, and practicality.

Volvo Cars are deeply committed to safety, aiming for a future with zero fatal collisions. This dedication drives their continuous development of safety, aiming to ensure that every journey in a Volvo is as safe as possible.

Volvo Cars aims to go fully electric by 2030, but as the former CEO stated "at Volvo cars we are not dogmatic about our 2030 ambitions, most importantly is that we will provide products that our customers want. We will be ready to go fully electric this decade but if the market, infrastructure and customer acceptance is not quite there we can allow that to take a few more years." (Rowan, 2024). This displays their commitment to sustainability, flexibility and engineering excellence.

1.1.2 Steering Column

Since the invention of the car, steering has looked the same, a physical connection connecting the steering wheel with the steering axle and thereby the wheels. Although the main function has been the same throughout the years, giving the driver a means to change direction of the vehicle, the list of sub-functions has increased. Today a steering column needs to comply with multiple sub-functions. **Safety Features** allow the column to collapse and absorb energy during a collision, reducing the risk of the driver sustaining an injury. **Comfortability Features** include the adjustability of the steering wheel position allowing every user to achieve a comfortable driving position. **Electrical Connectivity** allows driver interfaces such as horn, turn signals and windshield wipers to be placed closer to the driver. **Anti-Theft Devices** such as a steering lock mechanism prevents theft by locking the steering wheel in place when the key is removed.

1.1.3 Steer-By-Wire

Steer-by-wire technology originates in the aerospace industry, with the introduction of fly-by-wire systems in the 1960s. The system replaced mechanical flight controls with electric wires and thereby the name. The electric controls enhanced precision, increased flexibility, and reduced weight. The system was redeveloped for automotive use and conceptualized in the early 2000s. According to (UNECE, 2025), legislation now allows for true steer-by-wire systems to be sold in consumer cars given that they meet the requirements.

1.1.4 The drivers of Steer-By-Wire

Consumer automotive is a very competitive industry, meaning companies constantly strive for improvements. Steer-by-wire allows for several benefits both for the end consumer as well as the assembly. The following points present a number of these benefits.

- **Driver Comfort** would be increased as steer-by-wire systems can filter out road vibrations and noise, leading to a smoother driving experience. As the system is electrically actuated the steering sensitivity and feedback can be adjusted to suit driver's preferences.
- **Improved Maneuverability** as a result of removing the physical connection between steering wheel and steering rack. This allows the rotation of the steering wheel and the rotation of the tires to be disconnected from one another, meaning turning the steering wheel 90° degrees can lead to different steering angles depending on factors such as vehicle speed.
- **Ease of Assembly** is contributed to the fact that the steering system assembly can be done in two parts. The steering rack and the steering column can be installed independently as no physical connection is needed between them. Additionally, this also allows for the same steering rack and -column to be fitted in LHD and RHD cars. Minimizing variations in car production across different markets.
- **Design Flexibility** as interior designers can utilize the fact that the steering column can be freely moved. This grants the designers bigger design-freedom from their end.

1.2 Problem

In order to unlock all of these benefits, the steer-by-wire steering column needs to accomplish everything the current steering column does and more. For example, a steer-by-wire steering column needs to have an active feedback device, this allows the driver to still feel forces acting on the tires such as resistance from rubbing on the sidewalk or simulating levels of road noise to ensure a sufficient driving-feeling. This means that the new steering column needs to add some parts but it cannot add to overall length as it would require the entire cabin to be re-designed. The main problem lies in preserving existing functionality and requirements during the transition to a steer-by-wire system. In this transition, a multitude of new components will be introduced to the system (force feedback device, ECU, sensors and gearbox). While some components will be removed it still leads to a net-increase in the number of components. This will have to be maneuvered as the size is restrained by the environment, which remains unchanged.

1.3 Aim

The purpose of this project is to develop and evaluate multiple concepts for a steer-by-wire hand-wheel actuator. The project aims to identify possible areas of improvement when adding a force feedback module to an existing steering column and using this information to generate several new concepts. The most promising concepts will be further developed and tested in CAD to evaluate compatibility.

1.4 Research Questions

Questions that the project aims to answer are the following:

- Which steer-by-wire concept is the most suitable when current parameters are considered?
- Does the current CMA platform allow for a steer-by-wire HWA to be retrofitted?
- Are modifications to the environment required for the new HWA to function properly?
- What are the social, ethical, and ecological aspects to consider on the research and development, both in terms of how the work is performed and what is being developed?

1.5 Ethics

Every design process has aspects of ethics. For instance, questions like "Is this ethical?" or "How ethical is this?". This project has several questions that should be continuously kept in mind. Some of the key points are presented below.

Accessibility: The range of adjustment of a steering column should accommodate drivers of various sizes and physical abilities. Ethically, it is important to ensure that the steering column can be adjusted to suit a wide range of operators.
Reliability: The steering column must be reliable and durable during the vehicle's lifespan. Ethical design requires rigorous testing to prevent internal failures that could lead to accidents.
Safety: Ensuring that the steering column is safe in all conditions is required, no design choice should compromise the safety of the operator.

1.6 Limitations

- During the course of this project, there will be several different components that will be touched upon, but only the mechanical parts will be processed and covered in this report.

- One limitation of this project is the absence of traceability for the stated requirements in chapter 4. Due to constraints in scope and time, no formal mechanism was implemented for tracking the requirements throughout this project. Every requirement was retrieved from Volvo Cars but cannot be traced back further than that.

- During the continued development of a concept, only a concept is created, not a fully developed product ready for production. This is done to show how the concept could work mechanically and not how the parts could be produced.

- The project will focus on the mechanical part on how torque feedback can be created and transferred to the steering wheel, the project will therefore use materials and components that are already used in the automotive industries or similar.

- No physical prototype will be constructed as a result of limited resources. The prototype will be restricted to 3D CAD-files and the verification methods will reflect this.

- When it comes to electrical adjustment, no time was allocated to retrofitting electric adjustment to the existing steering column. Because of resource management, a decision was made to focus on overall design of the concepts rather than retrofitting electric feedback to the steering column that was received for this project.

2 Methodology

This chapter gives an explanation of how the project was carried out, and which tools that have been used to inquire the results. This chapter presents each of the methodologies used for developing concepts and reducing the batch size to a manageable size. The work follows the Waterfall model, meaning each method builds on the results retrieved from the previous step. The work follows the Waterfall model,

2.1 Research Methodology and Investigation

In this step, data was gathered in different ways to provide a nuanced picture of existing concepts and potential difficulties the project has faced. The patent investigation has been an important step in generating ideas and making sure not to develop anything that is already patented. In order to make sure that Volvo cars requirements have been met, a requirements specification has been developed to evaluate different concept during the concept elimination and the end verification of the winning concept.

2.1.1 Patent and Market Investigation

In order to conduct a valuable patent and market investigation, it is important to have a specific goal with what to look for, since there are several patents for different parts of a steer-by-wire system. In this case, the important part of this project is to find out where to mount the torque feedback device and how to connect it to the steering wheel. Therefore, the patents that has been selected has different ways of mounting and connecting the torque feedback device to the steering wheel.

2.1.2 Requirement Specification

The requirement specification is an important step in understanding the requirements and wishes set by Volvo Cars. The requirement specification is an important part of the screening matrixes, this makes it important to get right from the beginning as it sets the rules for the generated concepts. Therefore, the requirement specification was approved by Volvo Cars early in the process.

2.2 Ideation of concepts

In order to generate concepts, a mind-map was created consisting of multiple technical methods for solving each sub-component of the steering column. Once all the individual solutions were generated, they were added to an algorithm that crossbreed the solutions, resulting in a substantial number of concepts generated.

2.3 Screening of Concepts

To reduce the number of generated concepts, different types of matrixes were used to eliminate the concepts that did not meet the requirements set. An Elimination Matrix was initially used to reduce the number of concepts. To further reduce the number of concepts Pugh Matrixes were used, ranking each concept in respect to another. Lastly a Kesselring Matrix was used to get a final ranking of the remaining concepts.

3 Analysis of Known Concepts

This chapter covers the current steering column used by Volvo Cars on their CMA-platform, relevant patents and concepts found on the market.

3.1 Evaluation of Current Steering Column

Volvo Cars currently deploy several variations of a steering column, the one being evaluated originates from the CMA-platform found in the modern Volvo 40-series. Figure 1 illustrates the steering column in question.

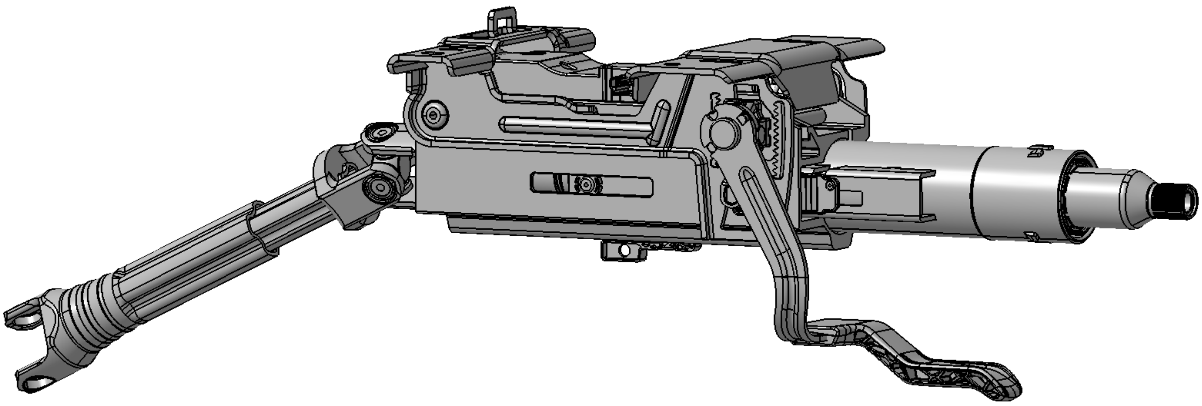


Figure 1 – Shows the steering column found on the CMA-platform. Retrieved from CAD-files.

3.1.1 Main function

The main function of the steering column is to transfer steering input through an adjustable, crash collapsible and theft protected column. Therefore, there is a need for multiple components that solve these needs. There are three bearings assisting in transferring the steering wheel input to the steering rack, this can be seen on figure 2 as number 1, 2 and 3. All of these bearings work together to give a smooth steering feel. Bearing number 1 sits fixed in place while bearing 2 and 3 moves with the upper jacket as highlighted in pink in figure 5. This ensures optimal function while still allowing for axial adjustment.

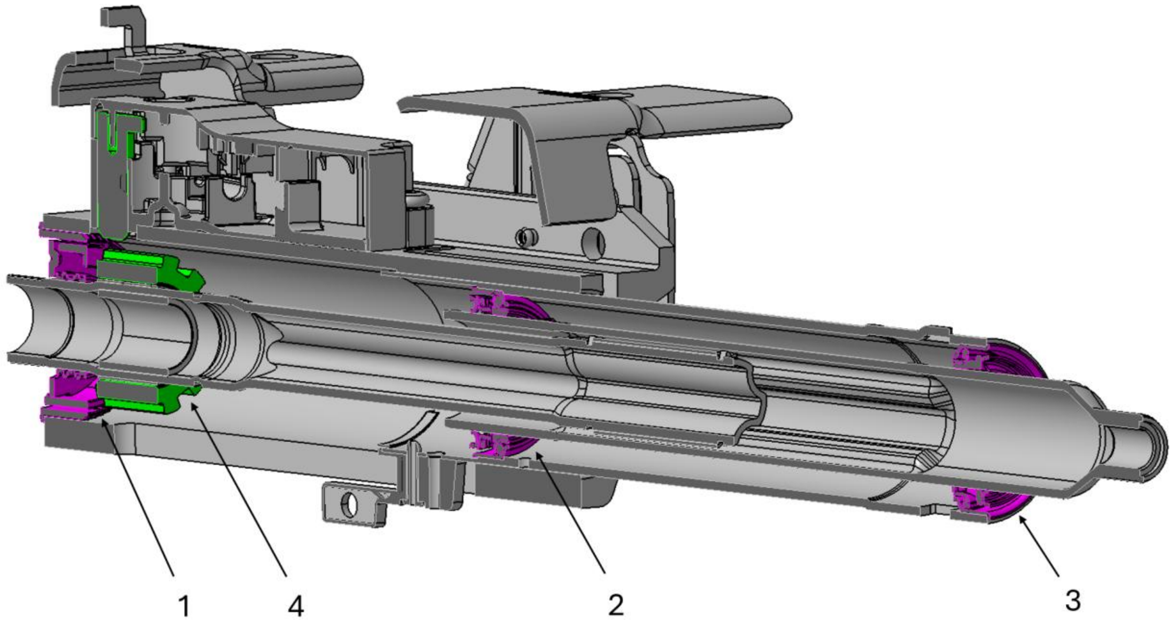


Figure 2 –Shows a section view of the steering column, marked in pink are the bearings and market in green are the steering lock.

3.1.2 Adjustment

Measuring the adjustment of height is complicated as it pivots around a pivot point making the steering column length a part of the equation. Therefore, the angle of adjustment was calculated to be 6.5°. The pivot point is marked in pink on figure 3 with the adjustment lock marked green.

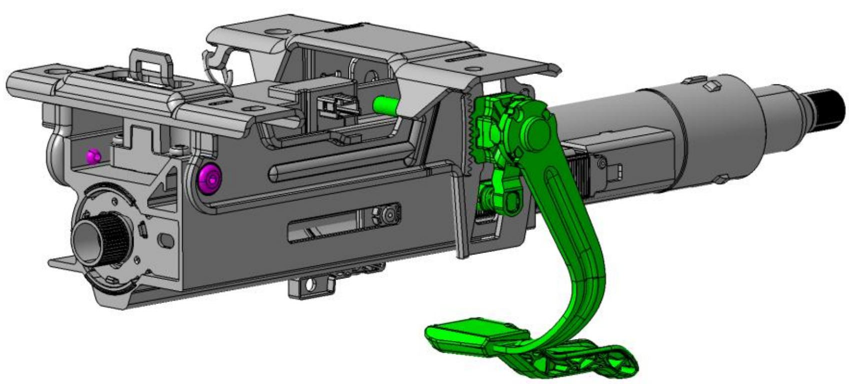


Figure 3 – Shows the pivot point for adjustment marked in pink and the adjustment lever marked in green. Illustrated with CAD files.

When the lever is pulled down the teethed part **2** is disconnected from the teethed plate **3** (see figure 4) allowing for axial movements of ±27.5 mm of the upper jacket (highlighted in pink as per figure 4 and 5). The outer- and innermost positions of the upper jacket can be seen on figure A1 and A2 in the appendix.

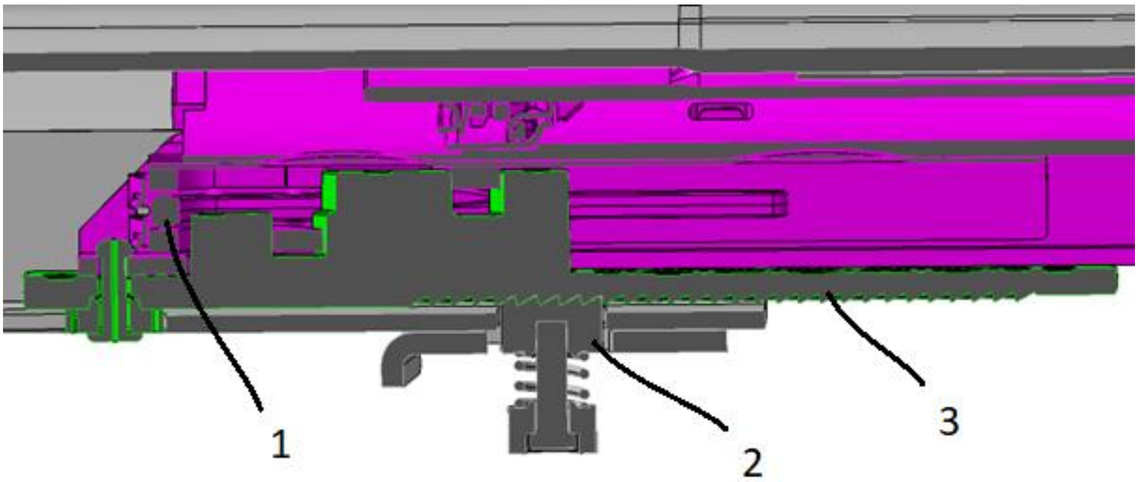


Figure 4 – Shows the deformation-strip from above, teethed plate and teethed component used for locking the axial adjustment.

3.1.3 Energy Absorption

In order to absorb energy in a severe collision, the steering column needs to contain components that can deform in a predictable manner, allowing for energy absorption regardless of the upper jackets position.

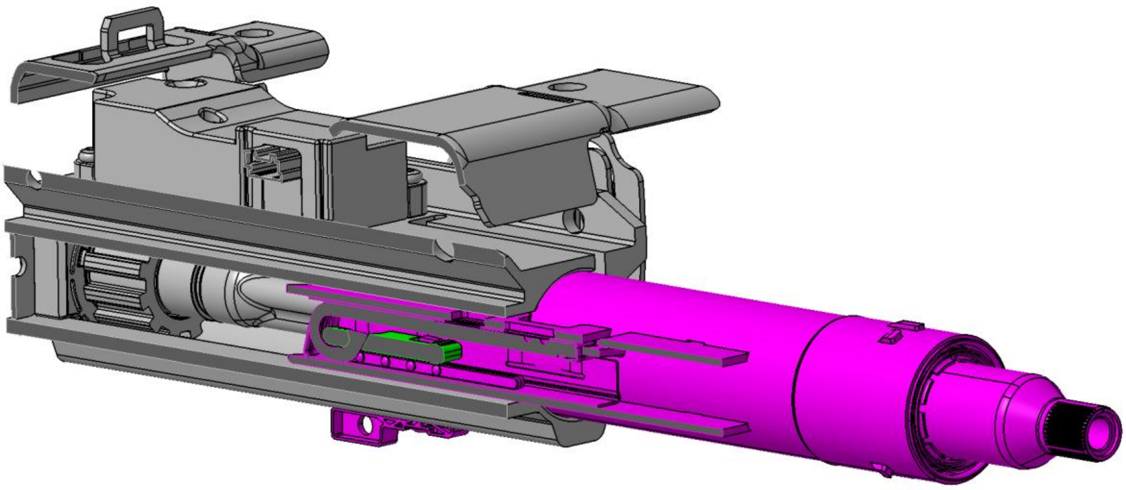


Figure 5 – shows the upper jacket and deformation-strip.

When an axial force directed from the operator pushes the steering wheel and thereby the column, the upper jacket highlighted in pink as seen in figures 4 and 5 will transfer the force via the absorption strip 1 as per figure 4. If the force is sufficient the strip will deform, absorbing energy until the upper jacket has collapsed and bottomed out. The collapsable length was approximately 11 to 90 mm, although it slightly differs from extended and retracted form as seen in figure A1 and A2 in the appendix. The part of the steering column that houses the energy absorption strip will be referred to as the “energy absorption device” later in this report.

3.1.4 Size and size limitations

The space where the steering column is situated is a quite crowded place in modern cars. Some of the components that must fit are as follows: knee airbag, HVAC system, pedals, cross car beam, electronic modules, mounting brackets and the driver’s legs. Therefore, it was determined that the steering column should minimize additional size/volume added in upward and downwards directions as these are the most crowded areas.

The size of the steering column in the existing car is therefore quite compact, with a length of 429.5 mm (total length of the steering column measured with the upper jacket positioned in the dead center of axial adjustment). The measurements are taken without the steering shaft that connects the steering column to the steering rack.

3.1.5 Steering lock

To make it harder to steal a car, a steering lock is installed in the steering column, this makes it hard to turn the steering wheel if the ignition is not turned on. As a result, it becomes more challenging for thieves to relocate the car. The part on the steering rack that is responsible for this function can be seen in figure 2 as number 4. This part is no longer needed since there is no physical connection between the steering wheel and the steering rack. This means that when the power is cut, it is not possible to steer the car using the steering wheel.

3.2 Patent Investigation

The patents have been collected from Espacenet which is a website where patents from the European Patent Office can be found. They have more than 150 million patents documented from all over the world which are free to the public via Espacenet (European Patent Office, 2025). To search for the patents, the search prompts used were (“steer-by-wire” AND “steering column”) and (“steer-by-wire” AND “hand actuator”), this resulted in 2784 and 4240 results respectively. The search prompts used narrowed the results to primarily car-related steer-by-wire systems, resulting in a large number of relevant patents. As a result, no further searches were conducted.

The most interesting patents were picked out and sorted into different groups depending on where the feedback device was positioned and how it was connected to the steering wheel. Three key functions were analyzed in the chosen patents, **1:** Use and placement of force feedback device, **2:** Solution for axial and pivot adjustment, **3:** solution for energy absorption in case of severe vehicle collision.

3.2.1 Patent 1 – Direct drive

The patent shows a solution using direct drive developed as part of the patent (Schulz, et al., 2025), this means that the steering wheel is directly connected to the motor shaft of the torque feedback device. The axial adjustment of the steering column is handled by slot **58** while slot **40** is housing the components used to lock the current position in place, this can be seen in figure 6 and 7. The patent notes an ability to adjust rake and thereby height of the steering column, but no components used for this appear in the documentation.

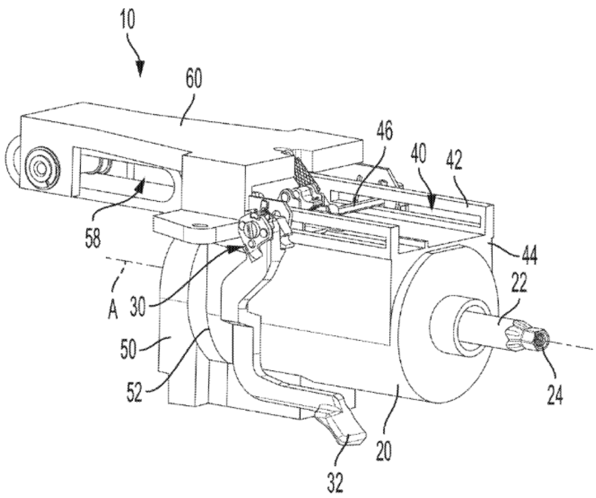


Figure 6 – Shows Steering Solutions IP holding (US2025010906A1) patent detailing a direct drive steer-by-wire HWA. Espacenet (2025)

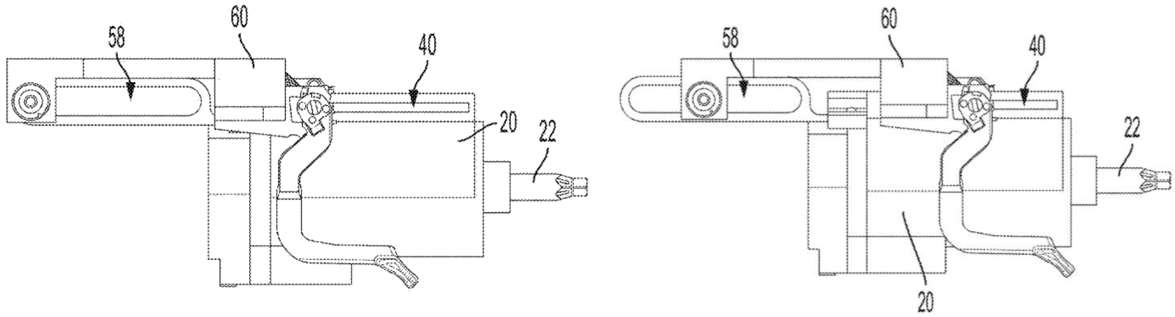


Figure 7 – Shows Steering Solutions IP holding (US2025010906A1) patent from a side-view with two different axial adjustments. Espacenet (2025)

In the case of a severe collision a force will be asserted on the HWA from the driver's direction illustrated by the blue arrow in figure 8. At a predetermined force a bolt will sheer as per the jagged line on the figure, this will allow the energy absorption strip **102** to deform within the red circle and absorb excess energy.

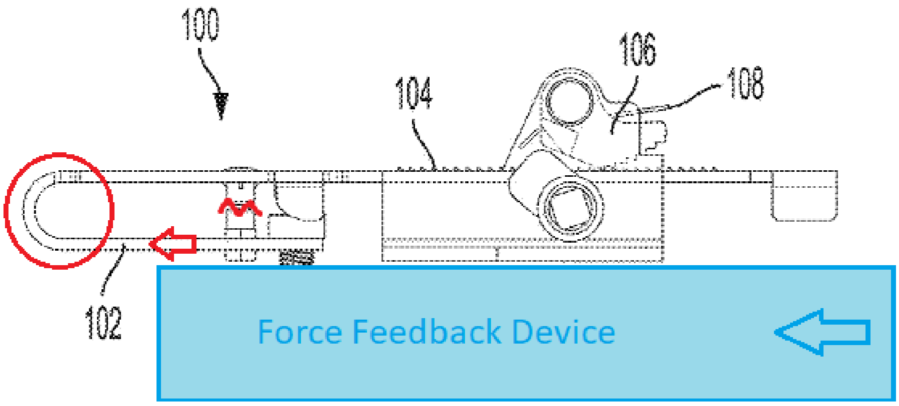


Figure 8 – Shows Steering Solutions IP holding (US2025010906A1) patent with a focus on the energy absorption component. Espacenet (2025). Further illustrated by the authors of this paper.

3.2.2 Patent 2 – Direct drive with telescopic shaft

The second concept (Anspaugh, et al., 2024) uses a telescopic shaft to divide the torque feedback actuator and steering wheel. This results in the motor being stationary while the axial adjustment and collapse zone only affects the upper jacket **19** as per figure 9.

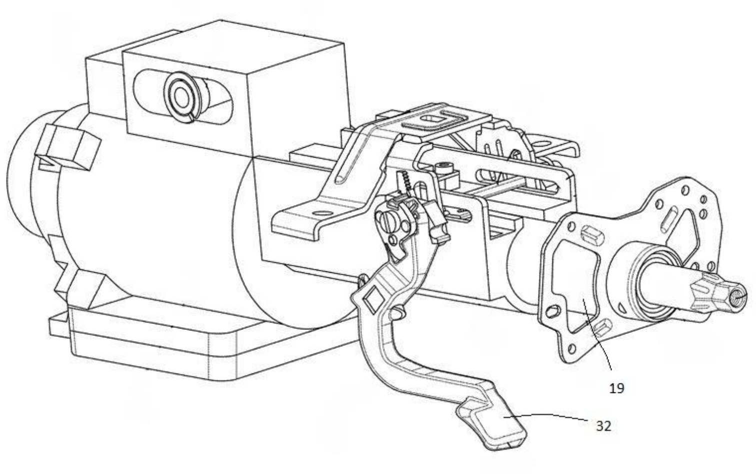


Figure 9 – Shows Steering Solutions IP holding (US2025010908A1) patent detailing a direct drive with a telescopic shaft steer-by-wire HWA. Espacenet (2025).

By disengaging the lever **32** as per figure 9 the teethed component **106** seen on figure 10 is disengaged from the teethed surface **104**, this allows for the axial movement of the upper jacket **19**. In case of a severe collision the energy absorption strip **102** deforms like the previous concept and allows the upper jacket **19** to move and absorb energy even though the adjustment is locked.

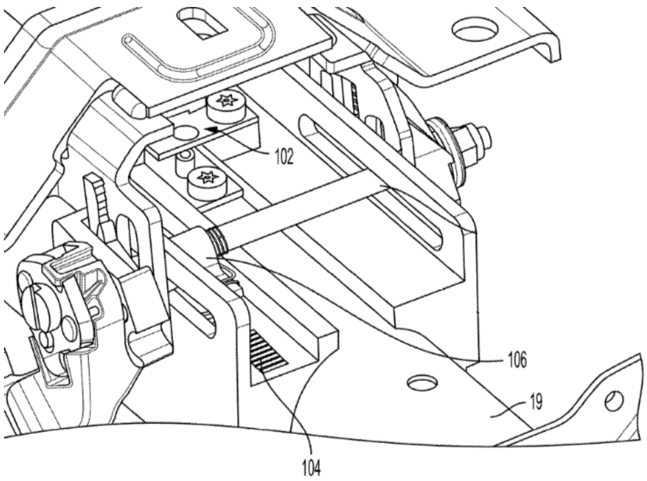


Figure 10 – Shows Steering Solutions IP holding (US2025010908A1) patent detailing the axial adjustment lock and energy absorption. Espacenet (2025).

3.2.3 Patent 3 – Direct drive with telescopic shaft

Another HWA with a telescopic adjustment and direct driven feedback is (Dannhäuser, Raber, & Vogel, 2025) figure 11. This patent achieves a high torque feedback by using both an electric motor and a brake band wrapped around a break disk.

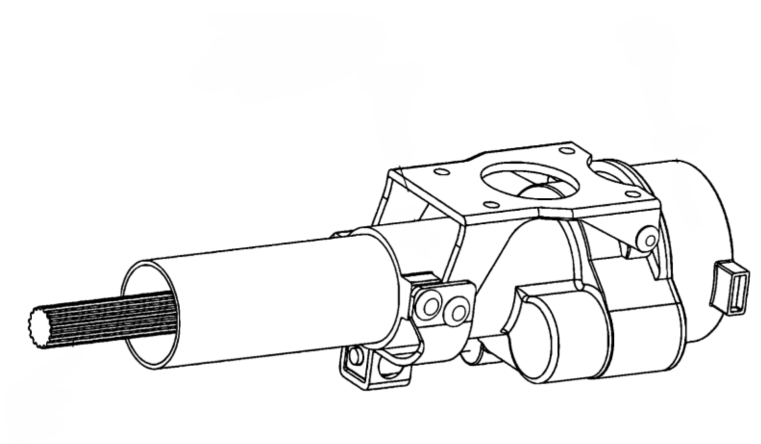


Figure 11 – Schaeffler Technologies Ag (DE102023119175A1) patent detailing a parallel torque feedback device belt driven steer-by-wire HWA. Espacenet (2025).

The brake band **8** is wrapped around the brake disc **6** which is adjusted with an electrical motor **14**, in figure 12. The brake band generates passive feedback while a primary electric motor handles the active feedback. The torque feedback motor is mounted on the back of the steering column and the break band and disc are mounted just in front of it. Since the force feedback motor only needs to comply with requirements on active feedback torque which are generally smaller than the requirements set on passive feedback. The motor can be made smaller and thus reduce the HWA overall length. The break band is constantly adjusted with the use of a small electric motor to achieve the desired passive torque.

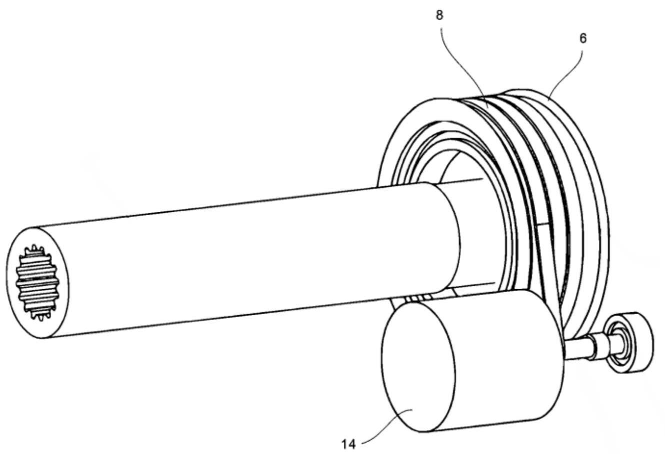


Figure 12 – Schaeffler Technologies Ag (DE102023119175A1) showing the brake band design. Espacenet (2025).

The patent does not explain how the HWA is going to be adjusted. Neither does the patent explain how the HWA complies with requirements set on crash safety.

3.2.4 Patent 4 – Parallel torque feedback device

The patent from (CUNQIANG, et al., 2023) is a patent where the torque feedback device is connected to the steering column via a pulley system, figure 13. The system has one motor that is mounted on the side of the steering column. According to the patent, one of the reasons to use a pulley system is to reduce the problems that come with worm gear, such as jamming and abnormal noise. To limit the amount of turns the steering wheel can turn, the HWA is equipped with a limit locking mechanism consisting of a thread and a guideblock that limits the number of turns. The pulley system is geared for optimal torque and allows the size of the feedback device to be decreased. The pulley system is driven via a belt that reduces the noise and vibration.

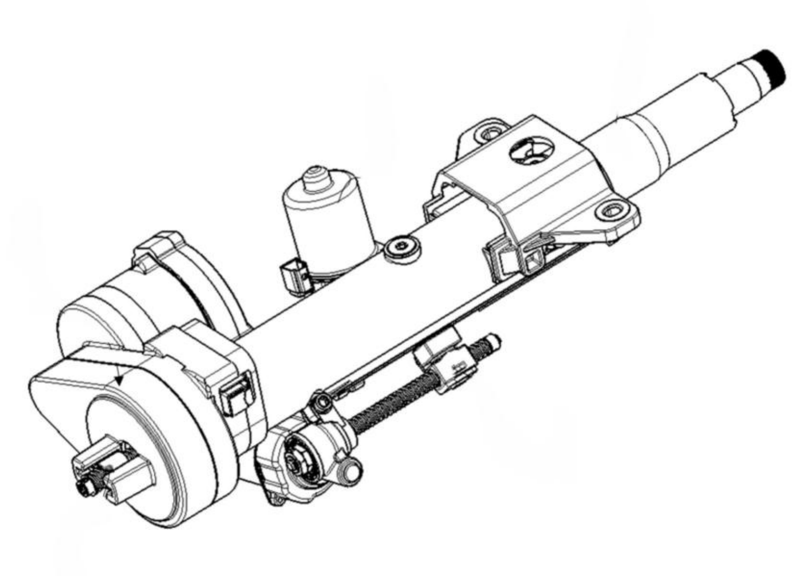


Figure 13 – Shows Shanghai Tongyu Automotive Tech Co Ltd (CN116873025A) patent detailing a parallel torque feedback device belt driven steer-by-wire HWA. Espacenet (2023).

The adjustability of the steering column is explained to be done via two electrically driven motors, both length and angular adjustment are possible. This is done via lead screws, which is an effective way of precise adjustments with a small motor that also locks in position because of self-locking threads. The patent does not explain how the HWA complies with the requirements set on crash safety.

3.2.5 Patent 5 – Torque feedback device connected via a worm gear

The patent (Steinkogler & Galehr, 2020) details a concept that takes some of the benefits that come with steer-by-wire and ads them to a traditional mechanical steering system, figure 14. Driver feedback is generated by an electric motor **13** (connected via a worm gear), the motor-position is measured with sensors that send the data to a central control unit. The data is then processed and sent to Motor **2** (connected via a worm gear) which drives the steering axel **7** and thereby the steering rack and the wheels as per figure 15. The patent (Steinkogler & Galehr, 2020) details a concept that takes some of the benefits that come with steer-by-wire and ads them to a traditional mechanical steering system, figure 14. Driver feedback is generated by an electric motor **13** (connected via a worm gear), the motor-position is measured with sensors that send the data to a central control unit. The data is then processed and sent to Motor **2** (connected via a worm gear) which drives the steering axel **7** and thereby the steering rack and the wheels as per figure 15.

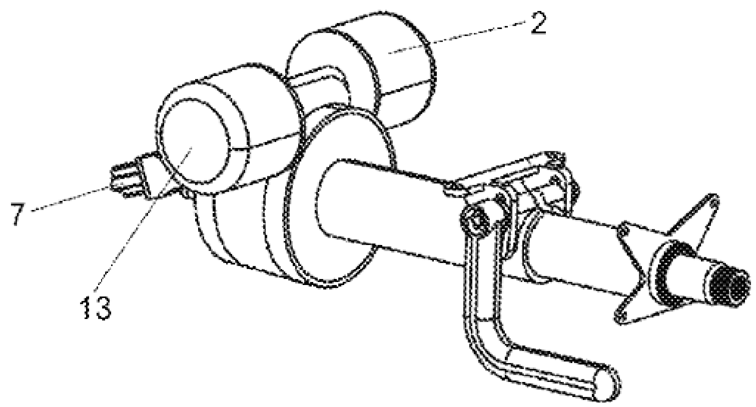


Figure 14 – Thyssenkrupp Presta Ag (US10597068B2) patent detailing a torque feedback device worm gear driven steer-by-wire HWA with two motors. Espacenet (2020).

As per figure 15 the part marked in blue carries the driver's steering input as well as the feedback produced by motor **13**. Motor **2** rotates the parts marked in red and drives the steering axel **7** independently of the blue area (steering input).

In the case of a critical malfunction to the steer-by-wire system a clutch **100** can be locked, locking the blue and red area and thereby give a direct mechanical path from the steering wheel to the steering rack, making it behave as a traditional steering system.

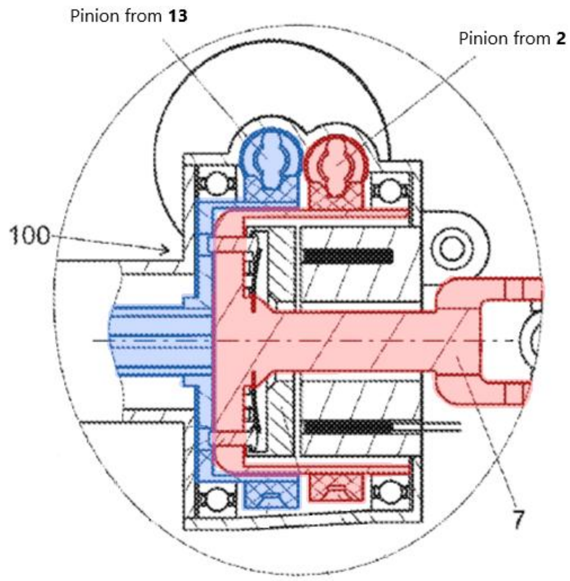


Figure 15 – Thyssenkrupp Presta Ag (US10597068B2) patent with focus on the pinions extruding from each motor and the clutch separating them. Espacenet (2020). Further illustrated by the authors of this paper.

3.2.6 Patent 6 - Torque feedback device connected via a worm gear

Another patent that uses worm gear as a primary transmission of the force feedback is (Kwon, 2024) figure 16. This patent is primarily focused on how much you can turn the steering wheel and how to limit the number of turns. Therefore, this patent does not explain anything about crash safety, the adjustability of the HWA or about how the torque feedback device is used. But it is still possible to get some ideas from how it is possible to mount a motor with a worm gear as a feedback device.

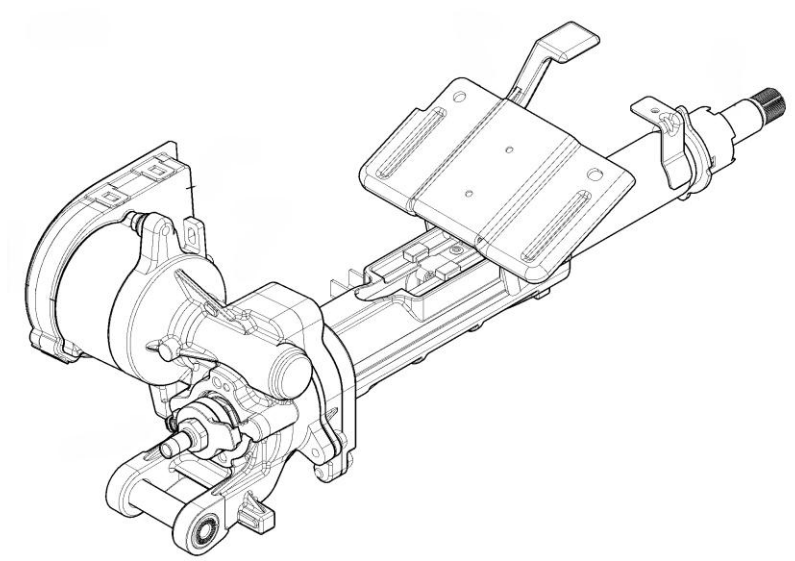


Figure 16 – Hl Mando Corp (US2024383521A1) patent detailing a parallel torque feedback device worm gear driven steer-by-wire HWA. Espacenet (2024).

In this patent, the motor and worm gear are mounted at the end of the steering column. Since the use of a worm gear transmission, the motor can be moved to the side of the steering column and a smaller motor can be used because of the gearing. Therefore, the motor can accommodate a high torque despite its small size.

3.3 Market Investigation

By investigating the market as a whole, parts of a solution can be found from sectors not necessarily connected to the one of interest. By investigating these concepts, ideas can be taken and implemented in a new solution for the automotive market.

3.3.1 Automotive Sector

There are several consumer cars that partially use steer-by-wire, these cars use a traditional steering column with the addition of a steer-by-wire system for the control of the rear tires. Some cars did use steer-by-wire for the control of the front tires but due to safety concerns the systems used a clutch to allow for a backup steering axel to be used as a safety precaution. This was done similarly to patent 4 presented earlier.

3.3.1.1 Tesla Cybertruck

Tesla Cybertruck is one of the first “true” steer-by-wire system of any production car, meaning the complete removal of a steering shaft.

The steer-by-wire HWA developed by Tesla (shown in figure 17) uses a parallel mounted belt driven electric motor for torque feedback. This offsets the motor from the steering axis meaning the overall length can be decreased as it builds on the width rather than the length. Additionally, the gearing provided by the belt connection allows the torque from the motor to be increased and thereby the motor-size to be decreased.

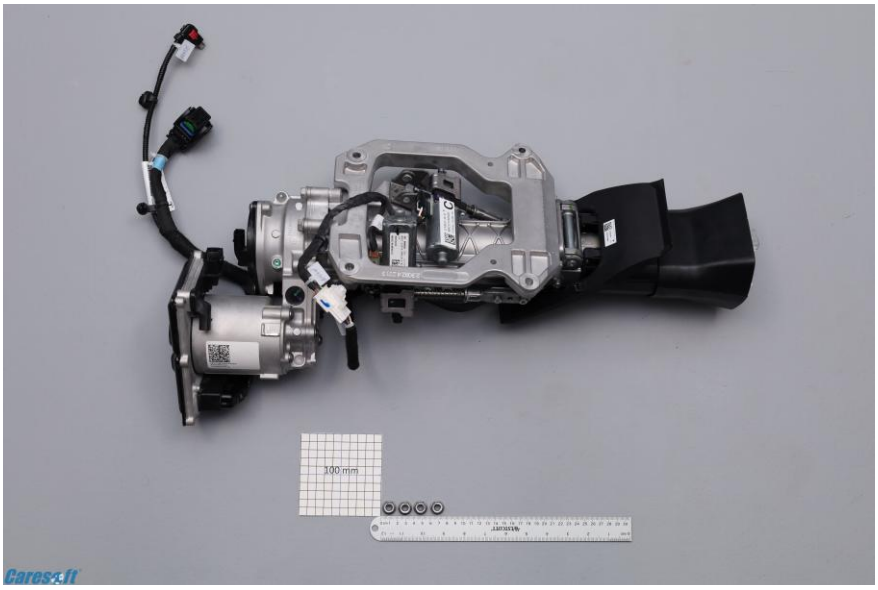


Figure 17 – Tesla Cybertruck HWA as per images retrieved from (Caresoft Global, 2025).

The complete steering column is measured to 685 mm in its extended form with the minimum length being 625 mm, this implies that there is an adjustable length of ~60 mm and therefore ~±30 mm of axial adjustment. The collapse length is visually approximated to ~90mm no matter the adjusted length. The information was approximated using ICEBERG, a software produced by (Caresoft Global, 2025).

The Tesla Cybertrucks steering column is electrically adjusted, this is done via two electric motors connecting to a lead screw which does the movement of the steering wheel. Most of the automotive companies with electrically adjusted steering wheels use this kind of system.

3.3.2 Maritime Sector

The maritime sector has many ways of steering a ship depending on which drive system is used. Usually, it is done via metal-wires on smaller boats and hydraulically or electrically on bigger boats. In the construction sector, the use of hydraulic steering is usually the primary system, but steer-by-wire is getting more common. One of the solutions for achieving electrical steering with adjustable steering torque is Parker Lord with their system called CAN-Enabled Tactile Feedback Device (TFDTM). It uses magnetic flux to generate a magnetic field that affects a material in the device, which they call MR Material, this can be seen in figure 18.

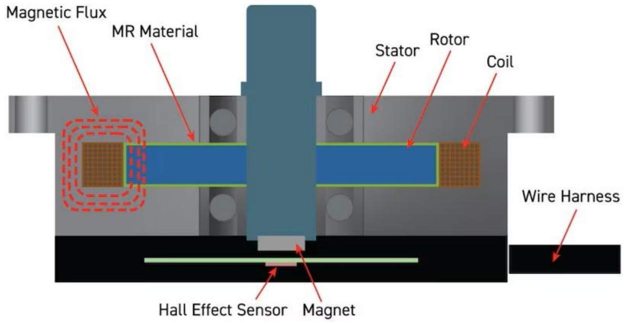


Figure 18 – CAN-Enabled Tactile Feedback Device (TFDTM), produced by Parker Lord.

When the MR Material gets affected by the magnetic flux, it gets harder to turn the steering wheel which gives feedback to the user. The key reason for why this is used is because you can achieve a high torque from a small device and that the device can achieve this torque with a low current. Note that this can only generate passive feedback and lacks the possibility of forced/active feedback.

3.3.3 Other Sectors

While steer-by-wire is also utilized in the aerospace industry, the hand-wheel-actuator (HWA) presents no major parallels due to substantial difference in cockpit architecture, operational environments and systems requirements.

Another sector that may appear similar is the gaming industry, particularly sim racing. The only relevant similarity is the use of a feedback device to transfer torque to the driver. Key aspects such as crash safety, adjustability, steering lock, and packaging constraints are not present. Therefore, no in-depth analysis was conducted within this project. The only aspect considered was how torque is transferred to the steering wheel, typically via direct drive or belt drive systems.

3.4 Assessment of sub-solutions

Direct drive involves a steering wheel directly connected to the motor shaft of a torque feedback device, this can be further developed by adding a telescopic shaft in-between the motor and steering wheel to separate the axial movement of these components. There are also multiple benefits to moving the torque feedback device to the side of the steering shaft. Firstly, it can save space along the axial length and secondly the gearing allows an increase in torque transmitted from the torque feedback-device to the steering shaft. By switching from gears or belt drive to worm gear the motor could be placed even more freely but with the drawback of increased energy losses due to high friction. The use of a magnetic brake for passive torque generation is not sufficient on its own for implementation in automotive steer-by-wire as the device solely applies torque on the force applied on the steering wheel by the operator and does not give force feedback to the driver.

4 Requirements Specification

Together with Volvo Cars, a Requirement Specification has been developed which shows both the requirements and wishes that the concept should meet, this can be seen in table 1. In the requirements specification, target values were established to verify the concepts and eliminate the ones that cannot meet the desired targets. The targets are comprised of requirements and wishes, the requirements must be met while the wishes are only used for sorting out the concepts that meet targets set above expectations. The verification method describes the technique that will be used for confirmation.

Table 1 – Requirement specifications, (R = Requirement, W = Wish)

Chalmers		**Dokument:**	**Requirements specification**		
		Project:	Steer-By-Wire HWA		
Author: Leo Ekström, Loke Lindblad			***Created:*** 2025-01-22		
			Modified: *2025-05-01*		
	Criterias		***Targetvalue***	***R/W***	***Verification method***
1.	**Measurments**				
	1.1	Clearance to firewall	Maximal	R	Measurement in CAD
	1.2	Total length	Minimal	W	Measurement in CAD
	1.3	Radius (from central axis)	Minimal	W	Measurement in CAD
	1.4	Symmetry (left/right)	Yes	W	Visual inspection
	1.5	Fit in allocated space	Yes	R	Verify in environment
2.	**Adjustability**				
	2.1	Length adjustment	Equal to today	R	Measurement in CAD
	2.2	Length adjustment	More than today	W	Measurement in CAD
	2.3	Electric adjustment	Yes	R	
3.	**Crash saftey**				
	3.1	Collapse zone	Greater or equal to current	R	Measurement in CAD
	3.2	Mass on collapsible parts	Minimal	W	Measurement in CAD
4.	**Functionality**				
	4.1	Cogging torque	Minimal	W	Physical test
	4.2	Friction torque	Minimal	W	Physical test
	4.3	Peak brake torque	[redacted]	R	Calculations
	4.4	Peak brake torque	Maximal	W	Calculations
	4.5	Peak active feedback	[redacted]	R	Calculations
	4.6	Peak active feedback	Maximal	W	Calculations
	4.7	Steering angle limiter	[redacted]	R	Calculations
	4.8	Steering angle limiter	[redacted]	W	Calculations
	4.9	Steering angle limiter, torque to failure	[redacted]	R	Calculations
	4.10	Angular velocity	Mimic todays steering	R	Calculations
				R	
	4.11	Backlash	[redacted]	R	Calculations

The requirement specification in this report has been simplified by replacing the actual target values with descriptive text outlining the intended goals, as the exact values are confidential.

1.1 **Clearance to the firewall** measures the distance between the steering column and the firewall located between the cabin and the engine bay on a car. This buffer zone is critical from a safety standpoint.
1.2 **Total length** refers to the total length of the steering column, measured at the “central position” meaning ±0 mm of adjustment.
1.3 **Radius from central axis** describes the distance from the central axis to the further most point found on a cross-section.
1.4 **Symmetry** refers to the symmetry across a vertical axis from a drivers point of view.

2.1 And 2.2 **Length adjustment** refers to the axial adjustment allowed by driver. (“+” is the direction towards the driver, “-“ is the direction towards the dashboard)
2.3 **Electric Adjustment** is the incorporation of motors for adjusting the steering columns position buttons rather than a physical lever.

3.1 **Collapse zone greater or equal to current HWA** refers to the ~90mm of collapsable length found on the current steering column.
3.2 **Minimal mass on collapsible parts**, meaning the mass that moves as the driver is pushed forward in the case of a severe collision. If the mass is too high the inertia would cause greater resistance as the driver is pushed forwards. This would in turn increase the risk of injury to the upper body as the steering column would be stiffer.

4.1 **Max cogging torque** refers to torque required to overcome the cogging created by the permanent magnets in an electric motor.
4.2 **Friction torque** is the additional torque required to overcome internal friction in the system. If there is too much internal friction a torque sensor needs to be placed close to driver as to give correct sensor readings.
4.3 And 4.4 **Peak brake torque** refers to the minimum torque required for limiting the movement of the steering wheel. Stopping the driver from moving the steering wheel faster than the steering rack can handle.

4.5 And 4.6 **Peak active feedback** refers to the minimum torque any active feedback device paired with a connection should produce.

4.7 And 4.8 **Steering angle-limiter** is required to limit the steering wheel angle as per not damaging the clock spring, which carries all the signals to the functions placed on the steering wheel.

4.9 **Steering angle limiter torque to failure**, is the torque that the steering angle limiter needs to withstand before failing.

4.10 **Angular velocity** is the speed that the steering wheel needs to be able to spin under its own power.

4.11 **Backlash** refers to the backlash (play) between the steering wheel and the force feedback-device.

5 Concept Generation and Screening

In order to create a mind map the system must be divided into its sub-components. This allows solutions for each sub-component to be generated individually, breaking the process down in to smaller and more manageable steps.

The main sub-functions that were identified can be summarized as following:

- **Feedback and Connection** covers the components that handle the simulation of a steering shaft. Simulating a connection between steering wheel and tires, this includes some sort of active and passive feedback as well as the method used for connecting the feedback device to the steering wheel.
- **Adjustment and Collapse Zone** includes the axial and vertical movement of the steering column as well as the collapse zone meant to absorb energy in case of a severe crash. This zone allows for axial movement outside of the ordinary adjustment interval.
- **Steering Angle Limiter** sets a hardware limit to the number of rotations allowed of the steering wheel. This is needed to protect the clock-spring located inside of the steering wheel from snapping due to excess turns.

A mind map allowed several possible solutions to be identified for each sub-function, breaking the system down into smaller and more manageable parts.

A Morphological matrix was used to create a large number of concepts using a limited number of sub-solutions by a method called "crossbreeding". The project delt with a large system containing multiple sub-functions and a vast number of sub-solutions. To keep the number of concepts generated manageable the system was divided into three independent parts, meaning a smaller and more manageable number of concepts where generated and evaluated individually before being combined. This reduced it from one large matrix containing approximately 500 000 solutions into three smaller and more manageable matrixes.

An Elimination matrix was used to eliminate the solutions that could not fulfill the requirement set in the requirement specification. Each possible concept was evaluated and compared to the requirements, eliminating all of the weakest concepts. This is done by giving the concept a "+"

for each requirement it could satisfy and a “-“ for every requirement that could not be meet. If more information was needed to evaluate a concepts performance for any given requirement a ”?” was set. As soon as a concept could not meet one or more requirement it was eliminated.

A Pugh matrix was used to reduce the number of possible solutions by comparing each solution to a reference solution. When the solutions were compared, they got a “+”, “-“ or “0” depending on how it performs compared to the set reference. This is done twice with two different reference solutions to see how the results were altered depending which concept was set as a reference.

Kesselring matrix was used to further eliminate solutions by giving each solution a score that was weighted depending on how important the requirement or wish was. Firstly, a matrix was created for weighting every requirement/wish based on its importance in reference to each other. Ranking a requirement, 0 if it was less important, 0,5 if it was equally important and 1 if it was more important than the referenced requirement/wish. The weighted score was then summarized and added to the Kesselring matrix. Additionally, every concept was ranked on a scale from 1-5 depending on how well it accomplishes the task. The concept was granted a 3 if it just manages to complete the requirement/wish, a higher number if it performed better, likewise a lower number was given if it performed worse. This score was then multiplied by the weighted value and summarized into a final score for each concept. This score indicates the rank given to each concept, higher equals better. Once the sub-solutions were generated and screened, they were combined and presented in 5.6.

5.1 Brainstorming and Mind map

The mind map found in appendix as figure A3 illustrates the mind map including sub-function and given sub-solutions. As stated previously the sub-functions were identified as **Feedback and Connection**, **Adjustment and Collapse zone** as well as **Steering Angle Limiter**.

5.1.1 Feedback and Connection

Three types of feedback were identified, being **Active**, **Passive** and **Semi-Passive**. These feedback types work differently and give different results, this has been presented below.

Additionally, these feedback options can be connected in several different ways leading to different pros and cons.

Active Feedback or Force Feedback can be summarized as forces generated in the opposing direction of the steering wheel movement or any force applied to move the steering wheel without input from the operator.

Passive Feedback acts as a break, constantly breaking the rotational movement produced by the operator. As seen in the requirement specification most of the torque produced by the steering column is used for braking rather than active feedback. By adding a passive feedback device, the size of the active feedback device can theoretically be decreased.

Semi-Passive Feedback also acts as a break, breaking the incoming rotational movement but as opposed to the fully passive feedback we can adjust the amount of breakage produced by this device.

Connection refers to the method used for transferring the power from the feedback device, this allows for different gearings and positions of the feedback device.

5.1.2 Adjustment and Collapse zone

Adjustment and collapse zone go hand in hand as both require space for movement, the main difference being that the collapse zone needs to be able to absorb a sufficient amount of energy no matter the adjustment position.

Axial Adjustment can be done in different ways, firstly the steering column can be moved as a unit similar to patent 1 presented in the patent investigation. Secondly a telescopic shaft can be utilized between the feedback device and the steering wheel to allow for parts to be moved independent of each other as illustrated in figure 19 below.

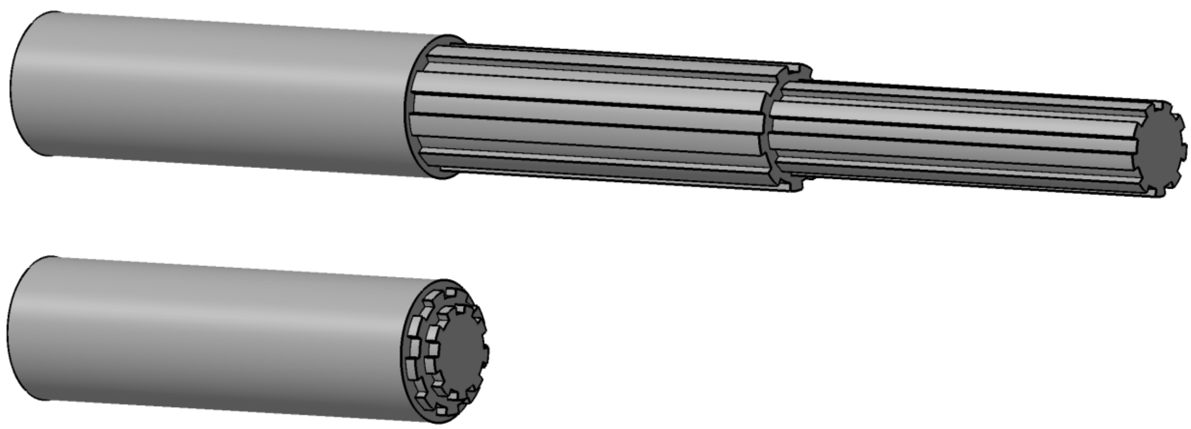


Figure 19 shows a double staged telescopic shaft with splines. Illustrated in the form of CAD-models created by the authors of this paper.

Lastly one sub-solution describes a pneumatic/hydraulic cylinder, the cylinder would be actuated via compressed air or hydraulic fluid to adjust the steering columns overall length similarly to the telescopic shaft.

Height Adjustment can be achieved either by pivoting the steering column like the existing CMA-column (see 3.1.2) or by moving the entire steering column vertically.

The **Collapse Zone** collapses the steering column in forward direction of the driver. Like the axial adjustment this can either be done including the entire steering column or with the use of a telescopic shaft to reduce the moving parts.

5.1.3 Steering Angle Limiter

Limiting the steering wheel rotation with hardware is important to protecting the clock spring as discussed before. The three main solutions have been created on how to limit the turns by the steering wheel.

Washer with Tab is a solution based on having a washer or several washers to adjust the total amount of turns the steering wheel can do. This is done by the tabs on the wasters hitting each other and hitting a solid endpoint which will limit the total amount of turns the steering wheel can do. By using several washers, more turns can be achieved before the washers have hit each other and the endpoint.

Thread and Guideblock is a solution where a type of screw is used for limiting the rotation. The threads are dimensioned to only allow that the block to travel up and down the treads the equal amount to the turns the steering wheel should turn. By keeping the block steady so that it only can move up and down, the thread will be the limiting factor of how many turns can be completed. This can be seen in the patent (CUNQIANG, et al., 2023).

Belt is a steering angle limiter where a belt is wound up on the steering axis and the end of the belt is connected to a fixed point which limits the turn the steering wheel can do in each direction. By changing the length of the belt or altering the size of the axis, the belt is wound upon, it is possible to adjust the turns the steering wheel can do.

5.2 Elimination of Weak Links (Mind map)

Some of the solutions that were created are far from optimal, which makes it unnecessary to continue creating concepts with them. Therefore, the sub-solutions that were determined to have the least potential were removed from the mind map to create a streamlined mind map. This new mind map had the solutions with the greatest potential to accomplish the requirements set in the requirement specification. Reasons for removing certain sub-solutions can be found below.

5.2.1 Feedback and Connection

Pneumatic or Hydraulic active feedback was considered as a possible solution, but it would have resulted in a complex system. For example, a compressor or hydraulic pump would be required. Additionally, a cylinder connected to a rack and pinion system would be needed to convert pressure into rotational movement. This concept is significantly more complex compared to other options, so the use of a hydraulic or a pneumatic systems for active feedback will not be further evaluated.

A **rack and pinion** system converts a linear movement into rotational movement, which was necessary when cylinders were used as a feedback device. Since a pneumatic or hydraulic cylinder was removed from the list of possible active feedback devices, the rack and pinion system is no longer required.

Passive feedback is a feedback type that is always engaged, meaning it cannot be disconnected from the steering wheel. Active feedback will always be required, so passive feedback must be complemented by separate active feedback. Since there is no possibility to disconnect the passive feedback, the active feedback must work against the passive feedback which is not optimal. This will lead to the need of a bigger active feedback. As the disadvantages outweigh the benefits, no further development will be pursued for a passive feedback sub-solution.

Achieving **semi-active feedback** is possible to do in several different ways, which can be seen in figure A3 in the appendix. Some of the solutions are difficult to control and get a smooth steering feel, theses sub-solutions include disc brake, drum brake and brake band. These solutions are challenging to adjust precisely and to monitor the braking torque applied, as it depends on factors like wear, temperature, and humidity. These solutions will also encounter break-dust and wear on the brake surfaces, meaning they likely require maintenance. Since there are existing solutions that are mostly maintenance free, disc brake, drum brake and brake band will not be further evaluated.

Because of the elimination of disc brake, drum brake and brake band, some other solutions can be eliminated since their connection to the steering axis is no longer used. The remaining solutions on the semi-active feedback are electromagnetic brake and high viscosity fluid. High viscosity fluid is the only one that will use rack and pinion as a connection and electromagnetic brake is going to be using direct drive or be connected on the same axis as active feedback. This means that electromagnetic brake will be using the same connection as active feedback. Therefore, some possible solutions will be eliminated in the Morphological matrix.

5.2.2 Adjustment and Collapse

Using a **hydraulic or pneumatic cylinder** as a steering column with built in adjustment would be both complex and hard to adjust reliably. Since air is compressible it is hard to get it to a fixed position and a compressor would be needed. If a hydraulic cylinder were used, the problem with movement would mostly be gone, but a hydraulic pump would be needed which makes the system quite complex compared to the existing solutions. Additionally, a telescopic axis would likely be needed to keep the feedback device stationary, further increasing complexity. Therefore, the use of a cylinder as a steering column will not be further investigated.

The **adjustment of the whole HWA** for vertical adjustment of the steering wheel is a more complex solution compared to adjusting the height via a pivot point in the back of the steering column. To adjust the whole HWA does not really come with any real benefits compared to the existing solution, therefore this solution will no longer be a sub-solution that is going to be further evaluated.

In case of a crash, the axial collapse of the steering wheel is an important part of the energy absorption of the human. It is important that the mass in front of the collapse zone is as small as possible to reduce the force needed to accelerate the mass. Therefore, the solution that the whole HWA would collapse is not optimal for crash safety, compared to the solution where collapse occurred between the feedback device and steering wheel. This results in the collapse of the whole HWA not going to be further evaluated.

To adjust the whole steering column axially is a solution that would benefit from where the whole steering column would collapse. But since the collapse of the whole steering column is eliminated as explained above, the justification for developing a system that can adjust the whole steering column is no longer deemed effective. Since there will be a need for 2 different types of axial movements, both for adjustment and for collapse. To use the axial movement for both adjustment and crash will result in a simpler and more cost-effective solution. Therefore, the adjustment of the whole steering column axially is no longer going to be evaluated.

5.2.3 Steering Angle Limiter

A **CVT** could be used to adjust the **steering angle limit** by varying when the steering limiter is applied, depending on driving conditions or driver settings. However, CVTs are typically designed to adjust gearing during continuous rotation, which does not occur when used with a steering angle limiter. Another issue is that a CVT capable of handling the required torque would be too large. The requirement specifies a torque-to-failure of over x Nm, while standard automotive CVTs are typically designed for around 300 Nm in a propulsion systems. Meeting the torque requirement without slip would likely result in a solution that is too large and complex compared to alternatives. Therefore, a CVT will not be further evaluated as a sub-solution.

5.2.4 Streamlined Mind Map

The streamlined mind map with the final sub-solutions can be found in the appendix as figure A4. Every sub-solution eliminated as per 5.2.1-5.2.3 have been removed.

5.3 Feedback and Connection Concepts

To reduce the total number of possible solutions from approximately 500 000 as explained previously the first three matrixes, Morphological-, Elimination- and Pugh-matrix were used for the concepts of feedback and connection. This is viable as Feedback and Connection are independent from the other sub-functions. By splitting the matrixes and working only with specific sub-functions there are far less solutions, making the outcome more manageable. The solutions from the Kesselring matrix were later combined with the result from the other independent sub-functions to create the final solutions.

5.3.1 Morphological Matrix

In the Morphological matrix, the solutions that remained after 5.2 were crossbreed to generate a list of solutions for feedback. The combination created in the Morphological matrix can be seen in table 2.

Table 2 – Morphological Matrix, presenting the crossbreed sub-solutions for feedback from the final mindmap.

Sub-Function	Active Feedback	Connection	Semi-Passive Feedback	Connection
1	Electric Motor	Direct Drive	No	No
2	Electric Motor	Belt Drive	No	No
3	Electric Motor	Gear Drive	No	No
4	Electric Motor	Worm-Gear	No	No
5	Electric Motor	Bevel-Gear	No	No
6	Electric Motor	Direct Drive	Electro Magnetic Brake	Direct Drive
7	Electric Motor	Belt Drive	Electro Magnetic Brake	Direct Drive
8	Electric Motor	Gear Drive	Electro Magnetic Brake	Direct Drive
9	Electric Motor	Worm-Gear	Electro Magnetic Brake	Direct Drive
10	Electric Motor	Bevel-Gear	Electro Magnetic Brake	Direct Drive
11	Electric Motor	Belt Drive	Electro Magnetic Brake	Belt Drive
12	Electric Motor	Gear Drive	Electro Magnetic Brake	Gear Drive
13	Electric Motor	Worm-Gear	Electro Magnetic Brake	Worm-Gear
14	Electric Motor	Bevel-Gear	Electro Magnetic Brake	Bevel-Gear
15	Electric Motor	Direct Drive	High Viscosity Fluid	Rack and Pinion
16	Electric Motor	Belt Drive	High Viscosity Fluid	Rack and Pinion
17	Electric Motor	Gear Drive	High Viscosity Fluid	Rack and Pinion
18	Electric Motor	Worm-Gear	High Viscosity Fluid	Rack and Pinion
19	Electric Motor	Bevel-Gear	High Viscosity Fluid	Rack and Pinion

5.3.2 Elimination Matrix

The concepts generated by the Morphological Matrix were further evaluated with an Eliminations Matrix reduce the solutions that cannot pass the requirements set in the requirement specification. Only the requirements that are relevant for feedback and connection are used in Elimination matrix. Quite a few of the solutions were hard to determine if they could complete the requirement for certain, therefore some solutions have a question mark to symbolize that. All the solutions have completed the Elimination matrix which means that no solution were eliminated, this can be seen in table A1 in appendix.

5.3.3 Pugh Matrix

To reduce the number of solutions, a Pugh matrix was used to compare how the different solutions theoretically would complete the requirements and relevant wishes. The first Pugh matrix as seen in table 3 used concept number 1 as a reference. This means that all of the remaining solutions were compared to concept 1. A second reference was used in table A2 found in the appendix, this was done to ensure sufficient quality of the retrieved data. The results from each Pugh matrix can be seen in table 4.

Table 3 - Pugh Matrix on Feedback and Connection 1.

Chalmers	*Document: Pugh Matrix, Feedback and Connection 1* *Project: Steer-By-Wire HWA*
Author: Leo Ekström, Loke Lindblad	*Created: 2025-02-27* *Modified: 2025-02-28*

Requirement/Wishes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Clearance to firewall	REFERENCE	+	+	+	+	-	0	0	0	0	+	+	+	+	-	0	0	0	0
Radius (from central axis)		-	-	-	-	0	-	-	-	-	-	-	-	-	-	-	-	-	
Max cogging torque		+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
Friction torque		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Peak brake torque		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Peak Active Feedback		0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Angular velocity		0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Backlash		0	-	-	-	0	0	-	-	-	0	-	-	-	-	-	-	-	-
Maintanance		0	0	0	0	0	0	0	0	0	0	0	0	0	-	-	-	-	-
Complexity		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Price		+	+	+	+	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Σ+	0	3	3	3	3	1	1	1	1	1	2	2	2	2	1	1	1	1	1
Σ 0	0	5	4	4	4	4	4	3	3	3	3	2	2	2	1	2	2	2	2
Σ -	0	3	4	4	4	6	6	7	7	7	6	7	7	7	9	8	8	8	7
Net	0	0	-1	-1	-1	-5	-5	-6	-6	-6	-4	-5	-5	-5	-8	-7	-7	-7	-6
Ranking	1	1	2	2	2	4	4	5	5	5	3	4	4	4	5	6	6	6	5
Further evaluation	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No

Table 4 - Clarification on the result from the Pugh Matrixes on Feedback and Connection.

Concepts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Feedback, Pugh Matrix 1	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	No	No	No	No	No	No	No	No
Feedback, Pugh Matrix 2	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No

As a result of the Pugh matrixes, concepts 7-10 and 12-19 were eliminated.

5.4 Adjustment and Collapse Concepts

After the weak links were eliminated as per 5.2, only two sub-solutions remained, these can be seen in table 5 below.

Table 5 – Matrix showing the sub-solutions for adjustment and collapse after elimination of weak links.

Sub-Function	Axial Adjustment	Height Adjustment	Collapse zone
1	Telescopic (Single)	Rotation around Pivot Point	Collapse between feedback and steering
2	Telescopic (Double)	Rotation around Pivot Point	Collapse between feedback and steering

The only difference between the two presented concepts were their choice between a single- or double-telescopic shaft for axial adjustment. As the original steering column utilized a single-telescopic shaft, the decision was made to not continue to evaluate a double-telescopic shaft. This decision was made to half the number of complete systems concepts presented in 5.6.

5.5 Steering Angle Limiter Concepts

Similarly to what was explained in 5.3, the screening-matrixes for steering angle limiting were carried out separately as to reduce the number of concepts to a more manageable batch.

5.5.1 Morphological Matrix

The morphological matrix was used to create combined solutions on steering angle limiting. The solutions created can be seen in table 6.

Table 6 – Morphological Matrix, presenting the crossbreed sub-solutions for steering angle limiter from the final mind map.

Sub-Function	Steering Angle Limiter	Multiplier	Adjustment
1	Washer with Tab/s	No	No
2	Washer with Tab/s	Multiple	No
3	Washer with Tab/s	Gearing	No
4	Thread and Guidblock	No	No
5	Thread and Guidblock	No	Continually Variable Endpoint
6	Belt	No	No
7	Belt	No	Continually Variable Endpoint

5.5.2 Elimination Matrix

The concepts generated by the Morphological Matrix were further evaluated with an Eliminations Matrix to eliminate the concepts that could not satisfy the requirements set in the requirement specification. Only the requirements that were relevant for steering angle limiter were used in the Elimination matrix, table 7.

Table 7 - Elimination Matrix Steering Angle Limiter.

Chalmers			Document: Elimination Matrix, Steering Angle Limiter Project: Steer-By-Wire HWA	
			Created: 2025-02-27 Modified: 2025-03-12	
			+ Yes - No ? Information is missing	+ Keep solution - Eliminate solution
Concepts	**Elimination Criterias**		**Comments**	**Results**
	Clearance to firewall	Steering angle limiter	Stering angle limiter torque to failure		
1	+	-	-	Limits to less than ±90°	-
2	+	+	+		+
3	+	+	+		+
4	?	+	+		+
5	-	-	-	Increases total lenght	-
6	+	+	+		+
7	+	+	+		+

Concept 1 utilized only one washer with tabs. The washers are constructed using two tabs to ensure sufficient redundancy and torque to failure. If one washer is used the angle is limited to less than ±90°.

Concept 5 used a similar steering angle limiter to the one presented in the patent as per 3.2.4, this concept adds substantial length to the overall HWA and was therefore eliminated.

5.5.3 Pugh Matrix

To further reduce the number of solutions, a Pugh matrix was used to compare how the different solutions theoretically would complete the requirements and relevant wishes. The first Pugh matrix as seen in table 8 used concept number 2 as a reference. This means that all of the remaining solutions were compared to concept 2. A second reference was used in table A3 found in the appendix, this was done to ensure sufficient quality of the retrieved data. The results from each Pugh matrix can be seen in table 9.

Table 8 - Pugh Matrix on Steering angle limiter 1.

Chalmers	**Document: Pugh Matrix Steering Angle Limiter 1**				
Author: Leo Ekström, Loke Lindblad			***Created: 2025-02-28 Modified: 2025-03-12***		
Requirement/Wishes	**2**	**3**	**4**	**6**	**7**
Clearance to firewall	REFERENCE	0	-	0	0
Radius (from central axis)		-	0	0	-
Degrees to limit		0	0	0	0
Stering angle limiter torque to failure		0	-	0	0
Complexity		-	-	0	-
Σ+	0	0	0	0	0
Σ 0	0	3	2	5	3
Σ -	0	2	3	0	2
Net	0	-2	-3	0	-2
Ranking	1	3	3	2	3
Further evaluation	Yes	No	No	Yes	No

Table 9 - Clarification on the result from the Pugh Matrixes on Steering Angle Limiting

Concepts	**2**	**3**	**4**	**6**	**7**
Steering Angle, Pugh Matrix 1	Yes	No	No	Yes	No
Steering Angle, Pugh Matrix 2	Yes	No	No	Yes	No

5.5.4 Assessment of Concepts

A belt can serve as an effective steering limiter, however, compared to a washer with tabs it has certain drawbacks that might outweigh its benefits. There is a risk of the belt becoming tangled if not designed properly. One advantage with the belt is its elasticity, this provides a softer impact as the limit is reached. The same effect can be achieved by fitting the washers with bushings on the tab faces. Therefore, there is no reason to further develop the belt as a steering angle limiter. In conclusion, only **multiple washers with tabs** were chosen to be further evaluated.

5.6 Complete System Concepts

The remaining concepts from 5.3-5.5 were combined, generating a final list of concepts. The concepts are explained further in the following sections to give a better understanding of how each concept works. The concepts are then assessed using a Kesselring matrix. Therefore, it is crucial to understand how each concept functions, to see why the concepts received the score it gets.

5.6.1 Concepts

The combined concepts are presented in table 10.

Table 10 – Final solutions of complete concepts.

Sub-Function	Active Feedback	Connection	Semi-Passive Feedback	Connection	Steering Angle Limiter	Multiplier	Axial Adjustment
1	Electric Motor	Direct Drive	No	No	Washer with Tab/s	Yes	Telescopic (Single)
2	Electric Motor	Belt Drive	No	No	Washer with Tab/s	Yes	Telescopic (Single)
3	Electric Motor	Gear Drive	No	No	Washer with Tab/s	Yes	Telescopic (Single)
4	Electric Motor	Worm-Gear	No	No	Washer with Tab/s	Yes	Telescopic (Single)
5	Electric Motor	Bevel-Gear	No	No	Washer with Tab/s	Yes	Telescopic (Single)
6	Electric Motor	Direct Drive	Electro Magnetic Brake	Dirrect drive	Washer with Tab/s	Yes	Telescopic (Single)
11	Electric Motor	Belt Drive	Electro Magnetic Brake	Belt Drive	Washer with Tab/s	Yes	Telescopic (Single)

5.6.1.1 Concept 1 – Direct Drive

Direct drive systems place the feedback device in direct connection to the steering axis, the motor then drives the steering axis directly. This direct transfer of power eliminates any backlash possibly caused by a mechanical transmission. The concepts simplicity proves to be a weak point, without a gearbox the motor size must be increased in order to comply with the required torque output. This increases its price in comparison to other concepts.

A planetary gearbox can be added to the end of the motor shaft to allow the torque output to be modified and therefore the engine size to be decreased. This comes with the additional drawback of further adding to the concepts total length and decreasing the length between firewall and steering column.

5.6.1.2 Concept 2 – Belt Drive

Belt drive is a system where the feedback motor is offset from the steering axis and placed parallel. This means that it is possible to place the motor on the side of the steering column instead of directly behind. It is also possible to change the gear ratio by adjusting the size of the belt pulley. Some advantages belt drive has is the quiet and smooth power transfer it can accomplish while being inexpensive. Backlash is not a problem with belt drive since the belt is partly elastic, this means that the belt can be tensioned around the pulleys and transfer power without any backlash.

A possible improvement to the solution could involve the use of two motors instead of one, distributing the load between them. This would reduce the distance that the motor protrudes beyond the original HWA, making it easier to fit the concept within the allocated space. However, there might be a need to implement a second belt to connect the new motor, this is to ensure a sufficient contact point between the belt and the pulleys. Doing so would further add to the steering columns length.

5.6.1.3 Concept 3 – Gear Drive

This concept utilizes a gear drive to connect the steering axis and the feedback motor, this functions similar to Concept 2 as the position of the motor remains the same. However, instead of using a belt and two pulleys, the system uses two gears to transfer the feedback.
One drawback of gear drive is that the gears can be quite large depending on how close the motor can be mounted to the central axis. Additionally, backlash is an important factor that must be carefully considered when designing any gearbox.

A second motor can be used to continuously apply torque in the opposite direction, effectively removing backslash. Similarly to the possible improvements described in Concept 2, this would distribute the size of the motor over two units and thereby decreasing the total radius of the concept.

5.6.1.4 Concept 4 – Worm Gear

A worm gear allows the motor to be placed orthogonally from the steering axis, this allows the concept to utilize space previously out of reach. In practice, a worm gear is often self-locking from rotational forces in one direction. This drawback can be eliminated by adjusting the thread pitch. But even with these adjustments the concept faces undesired properties in the shape of high friction losses, leading to the requirement of additional sensors.

5.6.1.5 Concept 5 – Bevel Gear

The concept utilizing a bevel gear presents the most flexible option for placing the feedback device, as its angle can be adjusted. This allows the motor to be mounted at almost any angle relative to the steering axis. It is also possible to move the input off center compared to the steering axis. The bevel gear also offers a vast range of gear ratios.

However, as a gear system, bevel gears are still susceptible to backlash. This issue could be resolved by incorporating a second motor, as outlined in Concept 3.

5.6.1.6 Concept 6 – Direct Drive + EMB

This concept adds a motor as well as an electromagnetic brake to the steering column via a direct drive connection. The electromagnetic brake can effectively provide braking torque, alleviating the motor and thereby reducing the required engine size as it only has to comply with the active feedback requirement. In addition to the increased complexity of having two devices working in synchronization, the electromagnetic brake exerts approximately 0.5 Nm of braking torque when turned off. This loss of efficiency requires the addition of sensors further adding to the concept's complexity.

5.6.1.7 Concept 11 – Belt Drive + EMB

This concept takes the electric motor and electromagnetic brake from the previous concept and offsets the devices from the steering axis using a belt driven connection. By doing so the concept total length can be reduced in comparison to the previous concept and a desired gear ratio can be achieved.

5.6.2 Kesselring

The Kesselring Matrix starts of by calculating the weight of each requirement/wish. Each row was compared to the column above the cell in question. “1” = The requirement stated on the row is more important than the one found on the top of the column, “0,5” = equally as important and “0” = less important than. The matrix can be seen in the appendix (table A4).

The weighted values were transferred to the final Kesselring matrix and can be seen in the column marked “W” in table 11. The columns marked “v” consists of each concepts criteria-score, the criteria-score is based on a 1-5 scale and describes how each concept performs at the given criteria, “3” means that the concept just meet the criteria. A higher number indicates an overachievement whilst a lower number means that the concept fell short. Column “W” and “v” were then multiplied to retrieve a weighted criteria-score, this can be found under the rows marked “t”.

Note that the concepts referred to in the Kesselring matrix in table 11 are the original solutions and do not take possible improvements into consideration. The adjustments evaluated at 5.6.1 were considered to not affect the outcome and were therefore not added as additional concepts.

Table 11 – Kesselring Matrix ranking the complete system concepts.

Chalmers		*Document type: Keselering Matrix, Complete System* *Project: Steer-By-Wire HWA*															
Author: Leo Ekström, Loke Lindblad									*Created: 2025-03-04* *Modified: 2025-03-06*								
		Concepts															
				1		2		3		4		5		6		11	
		Ideal		Direct Drive		Belt Drive		Gear Drive		Worm-Gear		Bevel-Gear		Direct Drive + EMB		Belt Drive + EMB	
Criterias	W	v	t	v	t	v	t	v	t	v	t	v	t	v	t	v	t
1.1 Clearance to firewall	0,189	5	0,944	2	0,378	4	0,756	4	0,756	3	0,567	4	0,756	1	0,189	4	0,756
1.3 Radius (from central axis)	0,133	5	0,667	5	0,667	4	0,533	4	0,533	2	0,267	3	0,400	5	0,667	3	0,400
4.1 Max cogging torque	0,033	5	0,167	3	0,100	5	0,167	5	0,167	5	0,167	5	0,167	4	0,133	5	0,167
4.2 Friction torque	0,033	5	0,167	5	0,167	5	0,167	4	0,133	2	0,067	4	0,133	2	0,067	1	0,033
4.3 Peak brake torque	0,111	5	0,556	3	0,333	4	0,444	4	0,444	4	0,444	4	0,444	4	0,444	4	0,444
4.5 Peak active feedback	0,056	5	0,278	4	0,222	5	0,278	5	0,278	5	0,278	5	0,278	3	0,167	3	0,167
4.12 Angular velocity	0,022	5	0,111	5	0,111	4	0,089	4	0,089	4	0,089	4	0,089	3	0,067	3	0,067
4.13 Backlash	0,078	5	0,389	5	0,389	5	0,389	3	0,233	3	0,233	3	0,233	5	0,389	5	0,389
Price	0,189	5	0,944	3	0,567	5	0,944	5	0,944	4	0,756	5	0,944	2	0,378	3	0,567
Complexity	0,156	5	0,778	5	0,778	3	0,467	4	0,622	2	0,311	3	0,467	2	0,311	1	0,156
T (Total weighted value)		50	5,000	40	3,711	44	4,233	42	4,200	34	3,178	40	3,911	31	2,811	32	3,144
		Weighted Value		3,711		4,233		4,200		3,178		3,911		2,811		3,144	
		Rank		4		1		2		5		3		7		6	

5.6.3 Analysis

As seen in table 11, belt- and gear drive were ranked first and second out of the concepts evaluated in the Kesselring matrix. This comes down to their performance in critical areas such as “clearance to firewall”, “Radius (from central axis)”, “Price” and “Complexity”. Both concepts performed very similarly with similar strengths, the main differences being the backlash (4.13) and complexity.

In order to fully grasp the differences between the two concepts they have been further explained and evaluated separately in 6.1 and 6.2 respectively.

6 Design of Components

The winning concept from the Kesselring matrix (Concept 2) was selected for design and further evaluation. Additionally, the concept that ranked second (Concept 3) was also chosen for further design and evaluation due to their close ranking. Furthermore, a solution for a steering angle limiter was designed along with a potential solution to increase the axial adjustment in the negative direction, as specified in the requirement specification (wish 2.2).

6.1 Concept 2 - Belt Drive

Concept 2 was designed to connect 1 motor to the steering column via a belt to give feedback and braking torque to the steering wheel, which can be seen in figure 20. The space that was allocated for the motor was on the same side as the energy absorption device. This was decided as there are less parts situated on that side in the steering column.

One of the pros of belt drive is that there is no big risk of backlash since the belt has some elasticity, therefore there is no need for pretensioning by using two motors or needing gears with high precision as explained in 5.6.1.3 with concept 3. Two motors can still be used if symmetry or smaller motor size is desired.

The belt type used in this application is a synchronous belt which is necessary to reduce the risk for slip while ensuring low friction during power transfer. Compared to a v-belt or a flat belt, the risk for slip is significantly reduced and power loss is still kept at a low level.

6.1.1 Motor Size

The electric motor that is used in the concept is a motor that is already used by Volvo cars. This motor was used to get realistic dimensions of a motor with the desired torque and speed. The total size of this motor is: 120 mm in length and 90 mm in diameter. According to (Volvo, 2025) the torque of the motor is 7 Nm with a maximum speed of 1500 rpm.

6.1.2 Gearing and resulting output

To increase the output torque, a gearing reduction was achieved by using differently sized belt pulleys. The current gearing reduction is 2.5:1 which means that the motor must turn 2.5 revolutions to turn the steering wheel 1 revolution. The result is a gearbox output of 17.5 Nm.

According to (Megadyne, 2025) a synchronous belt has an efficiency of 98 %, resulting in a final output of:

$$7 \times 2.5 \times 0.98 = 17.15\ Nm$$

$$\frac{1500}{2.5} = 600\ rpm$$

6.1.3 Design

The existing steering column was modified to make it possible to install a feedback device with a belt and pulley system. This concept mounts the motor by an adaptor plate installed at the back of the steering column. The two pulleys were installed, one on the motor axis and one at the end of the steering axis. This can be seen in figure 20.

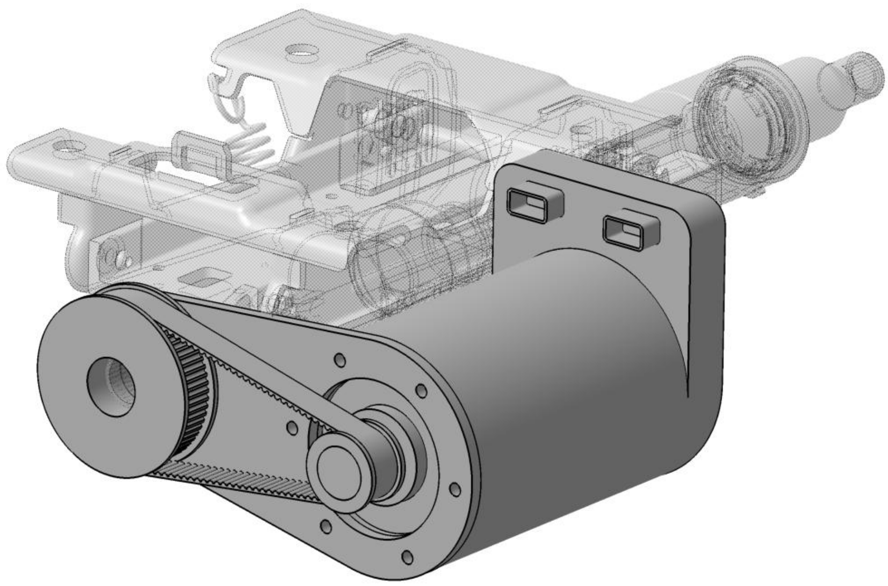


Figure 20 – Shows a 3D visualization of concept 2 with one electric motor connected via a belt. Created in Catia V5

6.1.4 Drawbacks

There are some drawbacks with having one feedback motor parallel to the steering column, especially when it comes to size and symmetry. The problem with having one big motor is that it takes up a lot of space. The current concept builds on the steering column from the CMA-platform, this column only comes with manual adjustment. This means that the concept currently only has manual adjustment and is therefore not fully representative of the desired final product.

6.2 Concept 3 - Gear Drive

Concept 3 was designed for two motors connected in parallel rather than one, this was done to allow the main gear to be preloaded (actuate the motors in opposing directions). This results in an elimination of backlash inside of the gearbox. An illustration of the concept can be seen in figure 21 below.

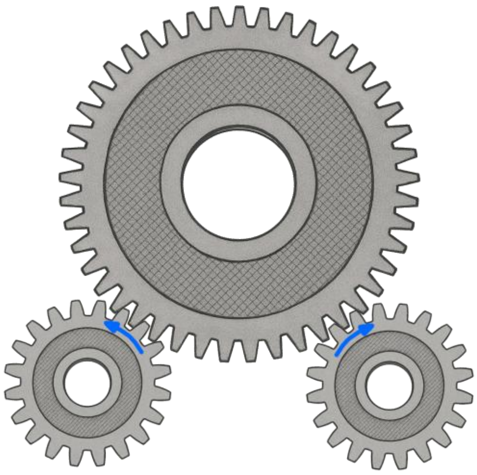


Figure 21 – Cross-section view of a preloaded gearbox, spur gears are generated by Dall-E (AI) with further illustrations of arrows added for explanation of elimination of backlash.

As per the figure 21, the blue arrows illustrate the constant rotation of the two motors. The two rotational forces cancel each other out and remove any backlash between the gears in the process.

In addition to the previously described advantages to two motors, it also allows for a more symmetric design that aligns with the requirements set on the concept while minimizing volume added above or under the existing steering column, beneficial as described in 3.1.4.

6.2.1 Motor Size

Given the desired torque output of Nm, a gear ratio of 5:1 was chosen as described in 6.2.2, this requires an input torque of Nm. When utilizing two motors, this requirement is divided, resulting in an input torque of Nm per motor. To account for potential system losses and to enhance customer value, a motor torque of 2 Nm per motor was selected.

Simple calculations were carried out to determine the size of this new motor, these calculations use the motor described in 6.1.1 as a reference. If the motor length remains the same, the torque is proportional to the square of the diameter. The following equation (1) can therefore be used to calculate the diameter of the new motor.

$$\frac{T_1}{T_2} = (\frac{D_1}{D_2})^2 \qquad (1)$$

Where:
T_1 = 7 Nm (Original torque)
T_2 = 2 Nm (Desired torque)
D_1 = 90 mm (Original diameter)
D_2 = New diameter

As we brake out D_2 from equation (1) we get the following:

$$D_2 = D_1 \times \sqrt{\frac{T_2}{T_1}} = 90 \times \sqrt{\frac{2}{7}} = 48.107$$

As to simplify production sourcing and production of the motor the diameter is rounded up to 50 mm.

$$D_2 = \text{Ø} = 50 \text{ mm}$$

This equals an expected torque output of:

$$T_2 = T_1 \times \left(\frac{D_2}{D_1}\right)^2 = 7 \times \left(\frac{50}{90}\right)^2 = 2.16\ Nm$$

This results in an electric motor with the following dimensions and specifications:

D = 50 mm

L = 120 mm

T = 2.16 Nm

ω = 1500 rpm

6.2.2 Gearing and resulting output

The electric motors have a max angular velocity of 1500 rpm, since we only need an output of 180 rpm, we can potentially have a gear ratio as high as 8.3:1. Since a lower gear ratio is beneficial for energy transfers, a gear ratio of 5:1 was chosen.

According to (Roymech, 2025), the efficiency of spur gears can be approximated to 98%. Accounting for the individual motor output, gearing and system losses the output from the gearbox should be:

$$2.16 \times 2 \times 5 \times 0.98 = 21.17\ Nm$$

$$\frac{12}{5} = 300\ rpm$$

6.2.3 Design

After removing the steering shaft from the current steering column, a spur gear was added in its place. The spur gear connects the two new motors as per described and dimensioned in 6.2.1 to the telescopic shaft and thereby the steering wheel. Presented below in figure 22 is the visualization of the concept.

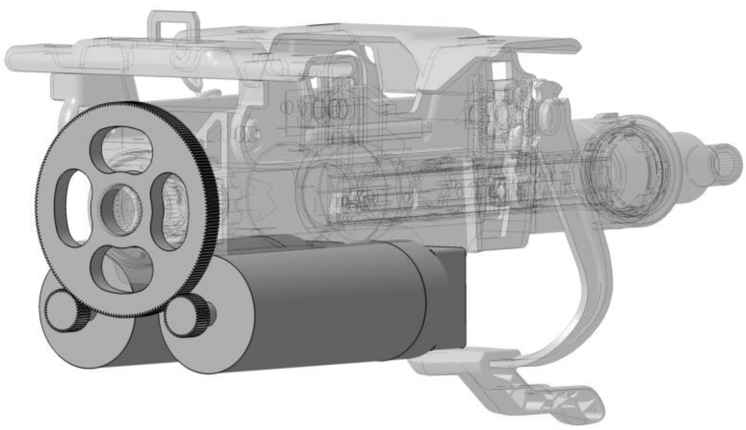


Figure 22 – Shows a 3D visualization of concept 3 with two electric motors connected via a spur gear. Created in Catia V5.

6.2.4 Drawbacks

One of the main drawbacks of this concept is the size of the main gear, it is large in comparison to the steering column which in turn means that the gearbox housing will be large. The current concept builds on the steering column from the CMA-platform, this column only comes with manual adjustment. This means that the concept currently only has manual adjustment and is therefore not fully representative of the desired final product.

6.3 Steering angle limiter

The winning concept for limiting the steering angle was decided to have several washers that work together to limit the steering input. By having several washers, a greater steering angle input can be accomplished. The washers were fitted where the steering lock previously was located.

6.3.1 Design

To decrease the force applied to each tab and eliminate the risk of washers pinching the central axis, each washer had two tabs. This creates a smother steering angle limiter with less risk of binding. One downside of having two tabs on each washer is that the number of washers needed to satisfy the requirements will double in respect to only using one tab. In this case, it was decided that the design would consist of one washer mounted to the steering column housing and one mounted to the steering axis with two washers in between. This will result in a steering angle of ±225° which is above the requirement set by Volvo Cars. If another steering angle limit is desired, washers can be added to the steering limiter. Every washer added increases the steering angle by ±75°. The design can be seen in figure 23.

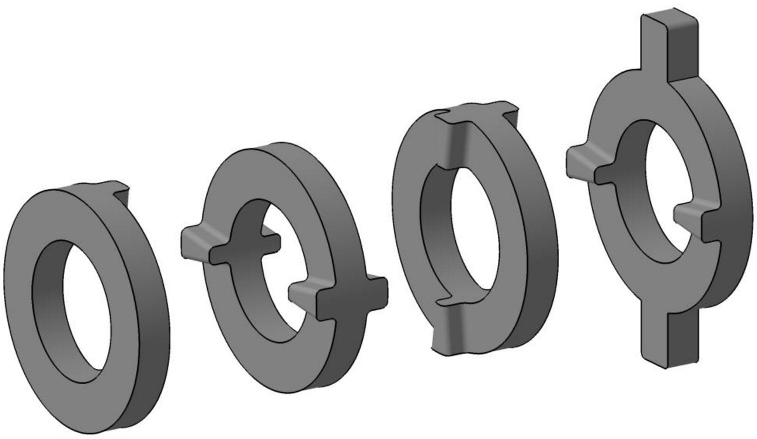


Figure 23 – Steering angle limiter assembly, created in Catia V5

6.3.2 Dimensioning

To make sure that the washers hold up to Nm applied to the steering wheel, a FEM-Analysis was done to one of the washers. The forces that were applied to the washers can be seen in figure 24 as yellow arrows. The forces were calculated by converting the torque acting along the central axis from the steering wheel. The forces were then placed on the tabs faces on both sides.

The result of the FEM-Analysis can be seen in figure 24, this shows that the steering angle limiter experiences a maximum of 556.4 MPa stress at Nm and 278.2 MPa at Nm.

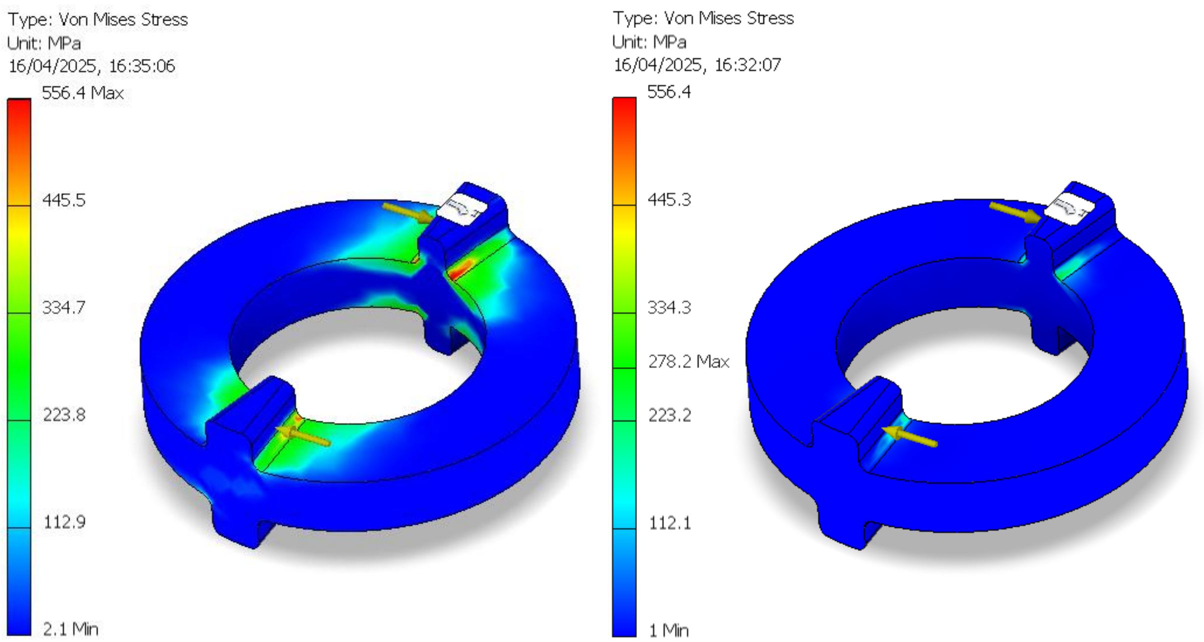


Figure 24 – FEM of the washer with tabs, exposed to forces equaling Nm and Nm. Created in Autodesk Inventor.

6.3.3 Fitment in the steering column

Since the steering angle limiter is installed inside the steering column, it is essential to not compromise any safety features in the process of installation. One important safety feature that must be considered is the collapse zone. Currently, the telescopic axis is designed to collapse over the original steering lock. This must remain the case for the steering angle limiter as to not affect the crash safety of the new concepts. Therefore, some minor modification had to be made.

Firstly, an internal bearing highlighted in green as per figure 25 had to be moved 3.5 mm towards the driver so as to not compromise the columns ability to collapse.

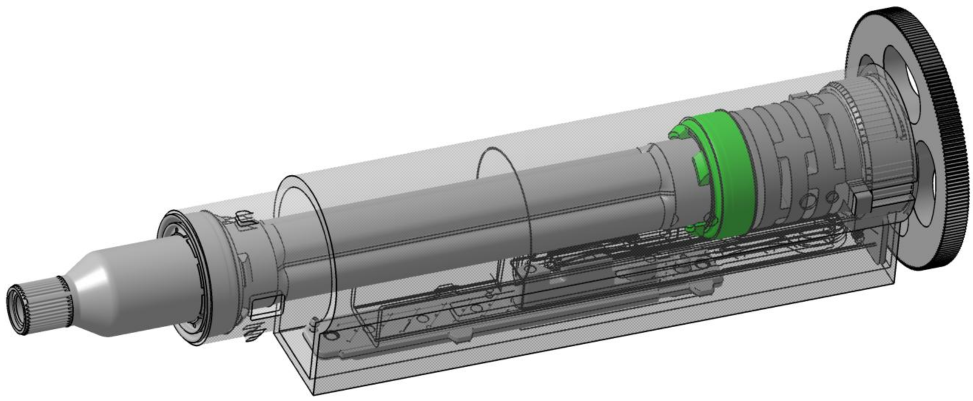


Figure 25 – The figure shows a fully collapsed column, the ball bearing that was repositioned is highlighted in green.

Secondly two squares had to be cut out from the upper jacket to allow it to collapse over the mounting tabs of the steering angle limiter as illustrated in figure 26.

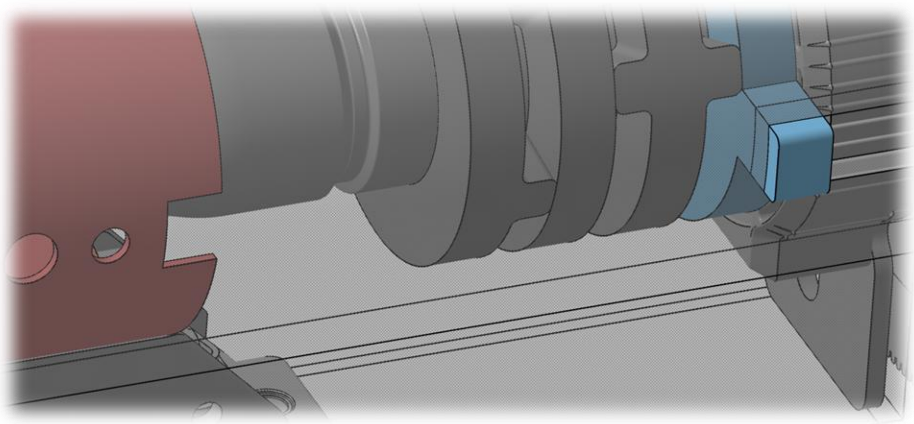


Figure 26 – The upper jacket is highlighted in red whilst the steering angle limiter with its mounting tabs are highlighted in blue.

6.4 Increased axial adjustment

Since there was a wish for a greater adjustability of the steering column in the requirement specification, some modifications have been made to increase the adjustability in the negative direction. This was done by utilizing parts of the collapse zone. To not compromise road safety, this adjustment would only be available while the vehicle is parked.

This would result in the possibility of the steering wheel retracting further into the dashboard once the car is parked, freeing up space once the collapse zone is not needed.

6.4.1 Modifications

One modification that had to be made in order to increase the adjustability was to lengthen the adjustment track located on the steering column housing, as illustrated in figure 27. The tracks length decides how far the upper jacket can move axially in respect to the housing. The track was therefore lengthened by an additional 55mm (highlighted in blue in figure).

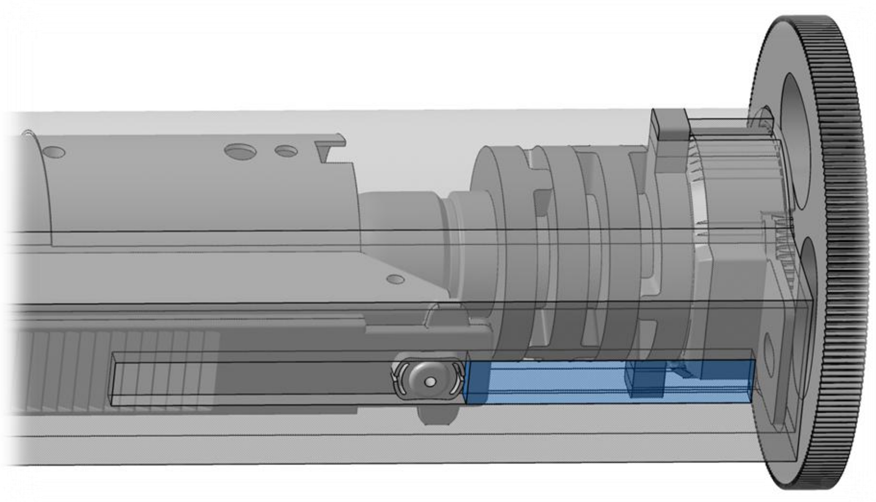


Figure 27 – Illustration of the adjustment track. The adjustment track highlighted in blue would only be available for utilization once the car is parked.

7 Test of Concepts

In order to verify that the concepts meet the required specifications, the designs have been evaluated on each of the points mentioned in the requirements specification. The requirement specification can be seen in table 1. As no physical prototype was constructed, the data used for evaluation was retrieved from CAD-files and calculations.

7.1 Measurements

Clearance to firewall were measured on both concepts at the shortest distance between the steering column and the firewall. For concept 2 this was determined to be the top of the belt pulley, and for concept 3 it was the main gear mounted to the back of the steering axis. Figure 28 shows the distance between concept 2 and the firewall, this was measured to approximately 70.8 mm. Figure 29 shows the distance between concept 3 and the firewall, this was measured to approximately 72.7 mm. Both concepts need a gearbox housing which will slightly decrease the length between the steering column and the firewall. Despite that, both concepts should still accomplish the requirement of more than mm between the HWA and the firewall.

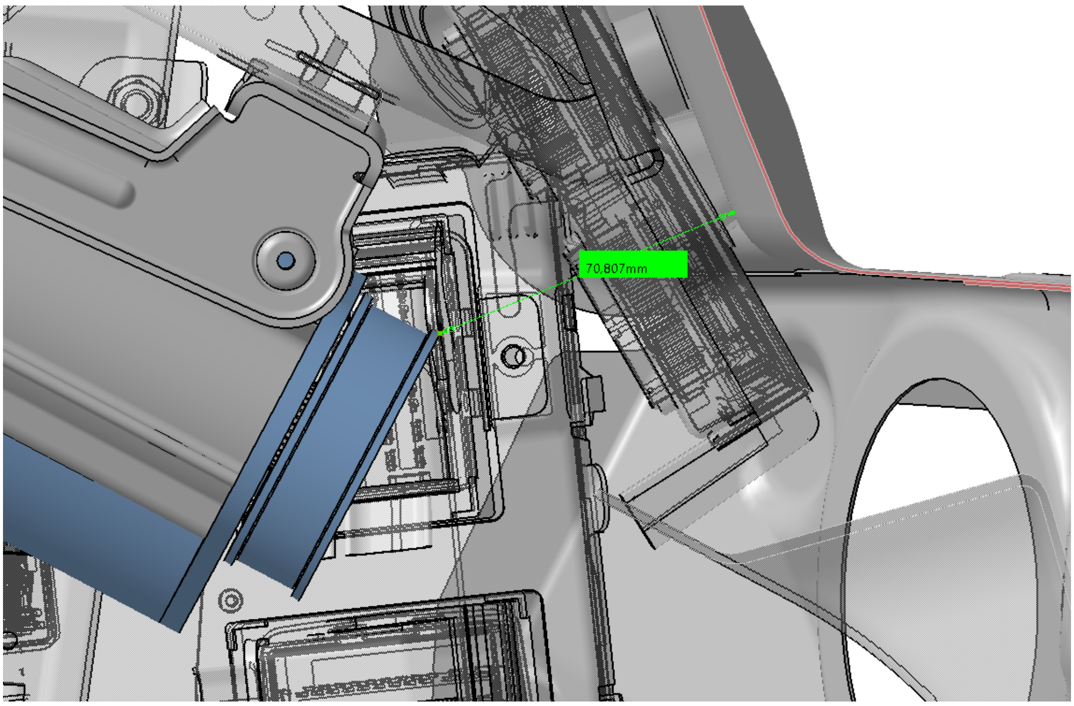


Figure 28 – Concept 2, clearance to the firewall in a EX40.

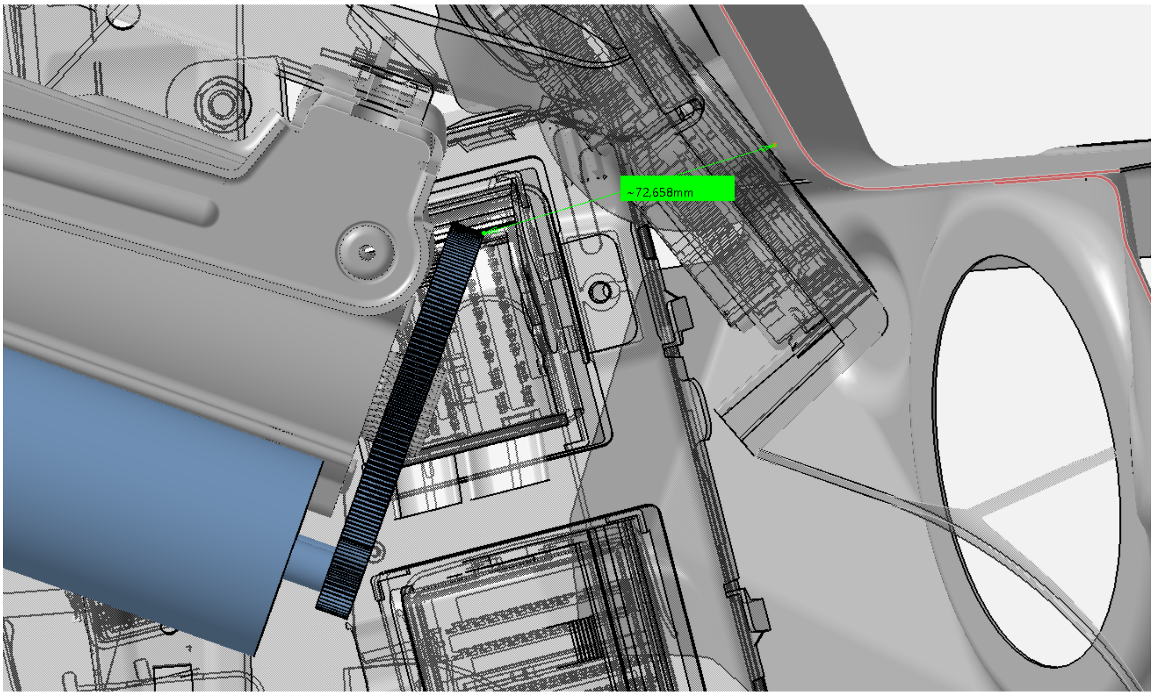


Figure 29 – Concept 3, clearance to the firewall in a EX40.

The **total length** of both concepts are below the mm target set as a wish in the requirement specification. Since the only length added on the steering column are a spur gear or belt pulley and a mounting bracket. Concept 2 is currently 10 mm longer than the original steering column and concept 3 is the same length as the current steering column, which is 429.5 mm. Both concepts are missing a gearbox housing but adding this will only add a couple of millimeters.

The two concepts have fulfilled the goal of **radius from steering axis** in different ways. The current steering column has a radius of approximately 215 mm from the steering axis, Concept 3 has been able to stay within the same radius of 215 mm since it has two motors. Concept 2 has a bigger footprint from the back, the total radius is approximately 295 mm, it would be possible to reduce this by using two motors as done in concept 3.

Concept 2 adds one motor to the steering column. To make this symmetrical the motor would have to be placed either directly over or under the steering column. This is not possible whilst fitting in the environment due to the restrictions of the HVAC system and driver's knees located under the steering column and the cross-car beam being located above the steering column.

This means that the motor had to be placed on the side of the steering column, making the concept asymmetrical.

Concept 3 on the other hand utilizes two motors, making it easy to place them symmetrically, ensuring that the steering column can be utilized in RHD and LHD cars alike without the need for modifications.

Both concepts are tested to see if they **fit in the allocated space** as specified by the requirement specification. Since concept 2 has one motor mounted on the side, one modification must be made to ensure it would fit in the current 40-series. The mount for the knee airbag must be moved slightly to the left to make space for the motor. With that modification done, there should be sufficient space for the steering column to fit. The steering column from concept 2, mounted in the car can be seen in figure 30.

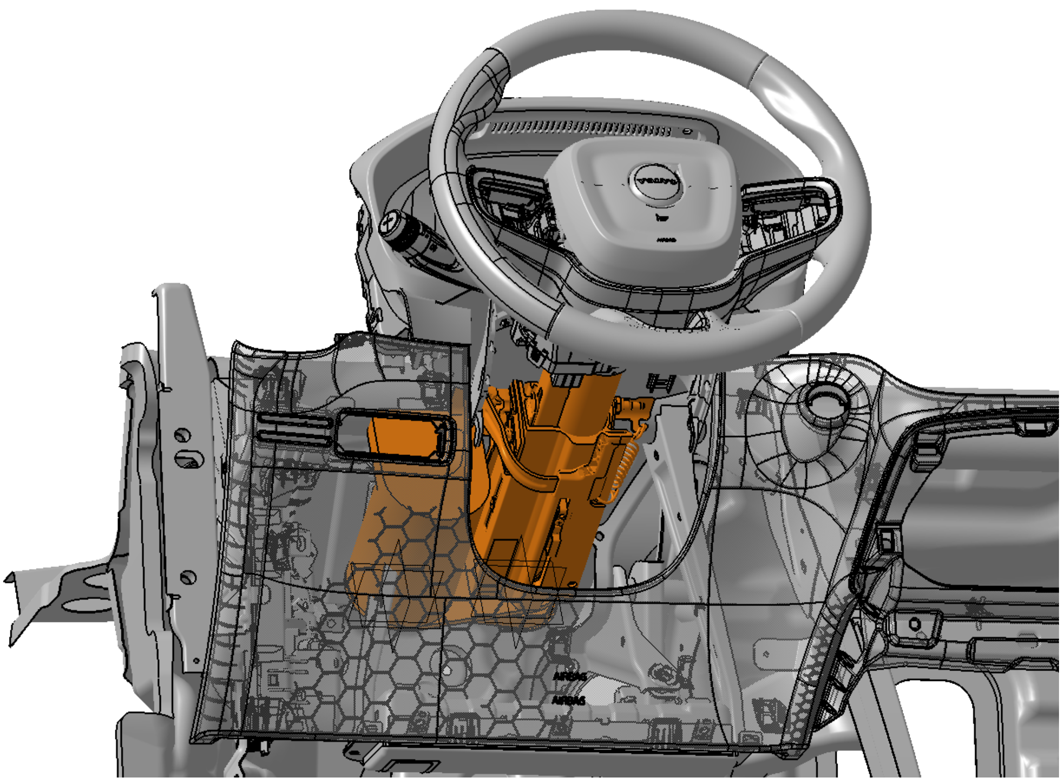


Figure 30 – Concept 2 placed in the in a EX40.

Since concept 3 has two smaller motors mounted on the underside of the steering column, there is no need for any further modification to make the steering column fit. It is possible to see concept 3 mounted in figure 31.

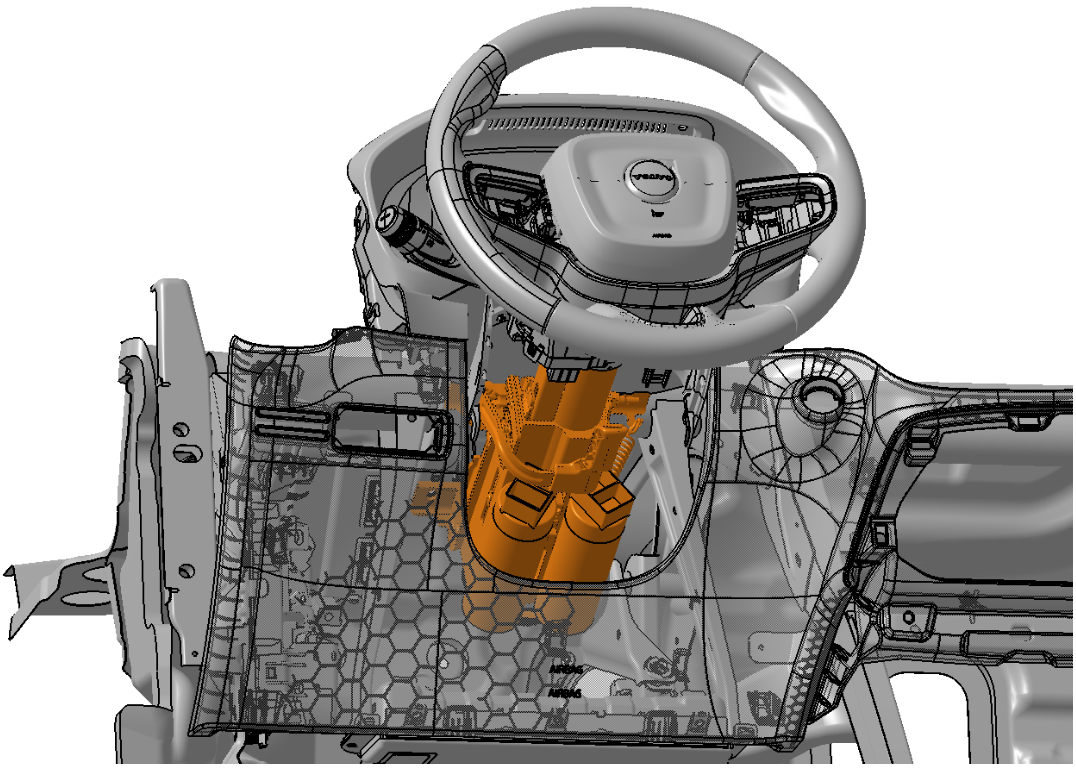


Figure 31 – Concept 3 placed in the in a EX40.

7.2 Adjustability

The ordinary adjustability of the steering column remains the same as before, no changes were made to reduce or increase the adjustment. Therefore, both concepts 2 and 3 meet the requirement of equal adjustment as of today that were specified in the requirement specification regarding length adjustment.

As per the requirements specification there was a wish to increase the axial adjustment in the negative direction to mm. As per the modification carried out in 6.4 the total adjustment is $+27.5\ /\ -(27.5 + 55)\ = +27.5/-82.5$ mm. This does not satisfy the wish of mm but surpasses the total adjustability of today.

7.3 Crash Safety

The steering columns crash safety is determined mainly by the collapsable length of the upper jacket. This distance had been unaffected up until 6.3, where the steering angle limiter was placed inside of the column. As described in 6.3.3 necessary measures were taken to ensure that this addition, under no circumstances would affect the collapse length. Figure 32 shows the conceptual steering column in its fully collapsed state. This shows that the changes made did not interrupt the collapse-zone.

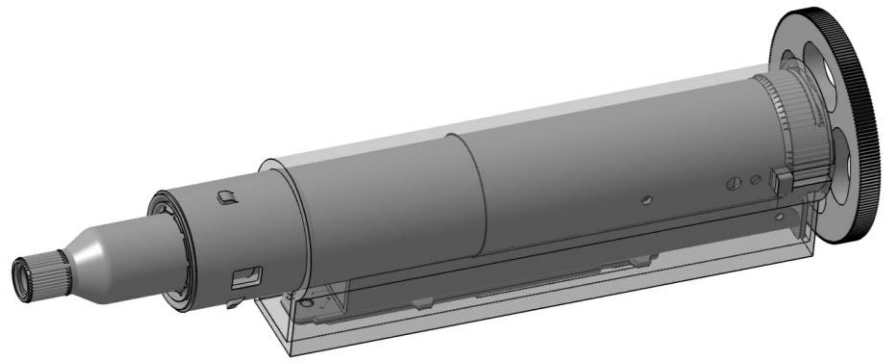


Figure 32 – Shows the conceptual steering column in a fully collapsed state.

Another factor affecting crash safety is the total mass that is accelerated once a collapse occurs. No parts to the upper jacket have been added or modified in a way that adds weight and therefore, the concepts have equal mass to the original upper jacket.

This means that the energy absorption of the steering column concepts performs on par with the original steering column.

7.4 Functionality

The **maximum cogging torque** depends on the motors design and use of gearing, which can either amplify or reduce the effect of cogging. In this report, the specific motor is not specified, making verification difficult. However, in both scenarios, the gearing reduces the effect of cogging. Additionally, it is possible to program the motor to compensate for its cogging.

Considering all the factors above, selecting a motor appropriate for the task should ensure that the cogging torque is less than Nm.

The current CMA column experiences approximately Nm of **friction torque** (Volvo, 2025), due to the removal of joints only 0.1 Nm of torque losses are carried over from the original steering column. The requirement specification declares that the **friction torque** should be less than Nm for the new concepts. This means that the changes made to the column as a part of this project should not add more than Nm of torque losses to the system. Therefore, the addition of a steering angle limiter, motor and gearbox should not add more than Nm of friction torque. Although it is not possible to accurately validate this, the concept is designed to achieve a minimal friction torque.

Peak brake torque and **peak active feedback** are both handled by the same electric motor. This means that the motors must be dimensioned to successfully handle the biggest load which in this case is a wish of more than Nm of torque as per the requirement specification. Therefor the motors and gearing of each concept were calculated and designed to not only accomplish this but to add a safety margin and increase customer value. As described in 6.1.1-6.1.2 and 6.2.1-6.2.2 the presented concepts achieve 17.15 and 21.17 Nm of output torque respectively. Even with respect to calculation errors due to oversimplification of new motor specifications and system losses, the wish for Nm should still be met.

The **steering angle limiter** limits rotational movement of the steering wheel to ± ° as per design choices elaborated in 6.3.1. This exceeds the requirements presented in the requirements specification but falls short of the wished ± °. As also described in 6.3.1 the design is modular, meaning that more washers can be added to increase the steering angle limiter. Note that this would require further modification of the steering column. Additionally described in the requirements specification, the steering angle limiter needs to be designed to take Nm of torque before failure. To verify this, FEM-analyses were done to ensure optimal design as per 6.3.2. As described during the dimensioning, the steering angle limiters will most likely perform arbitrarily but further simulations and physical testing will have to be carried out in order to determine exact results.

Angular velocity of revolutions per second within seconds refers to the need for the steering wheel to mimic today's speed. As to be able to spin at a speed of revolution per second which is equal to rpm and hit that speed within seconds from standing still. Several factors determine if a concept can theoretically do this, firstly the motors need to be able to spin this fast, secondly the torque must be sufficient to accelerate the steering wheel despite all of the rotational mass.

The full calculations to determine the acceleration time can be found under calculation A1 in appendix. The results of the calculations are presented below.

$$t_{concept\_2} = \frac{18.85}{416.87} = 0.045\ s$$
$$t_{concept\_3} = \frac{18.85}{493.44} = 0.038\ s$$

Backlash of less than arcmin is important to not encounter play between the steering axis and the feedback device. This is easy to achieve with a belt as the power transfer device, since the belt is slightly elastic there is no delay between the input and output. It is important to not have big cogs in the transmission as this might introduce a cogging-like feeling.
In the solution with gears as power transfer, it is harder to reduce the backlash. But since the concept in this report uses two feedback devices, they can preload the main gear and therefore eliminate the cogging which is further explained in chapter 6.2. This means that cogging should not be any problem with either of the concepts.

8 Discussion

In the discussion chapter of this report, the research questions are going to be answered from chapter 1.4. Thoughts and ideas that emerged during the thesis work will be discussed in terms of social and ethical aspects, the use and outcome of matrices, the final solution, potential further development of the concepts, and any transgressions that may have influenced the results.

8.1 Social, Ethical and Ecological aspects

The research and development process must take inclusivity and accessibility into consideration. By considering the diverse needs of users, such as differing levels of mobility and size, a steering column can be designed to increase user inclusion. Designing the HWA to retract further from the driver once the car is parked exemplifies a commitment to social inclusion. This feature enhances the ease of entry and exit, increasing user comfort.

However, during the project it was identified that the proposed solution for parked vehicle primary benefits individuals who experience difficulty entering and or exiting the vehicle. While this improves inclusion in a limited context, it does not significantly impact broader gender equality. On average, women tend to be shorter and smaller, while men are taller and larger. Therefore to achieve greater overall inclusivity the steering column would need to offer increased adjustability in all direction while in driving mode. This would lead to more flexible driving positions while under operation. The current solution addresses only one specific scenario and highlights the need for further development to meet a wide range of user needs.

From an ethical point of view, the HWA must be designed with safety and durability as a priority. By continuously verifying this through simulations and design we aim to prevent any unforeseen internal failure. This ensures that the HWA is safe in every condition.

From an ecological point of view, the developed concept utilizes most of the current steering column and allows for easy retrofitting. This means that most production tolling can be carried over from today's production, reducing waste and environmental impact.

8.2 Matrixes

To produce different solutions from the mind map, several matrixes have been used. This has resulted in a few concepts that have been further developed to create the best concepts to solve the steer-by-wire active feedback connection. One of the problems encountered when using the matrixes, was to give a value to each concept before they were developed. This resulted in numerous estimations. This might have altered the result depending on our estimations on each of each concept. To reduce the risk of incorrect scoring of the concepts, employees at Volvo Cars had been asked to give their opinion on values used in the matrixes, this was used to verify our estimations. Without this feedback, the method would have less validity.

With this consider, we would still say that the result from the matrixes are still relevant and the top 4 in the Kesselring matrix are all good solutions in different ways. Depending on the surrounding space and which requirements are prioritized, all the concepts can be a suitable solution.

8.3 Further development

There are improvements that can be made to the project to increase trustability and things that can be done to improve the concepts. Some ideas will be explained in the following chapter.

8.3.1 Possible improvements to concept 2

To reduce the footprint of concept 2, it would be possible to use a smaller motor with a different gearing ratio. This would reduce how much space the steering column takes horizontally. To reduce the radius of the steering column, two motors could be used as in concept 3. One aspect to consider if two motors would be used with belt drive is that an additional pulley needs to be added to the belt drive system. This would be necessary to ensure that there is sufficient contact between every pulley and the belt. A second belt could also be used but that will increase the total length of the steering column.

Another possible improvement could be to mount the motor in another place around the steering column depending on which car it would be fitted in and where the space exists in that car. For example, the motor could be mounted on top of the steering column, but to be able to do that some modification would have to be carried out to the cross-car beam.

8.3.2 Possible improvements of concept 3

One main point for improvement is the total height of the concept, if the energy absorption device was to be moved to the top or the bottom of the steering column. The motors could be moved higher up giving more clearance to components/objects located under the steering column such as HVAC lines or space for drivers legs depending on driving position.

Figure 33 shows how the motors could be positioned if the energy absorption device were to be moved. This could potentially free up 23.5 mm as per the green markings in figure 33. Note that the total volume of the steering column remains the same, but it is higher up as described beneficial in 3.1.4.

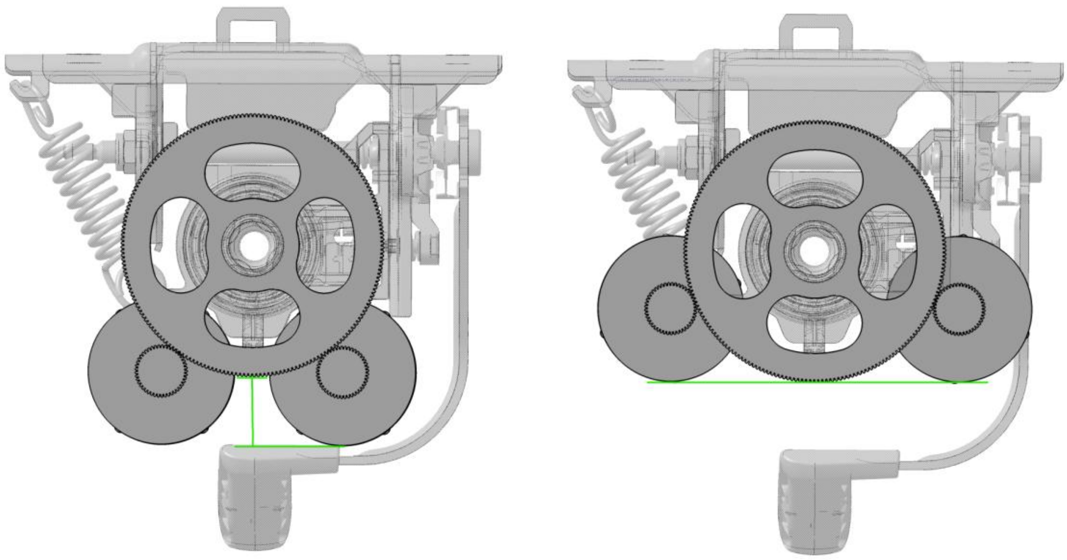


Figure 33 – shows the possible improved placement of the electric feedback motors, saving space under the steering column.

8.3.3 Double telescopic adjustment

Something that would also be interesting to further look at is the possibility of a double telescopic axis as axial adjustment. This would further increase the adjustability of the steering wheel without making the steering column longer. An important aspect to consider of the telescopic axis is the required overlap between segments to ensure stability, which may offset the benefit of increased length adjustability by consuming part of the available extension.

8.3.4 Electrical adjustment

When it comes to the increased axial adjustment when stationary, as explained in 6.4.1, there is one important modification that has to be done, it is to install electrical adjustment instead of manual. This is important since it should be impossible to drive the car once the collapse zone is compromised. This is easier to accomplish if the car automatically adjusts the steering wheel to the correct position when the car is turned on.

8.4 Prototype

To increase trustability that the chosen concept meets the requirements, prototypes should be developed and tested. This would make it possible to test the functionality and do some real-world testing. This would also be interesting to do with the steering angle limiter, to see at which torque it plasticizes and when a fracture occurs. This would give a better understanding of how it would behave when it is mounted in the steering column, since some forces might be transferred to other parts of the steering column.

8.5 Transgressions

As previously stated in 8.2, several estimations were made during the creation of the matrixes used for the screening concepts in chapter 5. This implies that the results presented in 5.6.1 will depend on the judgments made by the creators. Meaning that if this work were to be carried out by other people, the results might differ.

The electric motor referenced to in 6.1.1 was used as a starting point when calculating the specifications of an electric motor of differing size (as per 6.2.2). These calculations simply determine the relationship between volume and torque output of a motor, using this data to determine the theoretical output of a differently sized motor. This is a oversimplifies method of calculation that does not take the motors "effective volume" into account. In reality the motor presented in 6.2.2 (D=50, L=120) would be weaker.

The steering angle limiter presented in 6.3 was dimensioned to withstand Nm of torque, as per the FEM-analysis carried out in 6.3.2 it was determined that this translates to a maximum stress of 556.4 MPa acting on the component. The simulations carried out aims to recreate reality but the behavior such as fractures and fatigue failure depends on the used material. Therefore, tests should be carried out with physical prototypes to determine the real failure point.

The calculations presented in 7.4 aimed at determining the time needed to accelerate from 0 to 3 revolutions per second presents a result 10 times faster than the requirement. This value is theoretical, and real performance will probably be slower. Several external factors might affect the real performance of the motor such as additional system losses or power delivery limitations.

9 Conclusion

This bachelor's thesis has successfully demonstrated the theoretical possibility of retrofitting a steer-by-wire hand-wheel actuator into Volvo Cars existing 40-series. Through a structured and methodical design process comprising of, patent investigation, market investigations, concept generation, and rigorous evaluation resulting in two final concepts that were developed and tested, those being a belt driven system and a gear driven system.

The results show that both concepts theoretically meet or exceed the requirements set by Volvo Cars, including spatial constraints, adjustability, crash safety and torque feedback performance. Concept 2, the belt driven solution, offers a design flexibility regarding positioning of the feedback device around the steering axis and the possibility to easily change the gearing. It also has a quiet design with minimal backlash, making it ideal for applications where simplicity and flexibility is important. Concept 3, the gear driven solution with dual motors, provides a compact design that is symmetric, which is advantageous for vehicle platforms requiring both left- and right-hand drive configurations and has limited space around the steering column.

Essential points from this report include the importance of modularity and adaptability in steer-by-wire systems. The use of a telescopic shaft and modular steering angle limiter enables flexibility in design without compromising safety or performance. The study also highlights the potential for further innovation. For instance, increasing axial adjustability when the vehicle is stationary enhances driver comfort and accessibility.

This thesis not only proves that a steer-by-wire hand-wheel actuator theoretically can be implemented within the spatial and functional constraints of the Volvo 40-series platform but also provides an insight into next-generation steering systems.

10 Bibliography

Anspaugh, M. P., Jones, R. W., Schulz, J. F., Caverly, J. A., King, T. M., & Molinar, S. R. (2024). *Steer-by-wire steering column with low translating energy absorption mass.* (United States of America Patent No. US2025010908A1).

Caresoft Global. (2025). *Vehicle Teardown*. Retrieved from Iceberg.

CUNQIANG, W., QIANG, S., NIAN, D., ZHENGQING, W., JINHAO, G., & HUA, G. (2023). *Belt pulley type steer-by-wire electric adjusting steering column and system.* (China Patent No. CN116873025A).

Dannhäuser, M., Raber, C., & Vogel, F. (2025). *Bedieneinheit und steer-by-wire-lenksystem.* (Germany Patent No. DE102023119175A1).

European Patent Office. (2025, 01 30). *Services & organisational structure (organigram) of the European Patent Office*. Retrieved from Epo: https://www.epo.org/en/about-us/services-and-activities/services

Kwon, H. (2024). *Steer-by-wire steering device.* (United States of America Patent No. US2024383521A1).

Megadyne. (2025, 04 10). *Synchronous Belts vs. V-Belts*. Retrieved from www.megadynegroup.com: https://megadynegroup.com/en/blog/synchronous-belts-vs-v-belts

Rowan, J. (2024, September 4). 90/90, Welcome to a tale of two flagships. Retrieved from https://9090day.volvocars.com/

Roymech. (2025, 04 30). Retrieved from https://roymech.org/Useful_Tables/Drive/Gear_Efficiency.html

Schulz, J. F., Jones, R. W., Anspaugh, M. P., Molinar, S. R., King, T. M., & Caverly, J. A. (2025). *Steer-by-wire steering column.* (United States of America Patent No. US2025010906A1).

Steinkogler, B., & Galehr, R. (2020). *Vehicle steering system with steer-by-wire system and mechanical fallback system.* (United States of America Patent No. US10597068B2).

UNECE. (2025, 05 12). *UN Regulation No. 79 Revision 5.* Retrieved from UNECE: https://unece.org/transport/documents/2023/10/working-documents/un-regulation-no-79-revision-5

V. C. (2025, 04 30). Internal Documentation. (L. Ekström, & L. Lindblad, Interviewers)

Appendix

Figures

Figure A1 – Innermost axial adjustment of CMA-column.

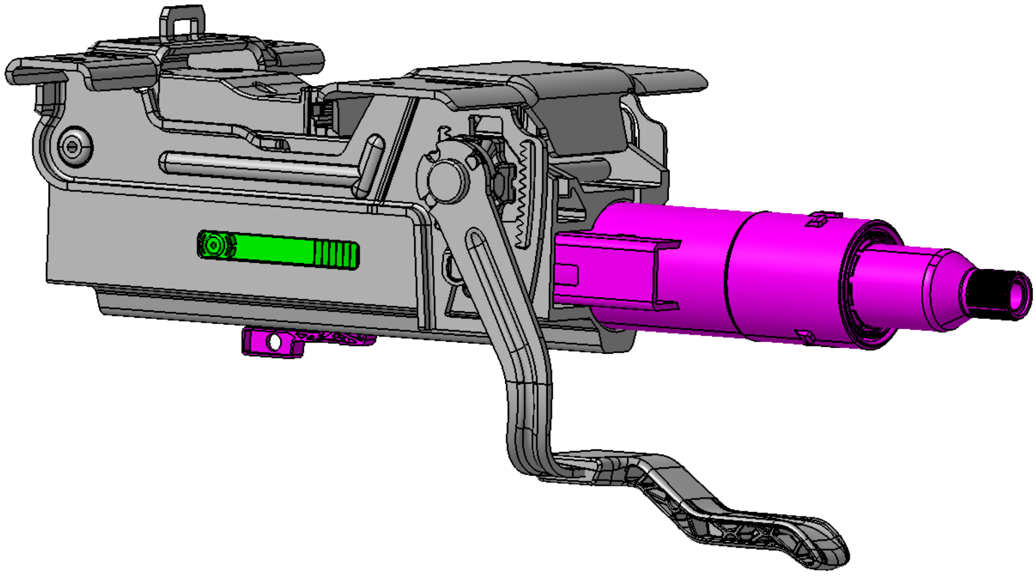


Figure A2 – Outermost axial adjustment of CMA-column.

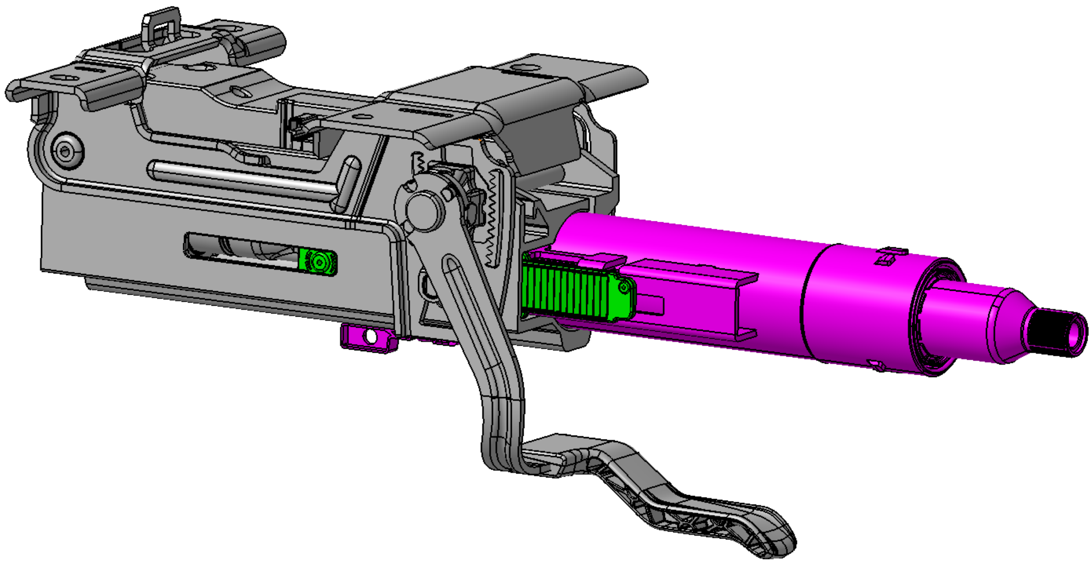


Figure A3 – Mind map containing sub-solutions to every sub-function

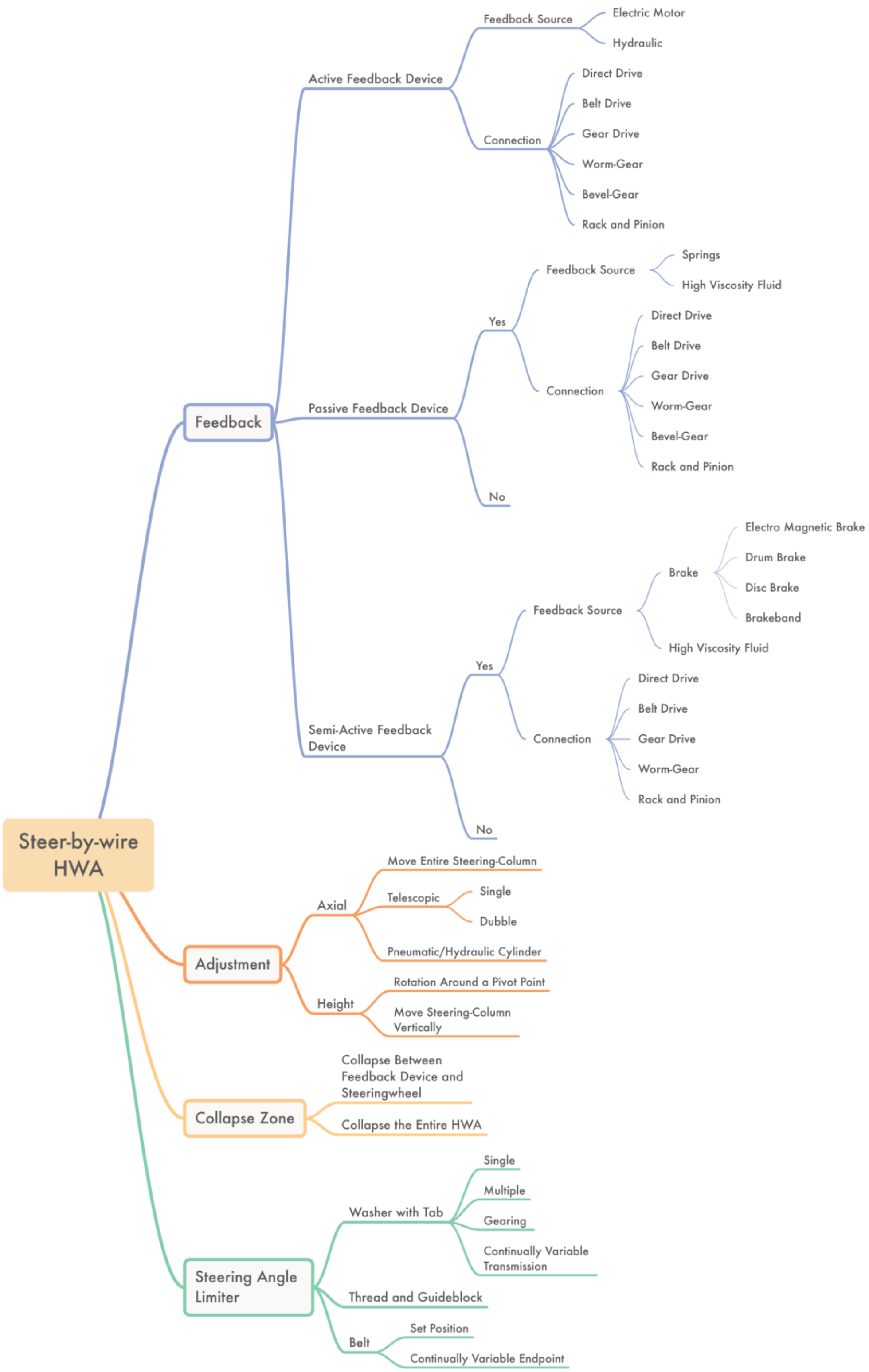
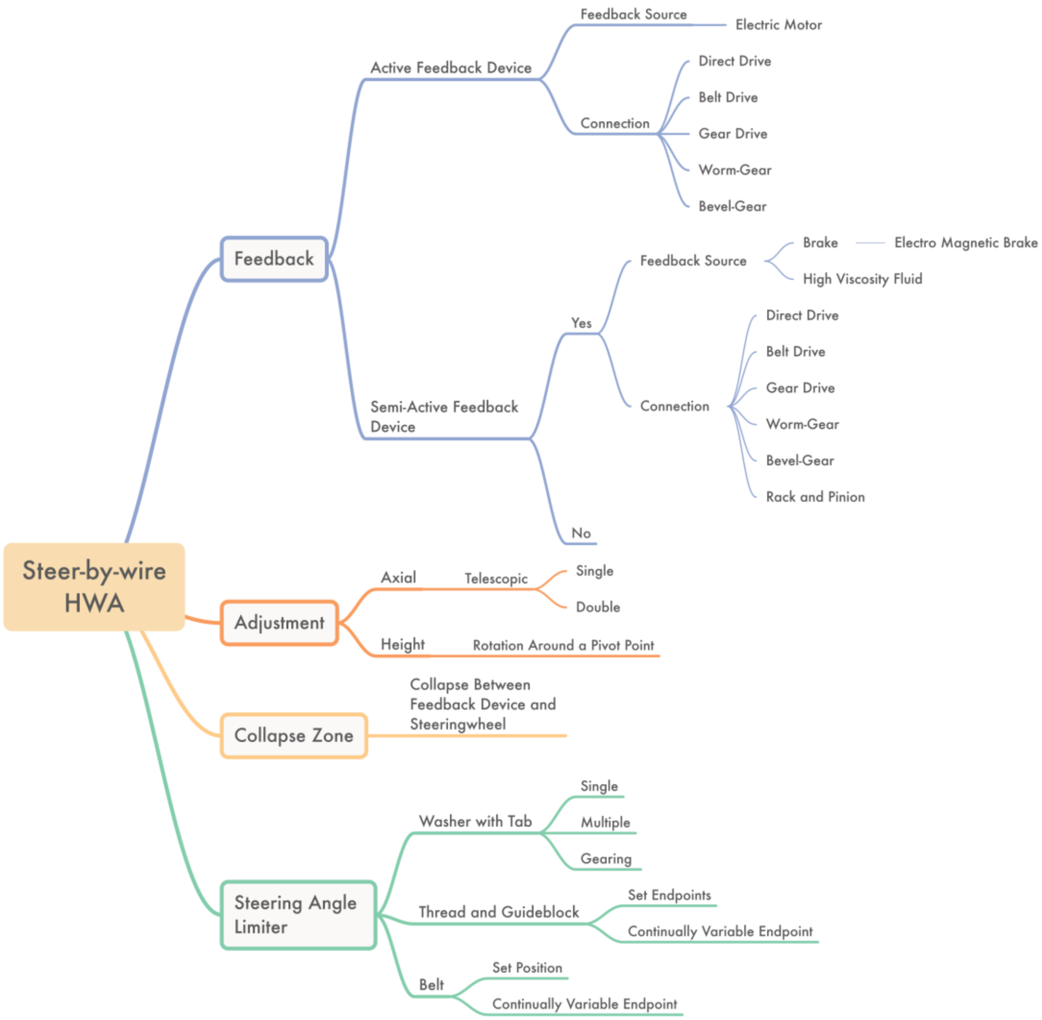


Figure A4 – Streamlined mind map containing sub-solutions



Tables

Table A1- Elimination Matrix on Feedback and Connection.

Chalmers	Document: Elimination Matrix, Feedback and Connection Project: Steer-By-Wire HWA						
Author: Leo Ekström, Loke Lindblad						***Created: 2025-02-27*** ***Modified: 2025-02-27***	
						+ Yes ***- No*** ***? Information is missing***	***+ Keep solution*** ***- Eliminate solution***
Solution	***Elimination Criterias***					***Comments***	***Results***
	Clearance to firewall	Peak brake torque	Peak Active Feedback	Angular velocity	Backlash		
1	?	+	+	?	+		+
2	+	+	+	?	+		+
3	+	+	+	?	?		+
4	+	+	+	?	?		+
5	+	+	+	?	?		+
6	?	+	+	?	+		+
7	?	+	+	?	+		+
8	?	+	+	?	?		+
9	?	+	+	?	?		+
10	?	+	+	?	?		+
11	+	+	+	?	+		+
12	+	+	+	?	?		+
13	+	+	+	?	?		+
14	+	+	+	?	?		+
15	?	+	+	?	?		+
16	+	+	+	?	?		+
17	+	+	+	?	?		+
18	+	+	+	?	?		+
19	+	+	+	?	?		+

Table A2- Pugh Matrix on Feedback and Connection 2.

Chalmers	Document: Pugh Matrix, Feedback and Connection 2 Project: Steer-By-Wire HWA																		
Author: Leo Ekström, Loke Lindblad	Created: 2025-02-27 Modified: 2025-02-28																		
Requirement/Wishes	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
Clearance to firewall	-	0	0	0	0	-	-	-	-	-	REFERENCE	0	0	0	-	0	0	0	0
Radius (from central axis)	+	0	0	0	0	+	0	0	-	-		0	-	-	-	-	-	-	-
Max cogging torque	-	-	-	-	-	-	0	0	0	0		0	0	0	0	-	-	-	-
Friction torque	+	+	+	+	+	+	0	0	0	0		-	-	-	-	-	-	-	-
Peak brake torque	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0
Peak Active Feedback	+	+	+	+	+	0	0	0	0	0		0	0	0	0	0	0	0	0
Angular velocity	+	+	+	+	+	0	0	0	0	0		0	0	0	0	0	0	0	0
Backlash	0	0	-	-	-	0	0	-	-	-		-	-	-	-	-	-	-	-
Maintanance	0	0	0	0	0	0	0	0	0	0		0	0	0	-	-	-	-	-
Complexity	+	+	+	+	+	0	0	0	0	0		0	0	0	-	-	-	-	-
Price	+	+	+	+	+	0	-	-	-	-		0	-	-	-	-	-	-	-
Σ+	6	5	5	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Σ 0	3	5	4	4	4	7	9	8	7	7	0	9	7	7	4	4	4	4	4
Σ -	2	1	2	2	2	2	2	3	4	4	0	2	4	4	7	7	7	7	7
Net	4	4	3	3	3	0	-2	-3	-4	-4	0	-2	-4	-4	-7	-7	-7	-7	-7
Ranking	1	1	2	2	2	3	5	6	7	7	3	5	7	7	8	8	8	8	8
Further evaluation	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes	No	No	No	No	No	No	No	No

Table A3- Pugh Matrix on Steering angle limiter 2.

Chalmers	Document: Pugh Matrix Steering Angle Limiter 2				
Author: Leo Ekström, Loke Lindblad	Created: 2025-02-28 Modified: 2025-03-12				
Requirement/Wishes	**2**	**3**	**4**	**6**	**7**
Clearance to firewall	0	0	-	REFERENCE	0
Radius (from central axis)	0	-	0		-
Degrees to limit	0	0	0		0
Stering angle limiter torque to failure	+	0	0		-
Complexity	0	-	-		-
Σ+	1	0	0	0	0
Σ 0	4	3	3	0	2
Σ -	0	2	2	0	3
Net	1	-2	-2	0	-3
Ranking	1	3	3	2	4
Further evaluation	Yes	No	No	Yes	No

Table A4 – Calculations of weighted values used in the Kesselring Matrix.

Requirements/Wishes/Extra	1.1	1.3	4.1	4.2	4.3	4.5	4.12	4.13	Price	Comp	Σ	Σrel
1.1 Clearance to firewall	-	1	1	1	1	1	1	1	0,5	1	8,5	0,18889
1.3 Radius (from central axis)	0	-	1	1	1	1	1	1	0	0	6	0,13333
4.1 Max cogging torque	0	0	-	0,5	0	0,5	0,5	0	0	0	1,5	0,03333
4.2 Friction torque	0	0	0,5	-	0	0,5	0,5	0	0	0	1,5	0,03333
4.3 Peak brake torque	0	0	1	1	-	1	1	1	0	0	5	0,11111
4.5 Peak active feedback	0	0	0,5	0,5	0	-	1	0,5	0	0	2,5	0,05556
4.12 Angular velocity	0	0	0,5	0,5	0	0	-	0	0	0	1	0,02222
4.13 Backlash	0	0	1	1	0	0,5	1	-	0	0	3,5	0,07778
Price	0,5	1	1	1	1	1	1	1	-	1	8,5	0,18889
Complexity	0	1	1	1	1	1	1	1	0	-	7	0,15556
											45	1,000

Calculations

Calculations A1 – Calculations of the time required to accelerate the Hand-Wheel-Actuator to the realistic angular velocity of 3 revolutions per second as determined by the authors of this paper.

Convert rpm to rad/s

$$rad/s \ = revolutions/s \times 2\pi \qquad (2)$$

$$\omega_{target} = 3\, revolutions/s \ = 18.85\, rad/s$$

Net torque

The net torque is calculated by taking the gearbox output from each concept and subtracting the friction torque caused by the system. This has been estimated to 0.1 Nm according to (Volvo, 2025).

$$T_{concept\ 2} = 17.15 - 0.1 = 17.05\, Nm$$

$$T_{concept\ 3} = 21.17 - 0.1 = 21.07\, Nm$$

Moment of inertia

The moment of inertia is dependent on several factors such as mass, size and shape. Rough calculations were made to approximate the inertia around the central axis. This was done by calculating the mass of components in CAD, assuming a solid cylindrical shape and using the following equation (3) for calculating the inertia of each component. Note that the belt pulley and gear from concept 2 and 3 respectively have been estimated to have the same mass and radius. This is due to the fact that the difference is determined to be negligible.

$$Moment\ of\ inertia\ (assuming\ a\ solid\ cylinder) = \frac{1}{2}mr^2 \qquad (3)$$

The following masses were calculated in CAD:

$$M_{steering\_axis} = 0.845\, kg$$

$$M_{gear/pulley} = 0.239\, kg$$

The follwing radiuses were mesured in CAD:

$$r_{steering\_axis} = 15\, mm = 0.015\, m$$

$$r_{gear/pulley} = 45\, mm = 0.045\, m$$

As per equation (3) of moment of inertia:

$$I_{steering\_axis} = \frac{1}{2} \times 0.845 \times 0.015^2 = 10^{-6}\ kgm^2$$

$$I_{gear/pulley} = \frac{1}{2} \times 0.239 \times 0.045^2 = 2.4 \times 10^{-4}\ kgm^2$$

The mass and radius were used to calculate the moment of inertia for each component of the steering column. Additionally, the steering wheel, airbag and motor inertia needs to be considered. According to (Volvo, 2025) the moment of inertia for the steering wheel and airbag is 0.04 kgm^2. In order to calculate the reflected inertia caused by the motor and gearing the following formula was used. R = Gear ratio and I_{motor} is approximately 10^{-4} kgm^2 as per (Volvo, 2025).

$$I_{steering\_wheel+airbag} = 0.04\ kgm^2$$

$$I_{reflected} = I_{motor} \times R^2$$

$$I_{reflected\_concept\_2} = 10^{-4} \times 2.5^2 = 6.25 \times 10^{-4}\ kgm^2$$

$$I_{reflected_{concept_3}} = 10^{-4} \times 5^2 = 2.5 \times 10^{-3}\ kgm^2$$

$$I_{total} = \sum I \qquad (4)$$

$$I_{concept\_2} = I_{steering\_axis} + I_{gear/pulley} + I_{steering\_wheel+airbag} + I_{reflected\_concept\_2}$$

$$I_{concept\_2} = 10^{-6} + 2.4 \times 10^{-4} + 0.04 + 6.25 \times 10^{-4} = 4.09 \times 10^{-2}\ kgm^2$$

$$I_{concept\_3} = I_{steering\_axis} + I_{gear/pulley} + I_{steering\_wheel+airbag} + I_{reflected\_concept\_3}$$

$$I_{concept\_3} = 10^{-6} + 2.4 \times 10^{-4} + 0.04 + 2.5 \times 10^{-3} = 4.27 \times 10^{-2}\ kgm^2$$

Angular acceleration

α = Angular acceleration

$$\alpha = \frac{T_{net}}{I_{total}} \quad (5)$$

$$\alpha_{concet\_2} = \frac{T_{concept\_2}}{I_{concept\_2}} = \frac{17.05}{4.09 \times 10^{-2}} = 416.87\ rad/s^2$$

$$\alpha_{concet\_3} = \frac{T_{concept\_3}}{I_{concept\_3}} = \frac{21.07}{4.27 \times 10^{-2}} = 493.44\ rad/s^2$$

Time to reach targeted angular velocity

t = time to reach the targeted angular velocity.

$$t = \frac{\omega_{target}}{\alpha} \quad (6)$$

$$t_{concept\_2} = \frac{18.85}{416.87} = 0.045\ s$$

$$t_{concept\_3} = \frac{18.85}{493.44} = 0.038\ s$$

DEPARMENT OF INDUSTRIAL- AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2025
www.chalmers.se

CHALMERS