Concept Exploration of Urban Mobility Vehicle

Master's thesis in Product Development

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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
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Concept Exploration of Urban Mobility Vehicle
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Abstract

Cities are striving to enhance their sustainability by changing their infrastructure. These can be dealt with promoting more sustainable modes of transport. In the current era of BEV's, the size and weight of the vehicle increases whereas the infrastructure of the cities has never changed. This is where C40, A global network which has a clear mission to create an urban life that is organised so that people can access all the services they need within their immediate vicinity, and where it's easy for people to walk or bike to work and to nearby stores. (C40 Cities Climate Leadership Group, Inc, 2023).

The aim of this thesis is to create a lightweight micro mobility platform which supports the urban cities that helps in creating a sustainable urban environment. One of the possible solutions for an urban mobility concept is Narrow tilting vehicle (NTV) which is the focus of this thesis. This concept involves understanding the principles of narrow tilting vehicles and investigating the possibilities for using this for the future mobility alternative for BEV's. Our concept of narrow tilting vehicle is to make use of the bike lanes in the cities for shorter commuting distances with a possibility to transport small goods.

The theory explains the principles behind narrow tilting vehicles and the components that are needed for this vehicle. The methodology used it the product development process by Ulrich and Eppinger. This product is developed by requirements that are given by Volvo Cars, where the master thesis was developed. Concepts were generated and the best fitting is created as a virtual prototype and a LEGO prototype. Calculations for the tilting mechanism were done and what we found is a hydraulic system needs to be created to allow tilting for this vehicle. This being an electrical vehicle the energy consumption had to be evaluated therefore a drive cycle was created to calculate the theoretical range of the vehicle. The final concept is presented as a virtual model.

In conclusion, a concept for a NTV was developed with the main focus being on the tilting mechanism. However future work should aim towards improving the design, enhancing safety aspects, reducing energy consumption, and evaluating market interest and acceptance of NTV:s on bike lanes

Keywords: Narrow Tilting Vehicle, NTV, Tilting Mechanism, Urban Mobility, Tilt Control, E-Bike, Urban Transportation.

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Edin Smajić & Niranjan Harikumar Gopalakrishnan Ramesh Babu, May 2023

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

NTV	Narrow Tilting Vehicle
CAD	Computer Aided Design
FoS	Factor of Safety
VRU	Vulnerable Road User
BEV	Battery Electric Vehicle
DFMA	Design for Manufacture and Assembly

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Introduction

In this section the topic will be introduced, the background, company, purpose and goals and scope for the thesis will be presented.

1.1 Background

Cities are striving to enhance their sustainability by focusing on changing infrastructure. To reach the necessary collective and individual goals to tackle the climate crisis, one example of an existing initiative is the C40, a global network of about 100 mayors to unite the cities looking in the same direction. One of the goals within the C40 cities relates with urban planning and the adoption of the concept of "15 minute cities". This concept aims to create an urban life that is organised so that people can access all the services they need within their immediate vicinity, and where it's easy to walk or bike to work and stores (C40 Cities Climate Leadership Group, Inc, 2023). One crucial aspect involves reallocating road space by encouraging the use of sustainable modes of transportation such as walking and cycling. These cities aim to create an environment where sustainable modes of transportation are promoted such as bicycles, electric bicycles and scooters. A goal that C40 holds is improved bike infrastructure which encourages cities to invest in cycling infrastructure to promote bikeability. Ways to implement this can be creating dedicated bike lanes, installing bike-sharing programs, more bike-friendly traffic policies, and expanding existing bike networks. Prioritizing biking can reduce congestion, improve air quality, and enhance the overall livability of urban areas. During the COVID-19 pandemic conversations sparked about transforming cities into systems that facilitate local and sustainable living for residents. This has created a demand for "complete neighbourhoods" where anything they need can be found locally.(C40 Cities Climate Leadership Group, Inc, 2023).

In Gothenburg, there are goals for the future city planing where pedestrians and cyclist are prioritised in the city development. Another goal of this is a city plan to decreases the need for lengthy travels and on creating a local environment that requires less traveling. Public transport, walking and cycling is encouraged and the future plan for the city aims to increase the availability of these transportation modes while also increasing their efficiency (Göteborgs Stad Trafikkontoret, 2014). A possible consequence of this is a more bikeable city. While walking and cycling are good ways of moving, especially considering the 15-minute city concept, there might be room and even need for other types of micromobility transport when carrying hefty weights and shelter, for example. Besides that, to some extent, some people will continue living a bit outside town, where usually public transport network does not work so well, and they will need to cover longer distances. In that sense the aim of this project was to explore ideas of such vehicle. Being a Master Thesis of Product Development Program, the explorations will focus in the platform of the vehicle.

With cites infrastructure changing and a bigger light being shed out on urban mobility, Volvo Cars decided to create a Master's thesis project where an urban mobility vehicle for the future infrastructure was designed. This vehicle should fit on bike lanes without taking to much space therefore it should be narrow. A narrow vehicle comes with stability problems and to decrease the risk of falling over it has to have the ability to tilt in corners. Therefore a concept of narrow tilting vehicle was proposed as a possible solution to this problem and was investigated in this project and was presented in this report.

1.1.1 Industrial Partners

This a exploratory project where we were partnered with Volvo Cars. Volvo Cars, headquartered in Torslanda, Gothenburg, is a Swedish automobile manufacturer that produces sedans, station wagons, and SUVs.

This thesis was conducted at Chalmers University of Technology and at the Open Innovation Arena at Volvo Cars. Open Innovation Arena is a unit at Volvo ”The role of the Open Innovation Arena is to prepare Volvo Cars for different futures by tackling our greatest uncertainties.” (Volvo Cars, 2023). The thesis team was working independently, under frequent supervision by Volvo and Chalmers.

Having in mind the changing in cities infrastructure and a bigger light being shed out on urban mobility, this project was proposed by Volvo Cars, aiming to explore the aforementioned possibilities of designing an urban mobility vehicle for the future. More information on the partnership, the purpose and goals including the given requirements, the considerations and limitations, research questions, and main deliverables are presented in the next sections of this introduction chapter.

1.2 Purpose and goals

The purpose was to design, develop, and verify the platform of a lightweight micromobility vehicle, supporting low-speed, short trips in urban environments. The vehicle itself is a part of Volvo Cars' ambition to help people achieve personal, sustainable, and safe mobility across modalities in the context of future mobility. Investigating the possibility of using a narrow tilted vehicle (NTV) as an urban mobility vehicle. The delivery in this project was a conceptual solution.

Goals for this project
- The vehicle should be able to be classified as a bike in the future
- Small scale model and virtual model that is verified with simulations

- Investigate safety

1.3 Consideration and limitations

Considerations and limitations are presented here

- No full size prototype was developed
- This work was conducted during 20 weeks and therefore literature review, testing, verification and similar topics were time limited
- This was an exploratory project and therefore was conducted in such a way
- The tilting mechanism was of focus and it aimed to look into the core values of Volvo Cars company brand holds
- The platform was the most important in this thesis, the top hat was secondary
- In this project most requirements were given only some had to be found
- Current bike regulations may not be followed
- DFMA was not considered in this project

1.4 Research questions

Questions that will be investigated during the project

- How was a simple tilting four wheeled vehicle constructed?
- Which were the important factors that have to be taken in to consideration when constructing an urban tilting vehicle?
- What were the biggest challenges when constructing a tilting vehicle?

1.5 Main deliverables

These were the deliverables for this project

- A vehicle with tilting capabilities that has a weather protection
- Proof of concept through a prototype, a virtual prototype and calculations
- A tilting mechanism with in depth explanations of construction

2

Theory

This chapter aims to provide the reader with a comprehensive understanding of narrow tilting vehicles (NTV:s) and their key components. The relevant theory is presented, starting with a literature study follwed by patent analysis that explores the existing knowledge and research gaps in the field of urban mobility and NTVs. Following the literature study, the chapter delves into the regulations governing NTVs in Sweden, the European Union (EU), and the United States (USA). The significance of these regulations is discussed, highlighting key safety, emissions, and classification requirements that NTVs must adhere to in each jurisdiction. The theory section then proceeds to explain the principles behind NTVs. Additionally, the theory section covers types of suspension and steering concepts which covers important subsections such as hub motors, batteries, and seating/ergonomics. This helps the readers by providing a solid knowledge base that facilitates a deeper understanding of the subsequent chapters in this report. It equips the reader with the necessary background knowledge and working principles of NTVs, their components, and related theories, which will be further explored and applied in the following chapters.

2.1 Literature Study

Initially, a literature study was carried out in order to understand the background behind narrow tilting vehicles and urban cities. There was a need to do research on the existing papers before starting with the concept generation. The studies showed that tilting suspension with actuators plays a major role in order for the vehicle to tilt and how it influences the dynamics of the tilting vehicle when compared to a conventional car. Theory on different sub-systems needed for the NTV has been studied and summarised to provide sufficient understanding to lead and follow the reasoning behind the development of tilting suspension.

The patent search was done to identify the existing and emerging technologies for narrow tilting vehicles in order to get inspirations and published concepts to ind the best possible solution. Several keywords such as ’tilting suspension’, ’narrow vehicles’, ’four wheel tilting’, etc., were used in order to explore the available patents and around 100 patents were found and filtered out the ones which were related to this project were selected. Google Patents (Google, n.d.) and Espacenet (Espacenet, n.d.) were the main sources for finding the patents.

2.2 Regulations

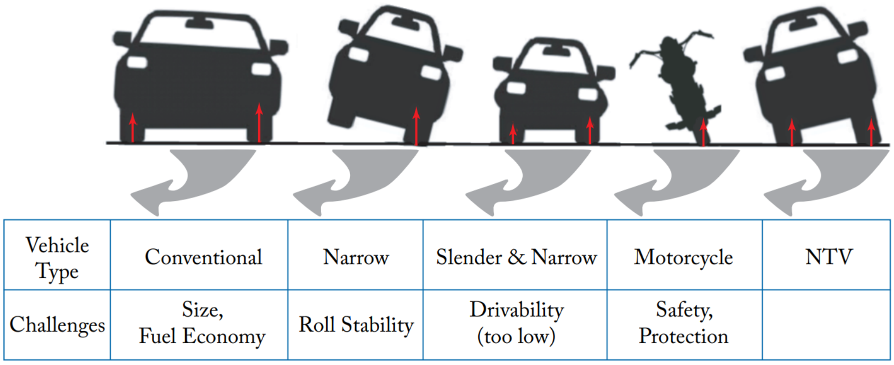
In this section the different regulations which apply in Sweden, EU and USA will be presented. Only the most relevant regulations for this project will be presented.

In Sweden, the regulations present two types of vehicles are consider bicycles which are bicycle with pedals and bicycle without pedals. The bicycle with pedals has to include pedals that propels it. A bicycle with pedals is allowed to travel at 25 km/h (only amplifying the pedaling up to that speed) with the maximum power of 250 watt.(Landsbygds- och infrastrukturdepartementet RSIB TM, 2023). The bicycle without pedals is constrained by length dimensions which we are unable to comply to in this project. These regulations also apply in EU but EU regulations are only recommendations since every country sets its own bike regulations. The EU regulations instead focuses on the amount of wheels on a vehicle and its propulsion (European Parliament and Council, 2020). US regulations have a wattage of 750 instead of 250 and the highest allowed speed is 20 mp/h which is about 32 km/h and pedals are required. Three wheels is the max amount to be classified as a bike in USA (National Archives and Records Administration, 2023).

2.3 Narrow Tilting Vehicles

Narrow tilting vehicles (NTV:s) are a type of vehicle that utilizes a narrow track width of conventional cars with a tilting mechanism to achieve high levels of stability and maneuverability, especially in urban environments. The principles behind NTV's involve optimizing the size and weight distribution of conventional cars with a more efficient and sustainable urban mobility solution. This includes challenges such as reducing emissions, improving fuel economy, and enhancing safety for passengers and other road users.

Vehicles with narrow footprint design make use of existing road infrastructures which enables them to operate on bike lanes and allows parking in compact spaces. With its track width reduced almost by half, a narrow vehicle becomes significantly less stable against rollover compared to a conventional car. To control rollover stability, an active tilting system is introduced to narrow footprint vehicles which improves the vehicle rollover stability and lateral forces while cornering at low or high speeds. (Tang & Khajepour, 2019)



Vehicle Type	Conventional	Narrow	Slender & Narrow	Motorcycle	NTV
Challenges	Size, Fuel Economy	Roll Stability	Drivability (too low)	Safety, Protection	

Figure 2.1: Vehicle types comparing with a NTV

The concept behind NTV's is inspired by two-wheelers such that the vehicle can actively lean into the curves like a motorcycle during cornering. This is achieved through a combination of mechanical and/or electronic systems, such as active tilting suspension, which can adjust the vehicle's angle of lean in response to the speed and direction of the turn with improved safety under different road conditions.

2.4 Suspension

The suspension system in NTV's ensures vehicle stability, handling, and passenger comfort. Designing suspensions for NTV's involves specific challenges and considerations. The primary goal of the suspension system is to keep the wheels in contact with the road surface at all times, while minimizing the impact of bumps and other obstacles on the vehicle's chassis. Suspension systems must be designed to provide adequate stability and tilt control, ensuring that the vehicle remains balanced and controllable during turns. The suspension system of a narrow tilting vehicle typically consists of several key components, which are Knuckles, Control Arms, Wheel Hub, including the ball joints, rubber bushes.

The tilting suspension system utilizes a combination of mechanical, hydraulic, or electronic actuation mechanisms to facilitate controlled vehicle tilt. These mechanisms include tilting mechanisms, such as articulated frames or interconnected suspension systems, that enable controlled lateral tilting of the vehicle body. In addition, introducing a control system and sensors that will monitor various parameters, including vehicle speed, steering input, lateral acceleration, and road conditions, to determine the appropriate amount of tilt required for optimal performance and stability. (Johansson, 2020)

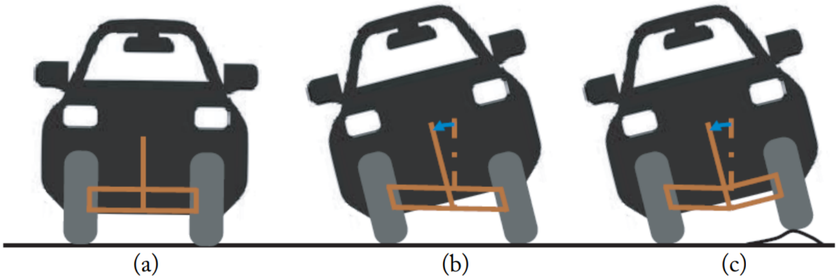


Figure 2.2: Tilting Suspension

According to (Tang & Khajepour, 2019), the tilting of the narrow vehicle is caused by the lateral acceleration experienced during cornering. When the car enters a bend, the centripetal force acting on the car causes the center of gravity to shift. To combat this change and maintain stability, the tilting suspension allows the vehicle to lean into corners, balancing gravity with centripetal force. This tilting motion reduces the lateral force exerted on the tyres, which improves traction and cornering.

2.5 Ackermann Steering

Steering is a critical aspect of any vehicle's functionality, including NTV's. Ackerman Steering is a well-known steering mechanism used in various vehicle applications, including NTV's. Ackerman Steering is based on the principle of maintaining ideal wheel angles during turns to ensure smooth and accurate cornering. It is named after the 19th-century engineer Rudolph Ackerman, who pioneered the concept. (Changrui Liu, 2019)

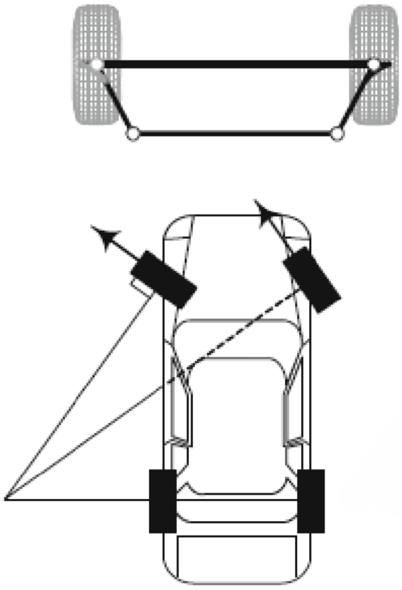


Figure 2.3: Ackerman Steering Geometry

The fundamental principle behind Ackerman steering is to ensure that the inner and outer wheels of a vehicle follow different turning radii while negotiating a turn. This allows the wheels to maintain optimal tire slip angles and reduces tire scrubbing, resulting in improved traction and reduced wear. As the driver turns the steering wheel, the linkage converts the input into rotary motion, causing the wheel to rotate through different angles. The linkage geometry should be carefully designed to achieve the desired Ackermann effect, in which the inner wheel turns at a sharper angle than the outer wheel during turns.

The introduction of a steering rack in narrow tilting vehicles prioritizes safety and enhances steering control. The steering rack is a mechanical device that converts the rotation of the steering wheel into a linear motion to control the movement of the wheel. This offers a more direct and precise steering response, empowering drivers with enhanced control over tilting of the vehicle. Rack and pinion design is a commonly used steering rack which improves the safety and responsiveness of the vehicle during slow and quick maneuvering.

2.6 Actuators

Actuators play a critical role in the operation and control of NTV:s. These electromechanical devices convert electrical signals into mechanical motion, enabling precise control of various vehicle systems. In the context of NTV:s, actuators are used for tilt control, suspension adjustment, steering assistance, and other functions. (Tang & Khajepour, 2019)

In narrow tilting vehicles, linear hydraulic actuator plays a crucial role in the operation of various systems, such as tilting mechanisms, suspension adjustments, or steering control. Tilting mechanism using hydraulic actuators are employed to initiate and control the tilting motion of the vehicle body during cornering. By adjusting the hydraulic pressure in the actuators on each side of the vehicle, the desired amount of tilt can be achieved, enhancing stability and improving cornering performance.

The benefits of linear hydraulic actuators include their high stability, ability to withstand substantial road bumps, and their responsiveness to tilt with high precision . Hence, this makes them suitable for applications that require precise and robust actuation, such as the dynamic control of narrow tilting vehicles.

2.7 Hub Motors

Hub motors are electric motors integrated directly into the wheel hubs of a vehicle. They operate on the principle of electromagnetic force generation and torque production. By eliminating the need for a central drivetrain, hub motors offer direct power delivery to the wheels, enabling independent control and precise torque distribution. Hub motors have gained significant attention in the development of narrow tilting vehicles due to their unique advantages and potential for improving performance, efficiency, and packaging. (Zheng Zhang, Xiao-jun Ma, Chun-guang Liu, Shu-guang Wei, 2020)

Based on the requirements, Hub Motor provides mainstream benefits for NTV:s. Firstly, they enable independent control of each wheel, allowing for enhanced stability, traction, and maneuverability. Secondly, hub motors eliminate the need for traditional drivetrain components, such as transmissions, driveshafts, and differentials, resulting in simplified vehicle architecture, reduced weight, and improved efficiency. Additionally, hub motors provide regenerative braking capabilities, enhancing energy recovery and overall range.

However, efficiency considerations such as motor efficiency, power losses, and energy consumption during operation should be carefully evaluated to maximize the overall efficiency of the NTV.

2.8 Battery

Electric propulsion is becoming increasingly popular in NTV:s as a sustainable alternative to conventional internal combustion engines. Swappable batteries offer a promising solution to address the limited range and charging infrastructure challenges of electric NTV:s. The working principle of swappable batteries involves the concept of interchangeable battery packs that can be easily removed and replaced in electric vehicles. These battery packs are designed to be modular and compatible with specific vehicle models(TUDelft, 2018).

Some of the potential benefits for NTV:s, including extended range, reduced charging time, and increased operational flexibility. By enabling quick battery swapping at designated stations, NTV:s can overcome range anxiety and eliminate the need for lengthy charging sessions. This technology also promotes scalability, as additional battery packs can be added or removed based on the desired range or specific operational requirements. The design and integration of the battery compartment, connectors, and locking mechanisms should ensure secure attachment and reliable electrical connections.

Swappable batteries have the potential to reduce the environmental impact of NTV:s by promoting the use of renewable energy, reducing dependence on fossil fuels, and facilitating efficient battery recycling and reuse. However, the overall environmental benefits depend on factors such as the energy sources used for charging, battery manufacturing processes, and the lifecycle analysis of the entire battery swapping ecosystem.

2.9 Seating and Ergonomics

Seating and ergonomics are essential considerations in the design of NTV's to ensure occupant comfort, safety, and optimal vehicle control. As NTV's operate in urban environments, providing comfortable seating positions and ergonomic interfaces is crucial for enhancing the overall user experience. Since NTV's are more likely to be used for shorter commuting purposes, it's important to have ergonomic seating position in order to decrease the chances of fatigue.

One of the key challenges in seating design for narrow tilting vehicles is enabling easy ingress and egress without compromising the stability of the vehicle. Due to the tilting nature of these vehicles, passengers must be able to enter and exit the vehicle without causing imbalance or the risk of tipping over. Therefore, designers need to consider the positioning and accessibility of the seating area to facilitate smooth ingress and egress while maintaining the vehicle's stability. This may involve incorporating features such as wider door openings, lower step heights, and ergonomic handle placements to assist passengers in safely entering and exiting the vehicle.

Anthropometric considerations are crucial in designing seating and ergonomic interfaces that accommodate different range of occupant sizes and shapes. For example, this focuses on all body type people. The design should account for variations in leg length, torso height, and body proportions to ensure a comfortable and supportive seating position for a diverse user population. (Allsteel Inc., 2006)

3

Methods

In this section the methodology followed in this thesis will be presented. The purpose of which is to guide the reader through the process and means of which the study has been carried out. An overview of the product development process that has been followed is presented in the following chapters.

The general product development process described by Ulrich & Eppinger in (Ulrich & Eppinger, 2016) was used as the main method for this thesis. Their process consist of 6 steps namely opportunity identification and selection, concept generation, concept evaluation, development, testing and validation, launch and commercialisation. The following paragraph is how this product development process is typically implemented.

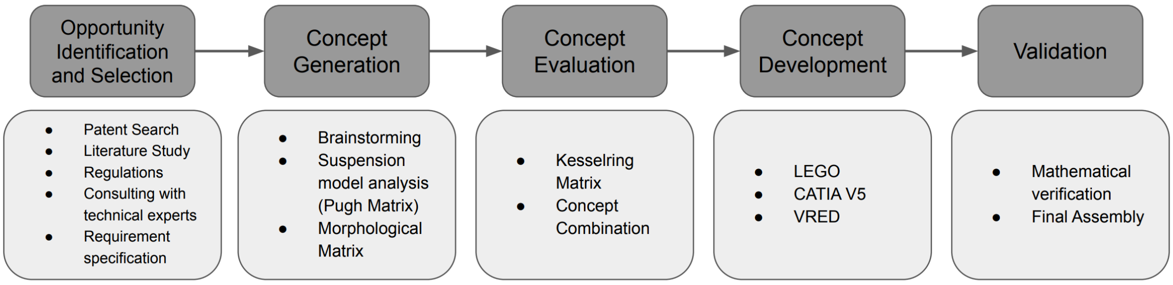


Figure 3.1: Methodology: Presenting the process steps that has been followed to conduct this project

- **Opportunity Identification and Selection:** This stage is where ideas for new products are generated and evaluated of their compliance with business targets, product brand and emerging markets. The objective is to recognise promising product concepts with potential to meet customer needs and in the future generate value the company. At the end of this phase the main requirements are one of the most tangible results.
- **Concept Generation:** When the opportunities are identified, the next step is to perform a brainstorming session and developing a range of product concepts. This process is conducted by idea generation, idea exploration and not abandoning unpromising concepts early. The main goal of this stage is to have a broad range of concepts that can be evaluated and further improved.

- **Concept Evaluation:** The generated concepts are evaluated against relevant criteria for the product as technical feasibility, safety, maintenance, and profitability potential. Concepts are analyzed, improved, and chosen for further development based on their ability to meet the requirements and align with the vision of the company.
- **Development:** When a concept is selected then the development stage start. In this step the selected concept is transformed in to a concrete product design. This process involves detailed engineering, prototyping, testing, and refining the design to fit requirements, manufacturability, cost analysis, and customer input.
- **Testing and Validation:** In this stage, the product is tested and validated to ensure it meets set requirements, works as intended and meets safety expectations. This requires conducting tests and simulations to recognize and address possible design flaws or issues encountered.
- **Launch and Commercialization:** After thorough testing and validation, the product can be launched. This stage consists of formulating a plan and executing it for the commercialization strategy, production ramp-up, marketing of the product, solving distribution question, and setting up customer support. The main goal for this stage is to introduce the product to the market- in an effective manner and committing to maximising the adoption and sales of the product.

This product development approach was followed but adapted to the fit this project. The opportunity identification and selection was given by Volvo thus a requirement specification already existed at the start of the project. Therefore the beginning of this project was spent on learning the theory of NTV:s and the different components that are included in such a vehicle. Concept generation and concept evaluation were done as Ulrich & Eppinger recommend. Using calculations, a virtual prototype and other possible tools that could validate the design were instead used. Launch and commercialisation was not a part of this project and was therefore omitted.

3.1 Opportunity identification and selection

Requirements that were based on Volvo's previous findings were given. However according to the findings made during the project it was possible to adjust requirements if needed. A document containing the purpose, design brief, wants and needs, dimensions, the technical challenge, explaining pictures, main deliveries and requirements was given by Volvo. These requirements were followed and new requirements were added for the parts that were included in the tilting mechanism.

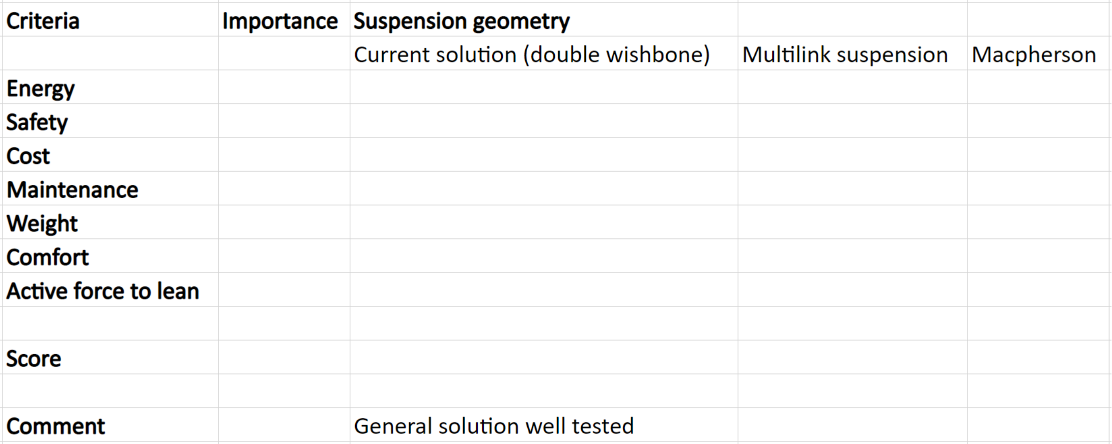
3.2 Concept generation

Different suspension models were explored and concepts were made of the ones scoring highest in the evaluation matrices. A brainstorming session took place in the early stages where all suspension models were explored and concepts were created.

After this step fitting elimination matrices were used to weed out the concepts with the least potential. The standing concepts were further developed and more thoroughly explored then another matrix was used to eliminated the least promising concepts until only two were left. These concepts were combined into one concept. Parallel with this the main focus of the thesis which was the tilting mechanism was developed. Calculations and a LEGO prototype were used in development. With these tools requirements were able to be set and an actuator could by chosen. This actuator was a hydraulic one and therefore a hydraulic system had to be developed.

3.2.1 Suspension model analysis

To confirm that the tilting mechanism of the NTV was feasible a study of different suspension models had to be conducted. What was researched was the complexity of the suspension models and the possibility of their usability in tilting purposes. The complexity had to be low in order to meet the time frame of the project. An elimination matrix was used to decide which suspension models were possible to move forward with. This was done with the help of a pugh matrix.



Criteria	**Importance**	**Suspension geometry**		
		Current solution (double wishbone)	Multilink suspension	Macpherson
Energy				
Safety				
Cost				
Maintenance				
Weight				
Comfort				
Active force to lean				
Score				
Comment		General solution well tested		

Figure 3.2: Empty pugh matrix

A Pugh matrix is a tool used to evaluate and compare different options or alternatives based on a set of criteria or factors. It is especially useful when complex decisions have to be made. The basic structure is a table with a list of solution alternatives in one column, and a list of evaluation criteria or factors in another column. Each option is then evaluated against each criterion using a scoring system where a higher scores indicates a better performance. One option is selected as a baseline, and then all other options are compared against it. The scores for each option are then added up, and the option with the highest total score is considered the best choice (Sridharan, 2021). A Pugh matrix was used for evaluating different suspension options and reaching a conclusion.

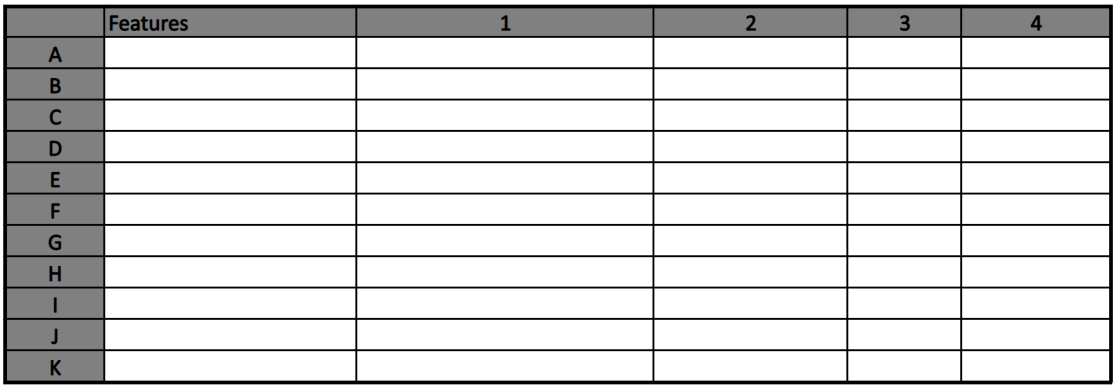
3.2.2 Brainstorming

Brainstorming is a technique for generating creative ideas. It involves participants trying to generate as many ideas as possible without worrying about the quality or feasibility of the ides. The goal was to generate as many ideas as possible then later identify and refine the most promising ones (Mind Tools Content Team, 2023).

A questionnaire was provided to colleague thesis workers that have some insight to the project. The goals of the questions provided was to create different solutions to use it in concept generation. The answers to these questions together with the requirements were used to build up the features of the morphological matrix were used for creating ideas for the concepts.

3.2.3 Morphological Matrix

A morphological matrix is a tool that is used to generate ideas for new products or to improve existing concepts. By breaking down a product into its component parts or features, and then creating a matrix that produce different combinations of those features. By systematically varying the different features of the product it can be explored in a wide range of possible configurations thus identify combinations that could have been previously overlooked. This can lead to the creation of new products that are more fitting to the needs of customers, or to the possible improvement of existing products in ways that make them more competitive in the marketplace(Cheshire, 2023). To get as much information from the morphological matrix as possible four concepts were randomly generated by using a random number generator and two concepts were created by us where the goal was for the concept to score as high as possible. Concept A, B, C and D were randomly generated then E and F were generated for a high score in the matrix. For every feature there were two, three or four alternative solutions.



	Features	1	2	3	4
A					
B					
C					
D					
E					
F					
G					
H					
I					
J					
K					

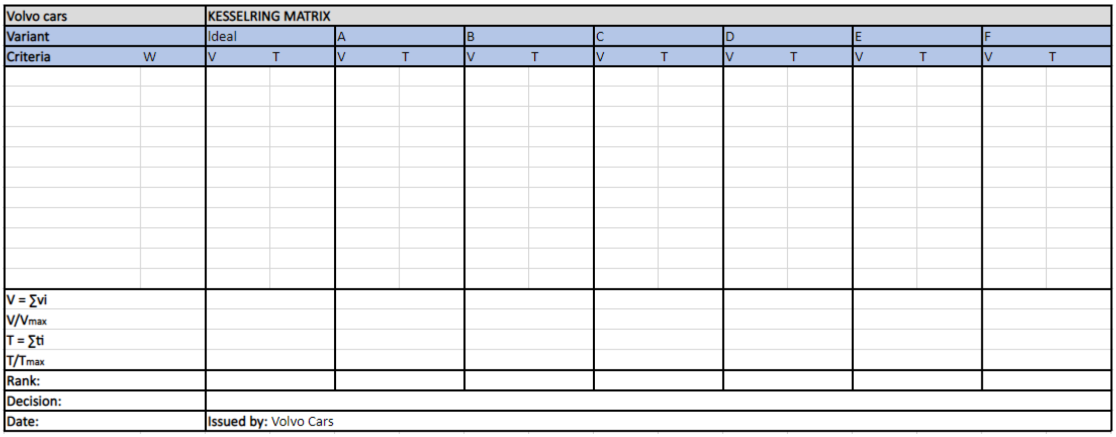
Figure 3.3: Empty morphological matrix

3.3 Concept evaluation

To evaluate the concepts generated in the previous phase, the first step was to compare them using a Kesselring Matrix. After that, one concept was selected for further development.

3.3.1 Kesselring Matrix

The concepts generated by the morphological matrix were used in a Kesselring matrix. The Kesselring matrix consists of criteria from the requirement specification and how well each concepts score in these individual criteria. A weight (W) is also added to each criteria to rank its importance relative to the other criteria.



Volvo cars		KESSELRING MATRIX													
Variant		Ideal		A		B		C		D		E		F	
Criteria	W	V	T	V	T	V	T	V	T	V	T	V	T	V	T
$V = \sum vi$															
V/V_{max}															
$T = \sum ti$															
T/T_{max}															
Rank:															
Decision:															
Date:		**Issued by:** Volvo Cars													

Figure 3.4: Empty Kesselring Matrix

Each concept in the matrix was graded based on how well it fulfilled each criterion, grades ranging from 1 to 10 and recorded in the 'v' column. The 't' column shows the multiplication of 'v' and the weightage 'w' for each concept.

The 'ideal' column represents a perfect solution that scores the highest in the 'v' column, with the sum of these scores used as the maximum value for 'V' (Vmax). The multiplication of 'w' and 'v' in the 'ideal' column results in the highest 't' values, and the sum of all 't' values in this column is used as Tmax.

To compare and rank the concepts, their 'V' and 'T' values are summed and recorded in the respective columns and cells. 'V/Vmax' and 'T/Tmax' values were then calculated to determine the relative performance and feasibility scores of each concept. Finally, the values of 'V', 'V/Vmax', 'T', and 'T/Tmax' were used to compare and rank the concepts based on the evaluation criteria.

3.3.2 Concept combination

Since two concepts had similar scores in the Kesselring matrix a combined solution was suggested. The combined concept was made with individual features that made the concept score high in the Kesselring, combining the strengths of each concept. This created a unique solution that had a higher score than all other concepts in the matrix. This was done in this project and will be explained further when presenting the results.

3.4 Concept Development and Validation

As previously mentioned, due to time limitations, the development phase of this project focused on having an extensively CAD prototype. Besides that, a simple LEGO model was used to verify the tilting mechanism. Also, at this phase, the simple geometry was tested in the CAD kinematics, along with features as emergency breaking, tilting and what happens during a crash. Furthermore, calculations were done regarding the brake, tilting mechanism, linear actuator, stroke speed, hydraulic, and drive cycles.

3.4.1 LEGO prototype

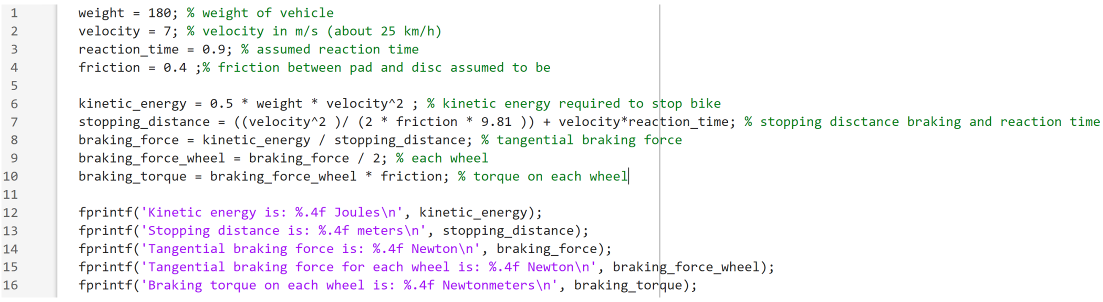
LEGO pieces were provided to us from Volvo to use for concept exploration. Simple LEGO models were created to explain different tilting mechanisms. The LEGO construction features a tilting mechanism and a steering mechanism and a tilt lock mechanism. The LEGO was also used to communicate different ideas and talk about possible solutions to different problems during the project. The LEGO was used to discuss CAD design and possible ways to solve design issues.

3.4.2 Mathematical Verification

Calculations in both Microsoft Excel and Matlab were made to verify different aspects of the prototype. Calculations were specifically focused on dimensioning the tilting mechanism, hydraulics used in the tilting mechanism and the drive cycle.

3.4.2.1 Brake

A code in MATLAB was written where the kinetic energy, stopping distance, tangential braking force, tangential braking force for each wheel and braking torque on each wheel and formulas from (Twiflex, 2021) were used for these calculations.



```
weight = 180; % weight of vehicle
velocity = 7; % velocity in m/s (about 25 km/h)
reaction_time = 0.9; % assumed reaction time
friction = 0.4 ;% friction between pad and disc assumed to be

kinetic_energy = 0.5 * weight * velocity^2 ; % kinetic energy required to stop bike
stopping_distance = ((velocity^2 )/ (2 * friction * 9.81 )) + velocity*reaction_time; % stopping disctance braking and reaction time
braking_force = kinetic_energy / stopping_distance; % tangential braking force
braking_force_wheel = braking_force / 2; % each wheel
braking_torque = braking_force_wheel * friction; % torque on each wheel

fprintf('Kinetic energy is: %.4f Joules\n', kinetic_energy);
fprintf('Stopping distance is: %.4f meters\n', stopping_distance);
fprintf('Tangential braking force is: %.4f Newton\n', braking_force);
fprintf('Tangential braking force for each wheel is: %.4f Newton\n', braking_force_wheel);
fprintf('Braking torque on each wheel is: %.4f Newtonmeters\n', braking_torque);
```

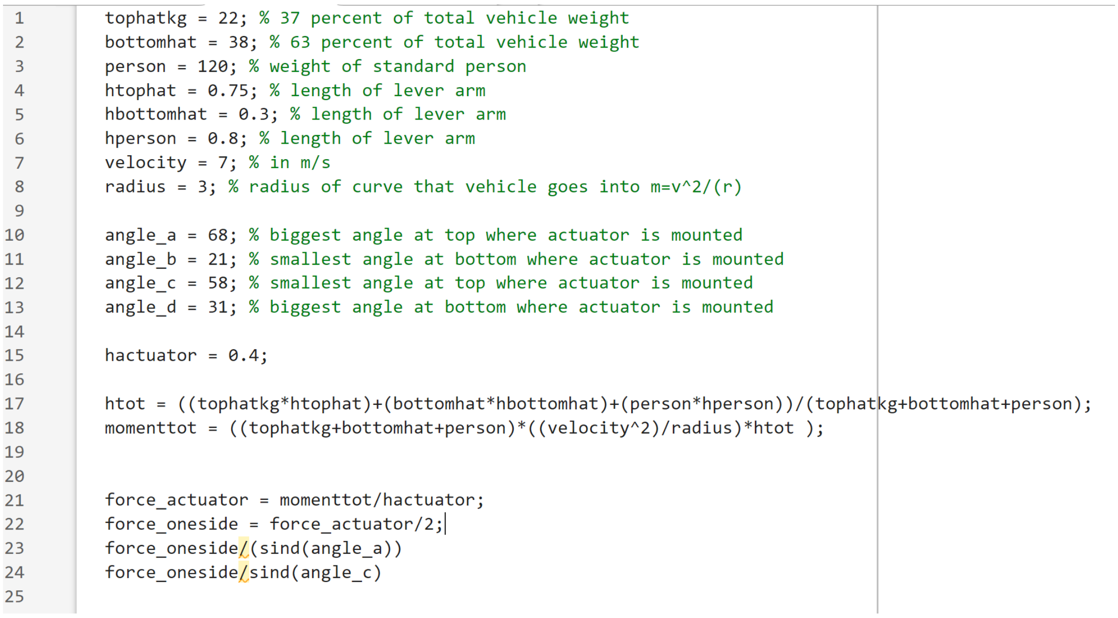
Figure 3.5: Code used for dimensioning of brakes

3.4.2.2 Tilting Mechanism

From the analysis of tilting and suspension models a model that was named romboid was selected. The dimensions for the frame were assumed to be around 400 mm x

200 mm and width was not considered for this type of modeling. After researching tilting options the conclusion to use a linear actuator reached. Calculations were performed on how much power was needed from the actuator to tilt the vehicle with a Matlab code. The code was written in a way that certain variables could be changed in order to fit dimensions of certain linear actuators and display the largest angle the actuator will be working in. This was important since at small angles the force for leaning could be very high which which was something that should be avoided. The code would also display the length of the actuator and the stroke length required when its been ran.

To avoid falling over when tilting calculations with Matlab and by hand were made. The maximum force that the vehicle would experience horizontally was calculated and the steepest turn the vehicle would have to be able to take was calculated. The calculation of the steepest turn resulted in finding out how fast the actuators should move which was used to dimension the hydraulic system.



```
tophatkg = 22; % 37 percent of total vehicle weight
bottomhat = 38; % 63 percent of total vehicle weight
person = 120; % weight of standard person
htophat = 0.75; % length of lever arm
hbottomhat = 0.3; % length of lever arm
hperson = 0.8; % length of lever arm
velocity = 7; % in m/s
radius = 3; % radius of curve that vehicle goes into m=v^2/(r)

angle_a = 68; % biggest angle at top where actuator is mounted
angle_b = 21; % smallest angle at bottom where actuator is mounted
angle_c = 58; % smallest angle at top where actuator is mounted
angle_d = 31; % biggest angle at bottom where actuator is mounted

hactuator = 0.4;

htot = ((tophatkg*htophat)+(bottomhat*hbottomhat)+(person*hperson))/(tophatkg+bottomhat+person);
momenttot = ((tophatkg+bottomhat+person)*((velocity^2)/radius)*htot );


force_actuator = momenttot/hactuator;
force_oneside = force_actuator/2;
force_oneside/(sind(angle_a))
force_oneside/sind(angle_c)

```

Figure 3.6: Matlab code for linear actuator strength requirement calculations

3.4.2.3 Linear actuator

Since the romboid solution was adopted an appropriate tilting actuation method had to be chosen. First electrical linear actuator were considered and simpler hand calculations were made to check if it was possible to use these. These simpler calculations did not result in any conclusive result and therefore it was decided to make in depth calculations with Matlab for verification.

As illustrated with the picture in figure 3.6 the different known lengths were used with Pythagoras theorem to investigate. To verify that the triangles were correct a triangle calculator website from (Maple Tech. International LLC, 2023) was used. The bottom red arrow was used as a variable called x, it could be changed and therefore different actuator lengths could be investigated depending on requirements. With this the length of the actuator when its fully extracted and fully retracted could be calculated by the help of Pythagoras theorem. When the fully extracted and fully retracted length were subtracted the appropriate stroke length was found. The needed length of the static part of the actuator was found also. The angles present in the triangles when its leaning fully (25°) were calculated and used in later calculations to find out how forces behaved in the fully tilted scenarios. Then the variable x was changed until it matched the length of an existing actuator.

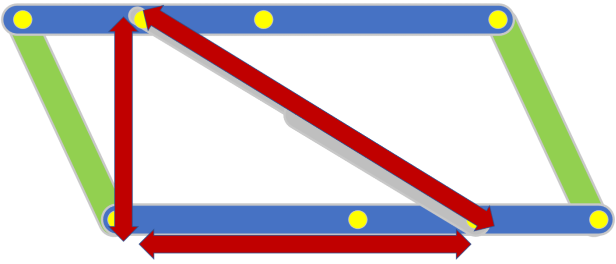
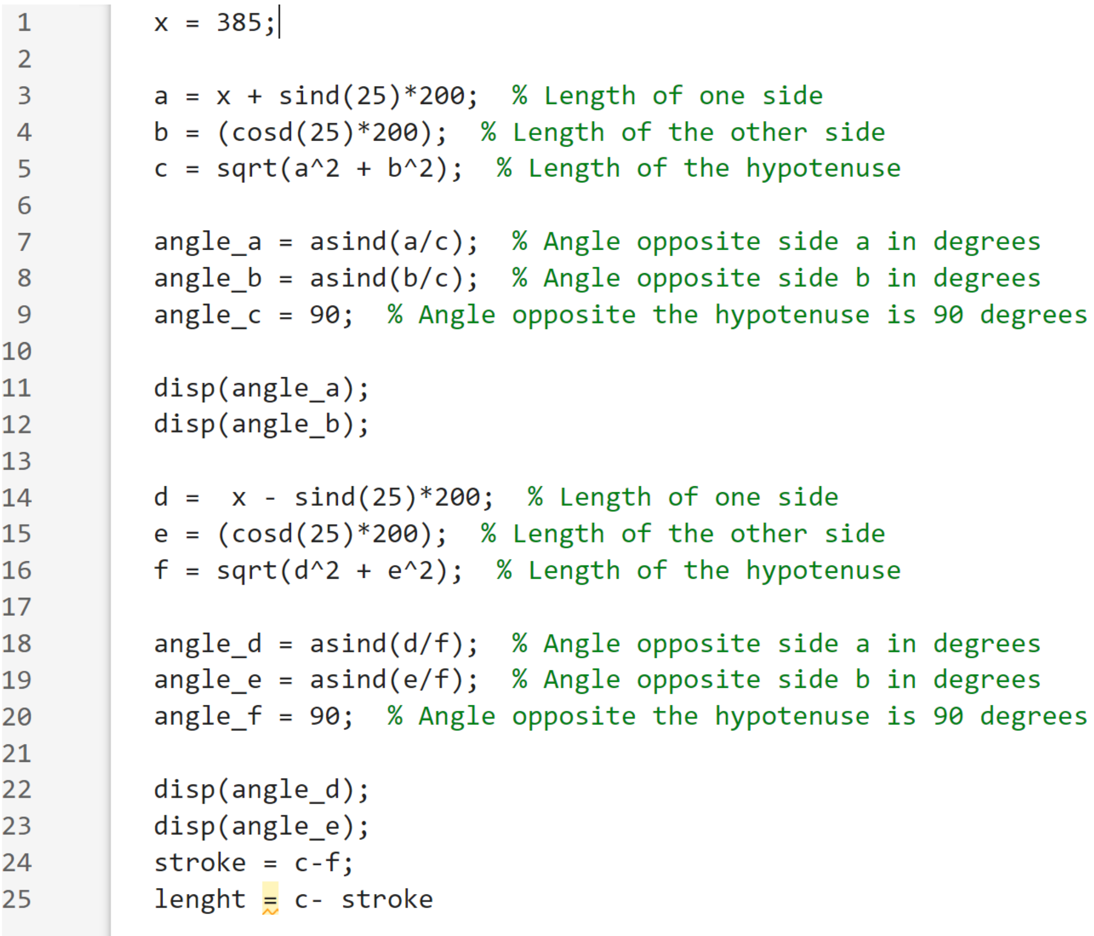


Figure 3.7: Red arrows describe triangle used for Pythagoras theorem



```
x = 385;

a = x + sind(25)*200;  % Length of one side
b = (cosd(25)*200);  % Length of the other side
c = sqrt(a^2 + b^2);  % Length of the hypotenuse

angle_a = asind(a/c);  % Angle opposite side a in degrees
angle_b = asind(b/c);  % Angle opposite side b in degrees
angle_c = 90;  % Angle opposite the hypotenuse is 90 degrees

disp(angle_a);
disp(angle_b);

d =  x - sind(25)*200;  % Length of one side
e = (cosd(25)*200);  % Length of the other side
f = sqrt(d^2 + e^2);  % Length of the hypotenuse

angle_d = asind(d/f);  % Angle opposite side a in degrees
angle_e = asind(e/f);  % Angle opposite side b in degrees
angle_f = 90;  % Angle opposite the hypotenuse is 90 degrees

disp(angle_d);
disp(angle_e);
stroke = c-f;
lenght = c- stroke
```

Figure 3.8: Matlab code for linear actuator size calculations

3.4.2.4 Stroke Speed Calculations

To find out the speed needed for the actuator the worst case scenario was considered. Which was a turn with 2,5 meters radius at max speed. With calculations we knew that the maximum possible speed in a corner with the radius 2,5 meters was 12 km/h when the vehicle is tilted 25°.

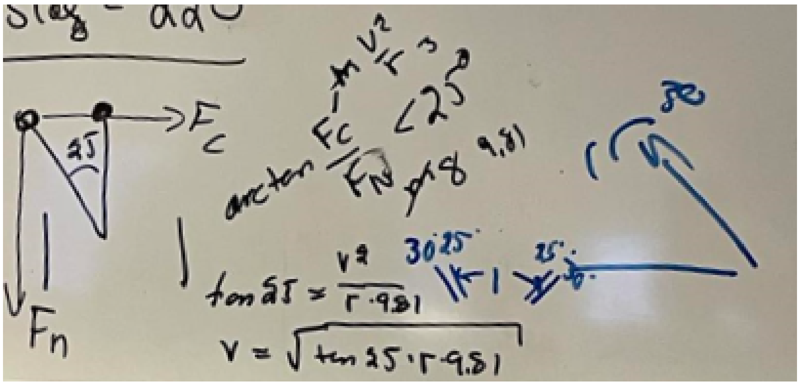


Figure 3.9: Calculation used for finding out the maximum possible speed in corner

Then it was assumed that the vehicle is driving in a straight line where it would have to go from 0° tilt to 25° tilt when its entering this corner. The part of the curve where the vehicle has to go from fully upright to tilted is called the clothoid. A clothoid in this case is a transitional curve roads are engineered after that is designed to make the ride comfortable when going in to the corner. The length of this clothoid was used to calculate the time needed for tilting to go from a 0° angle to a 25° angle at the speed of 12 km/h. The length of the clothoid used for the calculations was taken from a how the The Swedish Transport Administration in their guide on road design (The Swedish Transport Administration, 2016).

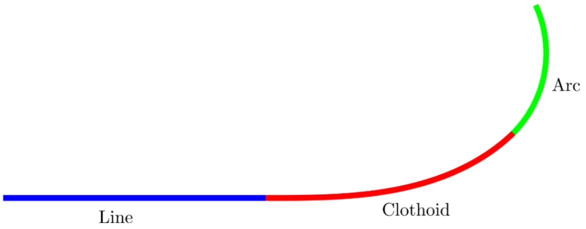


Figure 3.10: The red part of the curve represents the clothoid

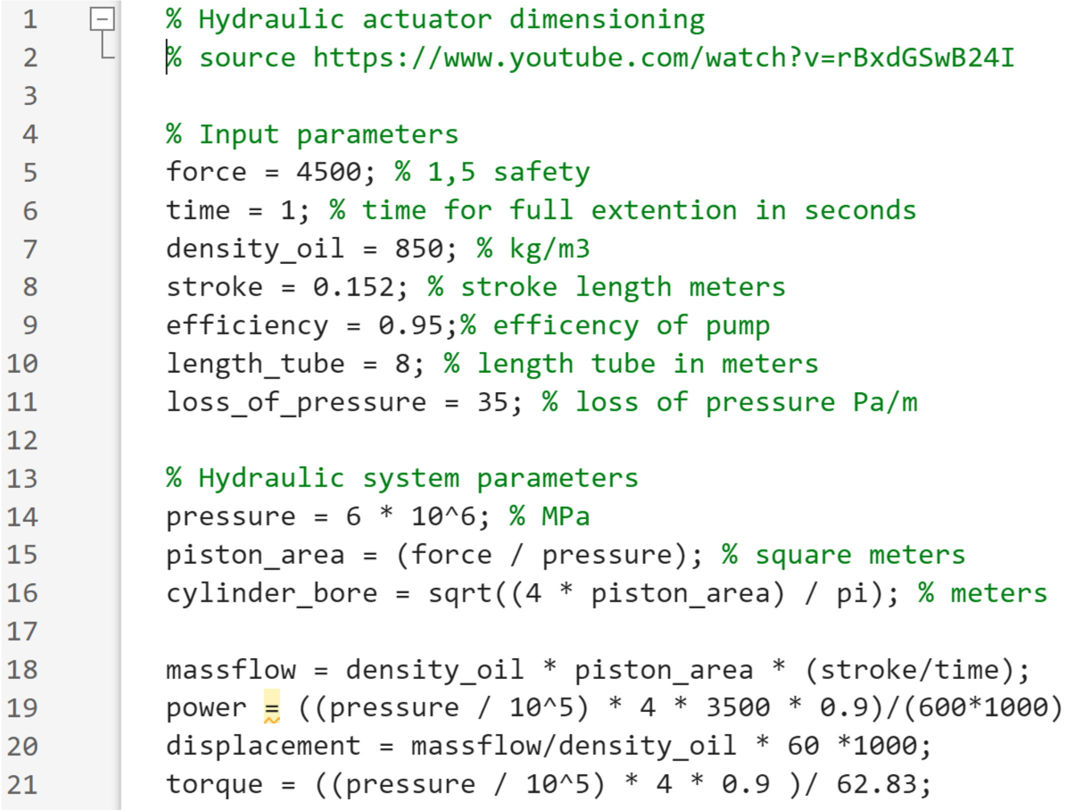
3.4.3 Actuator type

When the minimum load and speed needed for the actuator to work it was possible to choose the right kind of actuator. Since electrical linear actuators generally require least maintenance they were first investigated as a possible solution but it was discovered that they lacked in speed and strength. This led to them not being able to meet the requirements for speed and strength at the same time. The general other solutions found are hydraulics and pnuematics which both require a lot of energy. Since hydraulic systems are more common for NTV:s that was chosen as the actuator type.

3.4.3.1 Hydraulic Calculations

These calculations were made with Matlab and intended to create a hydraulic system which powers the actuator used for the tilting mechanism. Time for a full extension, stroke length and force required were used as variables for the hydraulic cylinder to be able to find out the required size of the piston area and the cylinder bore for it to handle the needed load.

It was assumed that oil used in hydraulic purposes is used and its density was assumed to be 850 kg/m^3 since usually hydraulic oils range between 800-900 kg/m^3 (Valvoline Global Operations, 2023). Assumptions of efficiency, pressure used in the system, pressure loss and tube length were made. Using these parameters the required bore piston area, cylinder bore and displacement in the pump could be calculated. Once these requirements were set a pump could be found that fit them and some parameters could be changed to try to optimize the system and the pump needed. After a few iterations a fitting pump was found.



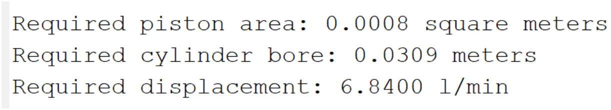
```
% Hydraulic actuator dimensioning
% source https://www.youtube.com/watch?v=rBxdGSwB24I

% Input parameters
force = 4500; % 1,5 safety
time = 1; % time for full extention in seconds
density_oil = 850; % kg/m3
stroke = 0.152; % stroke length meters
efficiency = 0.95;% efficency of pump
length_tube = 8; % length tube in meters
loss_of_pressure = 35; % loss of pressure Pa/m

% Hydraulic system parameters
pressure = 6 * 10^6; % MPa
piston_area = (force / pressure); % square meters
cylinder_bore = sqrt((4 * piston_area) / pi); % meters

massflow = density_oil * piston_area * (stroke/time);
power = ((pressure / 10^5) * 4 * 3500 * 0.9)/(600*1000)
displacement = massflow/density_oil * 60 *1000;
torque = ((pressure / 10^5) * 4 * 0.9 )/ 62.83;
```

Figure 3.11: Matlab code for hydraulics calculations



```
Required piston area: 0.0008 square meters
Required cylinder bore: 0.0309 meters
Required displacement: 6.8400 l/min
```

Figure 3.12: Results from hydraulics calculations in matlab

3.4.3.2 Drive Cycle

The drive cycle was calculated in an Microsoft Excel sheet with formulas for rolling resistance, wind resistance, self weight, downhills and power needed for acceleration. Three different scenarios for a driving cycle were examined. This driving cycles were estimations of real driving cycles with features as standstill, flat drive, uphill drive, downhill drive and accelerations were considered. These scenarios where then broken down in to a drive cycle where it was calculated how much Watt each of these actions would require for the specific use case designed. This gave a reasonably realistic drive cycle. Factors as the weight of the vehicle and other variables could be changed to investigate different cases and possible scenarios. Different batteries with different voltages could also be researched since that was also a variable that could be tweaked.

This equation calculates the possible speed with a certain amount of wattage with the following variables.
Watt = w, Air resistance = AR, Tire resistance = TR, self weight and angle of hill = W, Speed in km/h = speed

$$W/(AR + TR + W) * 3.6 = Speed \tag{3.1}$$

This speed was multiplied with the drive cycle meaning if the drive cycle has 50% flat the speed calculated for flat areas will be used in the next for range. The power consumed during this scenario was calculated meaning it was also 50% and the battery consumption which also contributes to the range. The rest of the driving cycle consist of standstill, uphill drive, downhill drive and accelerations which also have their own percentage of use in the drive cycle which were calculated in the same way. The average watt usage of the driving cycle was then calculated and then with the following formula was used to find out the range. AW = average watt usage, AH = ampere hour, V = battery voltage, AS= average speed during driving cycle, range = range in km

$$(AH/(AW/V)) * AS = range \tag{3.2}$$

The hydraulic system was also dimensioned with the help of this Excel sheet with the same idea of a driving cycle where the tilting was used 20%, 40% and 60% of the time when riding.

4

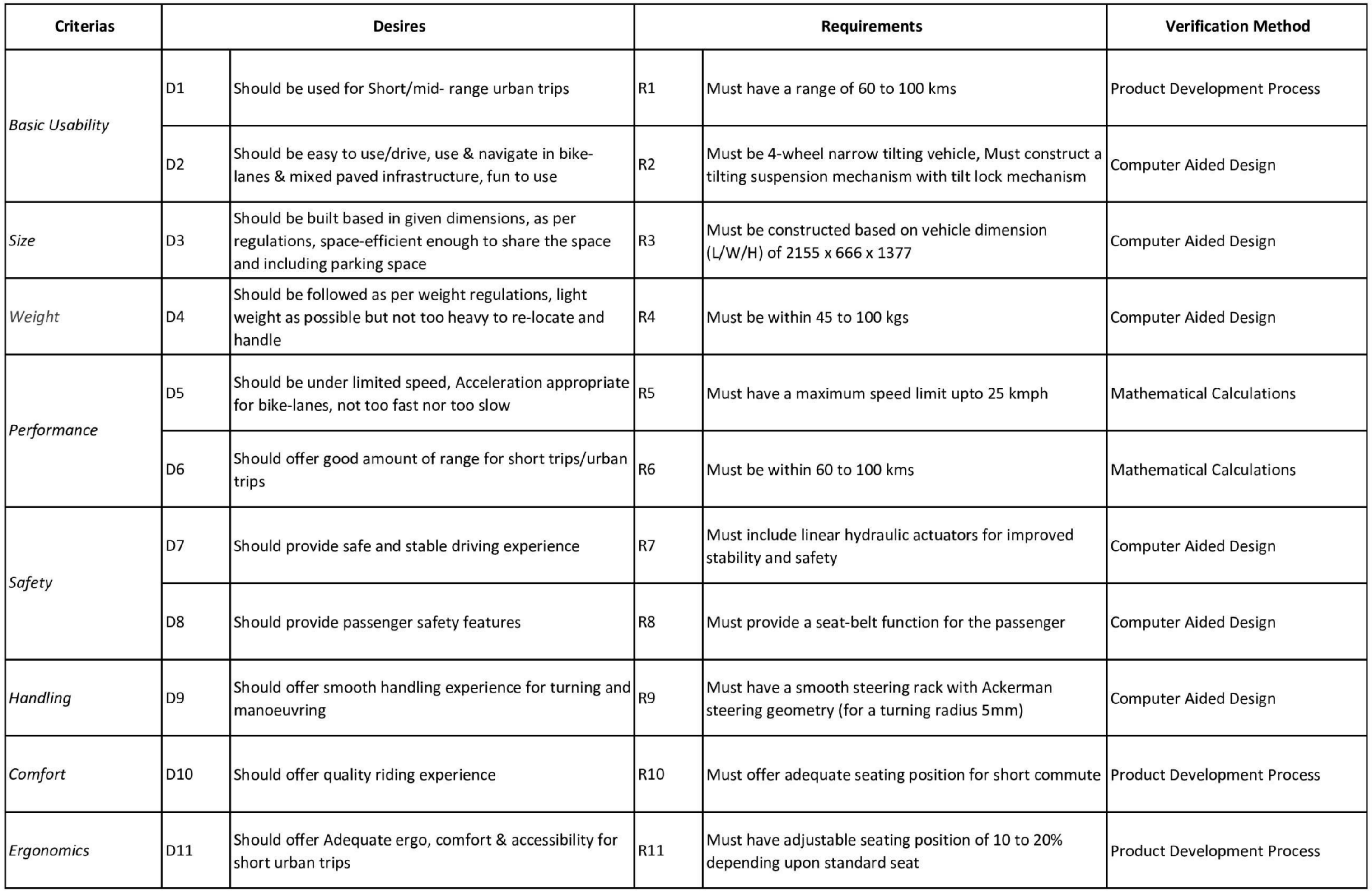
Results

This chapter will include the results from the method we followed during the thesis

4.1 Requirement Specification

The design and development of narrow tilting vehicles was guided by a comprehensive set of requirement specifications and core values to ensure that it can operate in specific urban mobility contexts. As mentioned in the methods section, the opportunity identification and selection phase was made by Volvo and one of the results was this set of criterias, desires, requirements, and verification method presented in Figure 4.1. This project was done considering the requirements as insights in to what type of vehicle should be developed, its intended use, and trying to verify them accordingly.

The requirement specifications were divided into Desires (D) and requirements (R) as shown in figure 4.1 down below. There were 11 functions or criterias were defined based on user study and identifying the needs of NTV's. The vehicle serves the purpose of semi-protected short to medium-range urban travel, with a focus on light urban errands and small cargo transport, but also for rural commuting. It should be compatible with existing infrastructure such as bike lanes, mixed sidewalks and local urban motorways, with a targeted speed limit of 25 km/h. Vehicles must provide a comfortable and accessible experience for short city journeys, including basic weather protection, four-wheel vehicle "reclining" vehicle dynamics, ease of use, balance and tilting mechanisms to enhance safety. The vehicle should also maintain a lean angle of 25 degrees under low and high speed corners. Performance specifications include a top speed of 25 km/h, a range of 100 km (60 miles), good acceleration in bike lanes and the ability to change batteries. Safety features include four wheels for weather protection and stability, excellent visibility, upright position at rest, safe avoidance, wheel configuration to prevent collisions from curbs, rails, gravel, leaves or holes included. Vehicles must be equipped with a steering system that allows safe and stable entry and exit and minimizes the risk of intrusion in the event of an impact. Core function of this vehicle was to create a fun and enjoyable riding experience with minimal maintenance and the use of lightweight and durable materials for environmental sustainability. By meeting these requirements and adhering to basic values, verification of these requirements are shown in the upcoming sections of this chapter.

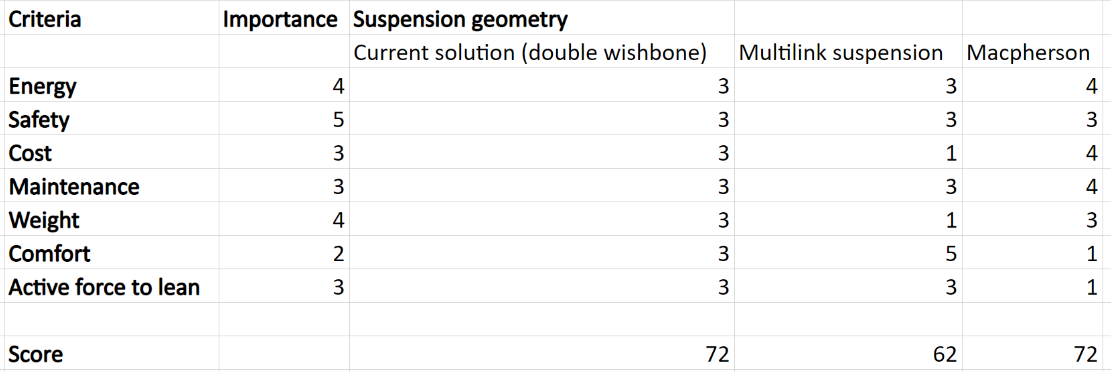


Criterias	Desires		Requirements		Verification Method
Basic Usability	D1	Should be used for Short/mid- range urban trips	R1	Must have a range of 60 to 100 kms	Product Development Process
	D2	Should be easy to use/drive, use & navigate in bike-lanes & mixed paved infrastructure, fun to use	R2	Must be 4-wheel narrow tilting vehicle, Must construct a tilting suspension mechanism with tilt lock mechanism	Computer Aided Design
Size	D3	Should be built based in given dimensions, as per regulations, space-efficient enough to share the space and including parking space	R3	Must be constructed based on vehicle dimension (L/W/H) of 2155 x 666 x 1377	Computer Aided Design
Weight	D4	Should be followed as per weight regulations, light weight as possible but not too heavy to re-locate and handle	R4	Must be within 45 to 100 kgs	Computer Aided Design
Performance	D5	Should be under limited speed, Acceleration appropriate for bike-lanes, not too fast nor too slow	R5	Must have a maximum speed limit upto 25 kmph	Mathematical Calculations
	D6	Should offer good amount of range for short trips/urban trips	R6	Must be within 60 to 100 kms	Mathematical Calculations
Safety	D7	Should provide safe and stable driving experience	R7	Must include linear hydraulic actuators for improved stability and safety	Computer Aided Design
	D8	Should provide passenger safety features	R8	Must provide a seat-belt function for the passenger	Computer Aided Design
Handling	D9	Should offer smooth handling experience for turning and manoeuvring	R9	Must have a smooth steering rack with Ackerman steering geometry (for a turning radius 5mm)	Computer Aided Design
Comfort	D10	Should offer quality riding experience	R10	Must offer adequate seating position for short commute	Product Development Process
Ergonomics	D11	Should offer Adequate ergo, comfort & accessibility for short urban trips	R11	Must have adjustable seating position of 10 to 20% depending upon standard seat	Product Development Process

Figure 4.1: Initial requirements Specifications

4.2 Concept Generation

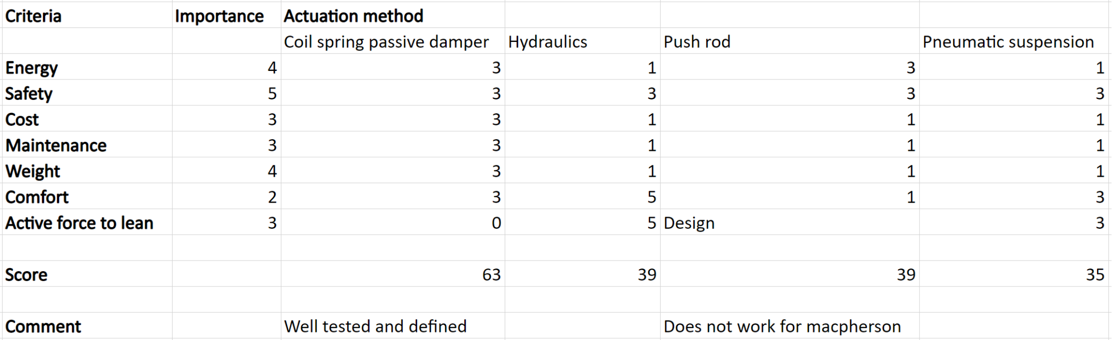
Tilting mechanism were investigated and then put through a matrix to decide which one was most feasible with the help of an expert in suspension. The suspension types investigated were double wishbone, multilink suspension and MacPherson strut.



Criteria	**Importance**	**Suspension geometry**		
		Current solution (double wishbone)	Multilink suspension	Macpherson
Energy	4	3	3	4
Safety	5	3	3	3
Cost	3	3	1	4
Maintenance	3	3	3	4
Weight	4	3	1	3
Comfort	2	3	5	1
Active force to lean	3	3	3	1
Score		72	62	72

Figure 4.2: Suspension geometries

It was decided to rank them according to some of the most important factors in this project and out a weight on each requirement. Then the weight of the requirement was multiplied with the score it got in that category. The score was the added to a total score where it could be seen which concept was the best suited for the purpose of this project.



Criteria	**Importance**	**Actuation method**			
		Coil spring passive damper	Hydraulics	Push rod	Pneumatic suspension
Energy	4	3	1	3	1
Safety	5	3	3	3	3
Cost	3	3	1	1	1
Maintenance	3	3	1	1	1
Weight	4	3	1	1	1
Comfort	2	3	5	1	3
Active force to lean	3	0	5	Design	3
Score		63	39	39	35
Comment		Well tested and defined		Does not work for macpherson	

Figure 4.3: Actuation method

The actuation method was evaluated in the same way as the suspension. Some designs were not compatible with each other.

After consultation an expert it was concluded that the investigated solutions were to complex for the time frame of this project. It was decided to use a simpler solution found in tilting bikes. It was decided to call this specific solution the romboid solution since it resembles a romboid while tilting.

4.2.1 Romboid solution

This solution is the simplest possible for a tilting vehicle since it avoids the problem of using suspension. The solution is two arms one lower and one upper that are connceted to a knuckle that holds the wheel. When tilting the romboid shape can be very clearly seen. A linear actuator is connected to the arm and when its extracted it tilts one way and when its retracted it tilts the other way.

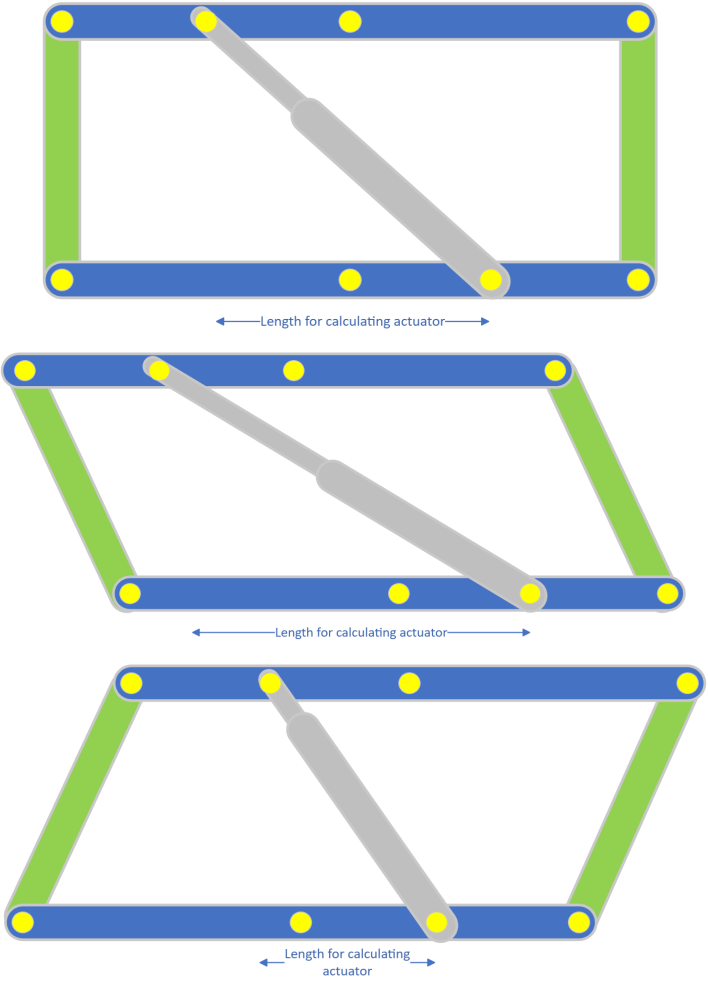
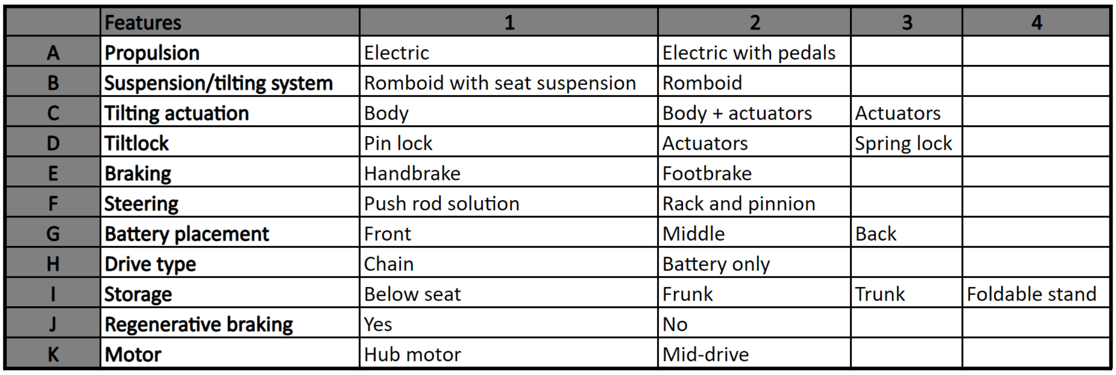


Figure 4.4: Linear actuator during tilting

4.2.2 Morphological Matrix

A morphological matrix was created to find different combinations of solutions. By combining from the columns and rows 6 different concepts were created.



	Features	1	2	3	4
A	**Propulsion**	Electric	Electric with pedals		
B	**Suspension/tilting system**	Romboid with seat suspension	Romboid		
C	**Tilting actuation**	Body	Body + actuators	Actuators	
D	**Tiltlock**	Pin lock	Actuators	Spring lock	
E	**Braking**	Handbrake	Footbrake		
F	**Steering**	Push rod solution	Rack and pinnion		
G	**Battery placement**	Front	Middle	Back	
H	**Drive type**	Chain	Battery only		
I	**Storage**	Below seat	Frunk	Trunk	Foldable stand
J	**Regenerative braking**	Yes	No		
K	**Motor**	Hub motor	Mid-drive		

Figure 4.5: Morphological matrix

The concepts generated by combining from each column and row are presented here.

- **Concept A** A1, B1, C1, D1, E2, F1, G1, H1, I4, J1, K1
- **Concept B** A2, B2, C2, D3, E1, F2, G2, H2, I2, J2, K1
- **Concept C** A1, B1, C3, D2, E2, F2, G3, H3, I3, J1, K1
- **Concept D** A2, B2, C1, D1, E1, F1, G2, H1, I1, J1, K1
- **Concept E** A1, B1, C3, D1, E2, F1, G2, H2, I4, J1, K1
- **Concept F** A2, B2, C2, D3, E1, F1, G3, H1, I1, J1, K2,

4.2.3 Concepts Generated

The concepts generated from the morphological matrix are presented here.

4.2.3.1 Concept A

Fully electric vehicle where the tilting is realised with a romboid solution that includes seat suspension. Tilting is done purely by body weight. To lock the tilting at standstill a pin lock is used. A gas pedal and a footbrake is used as in a normal car. A pushrod solution is used for the steering mechanism. The battery is placed in the front part of the vehicle. The drive chain is a chain similar to the ones found in E-bikes. It uses regenerative braking. The propulsion comes from hub motors.

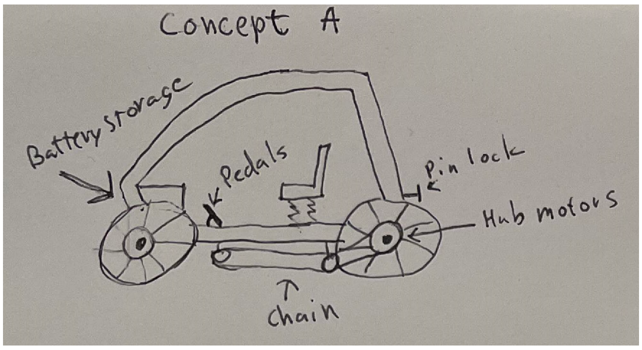


Figure 4.6: Concept A

4.2.3.2 Concept B

Electric vehicle that has to be pedaled to move forward. The tilting system is a romboid without any suspension. Tiling is done by the persons body movement and actuators. A spring lock is used to lock the tilting at standstill. A handbrake as used in motorcycles and bikes is used for breaking. Rack and pinion solution is used for the steering. Battery is placed in the middle. A front trunk is used for the storage. The vehicle is powered by battery. It does not have regenerative braking. Its propulsion comes from a mid drive.

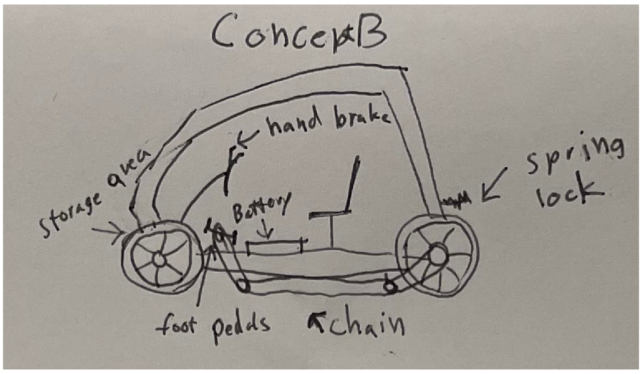


Figure 4.7: Concept B

4.2.3.3 Concept C

Fully electric vehicle with actuators used for the tilting. The tilt is locked with the actuators. A footbrake as in cars is used in this solution. Rack and pinion is used for the steering and the battery is placed in the back of the vehicle. The drivechain is a chain similar to the ones used in bikes. Main place for storage is in the back of the vehicle. It uses regenerative braking and a hub motor for propulsion.

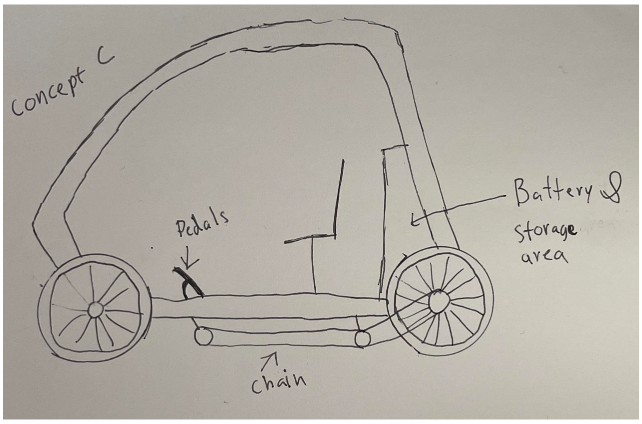


Figure 4.8: Concept C

4.2.3.4 Concept D

This concept is electric with pedals and a romboid tilting system will be applied. The tilting is used with the help of the drivers body. Locking the tilting at standstill is done with a pin lock. A simple handbrake is used as the ones in regular bikes. The steering is actualized with a push rod solution. The battery is placed in the middle of the vehicle. A classic chain is used as the drive chain and the storage is below the seat. It has a hub motor and regenerative braking.

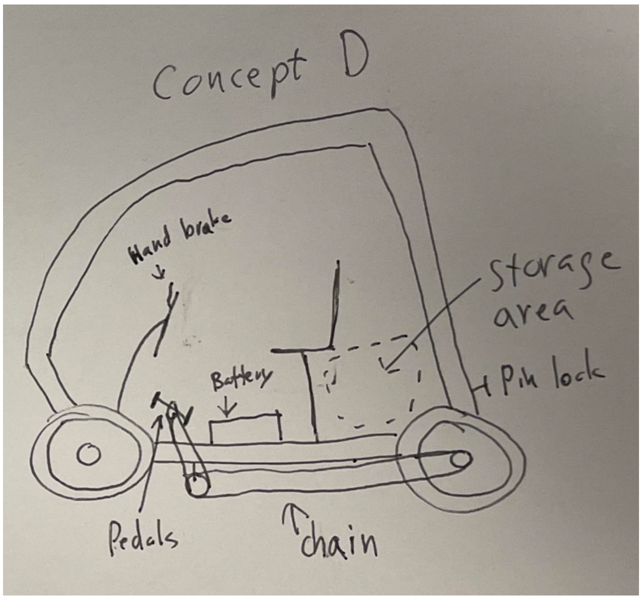


Figure 4.9: Concept D

4.2.3.5 Concept E

This concept is electric and has a rombiod solution for the tilting system. Actuators are used for the tilting. A pin lock is used for locking the tilting when the vehicle is standing still. A push rod solution is used for the steering. A footbrake is used in this concept and the battery is placed in the middle. The drive type is battery only. A Stand at the back of the vehicle that can be folded down is used for storage. It has a hub motor and regenerative braking.

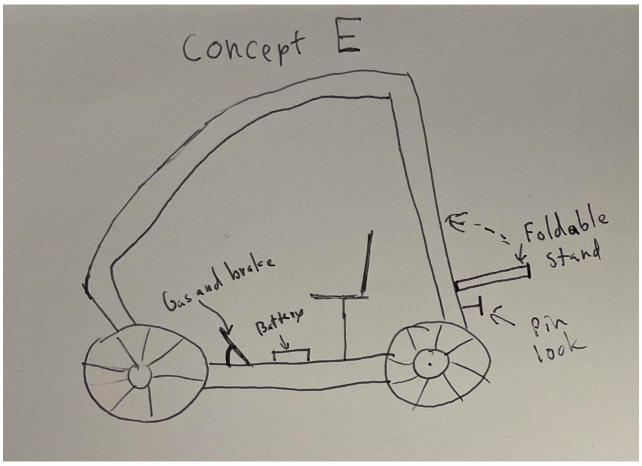


Figure 4.10: Concept E

4.2.3.6 Concept F

This vehicles propulsion is electric with aid from the pedals. The tilting system is a romboid tilting solution. To tilt both the body and actuators are used. A spring lock is used to lock the tilting at standstill. A classic bike handbrake is used. For the steering a push rod solutions is used. The battery is in the back of the vehicle. The drive type is a battery only and the storage is in a front trunk. It uses regenerative braking and a mid drive for propulsion.

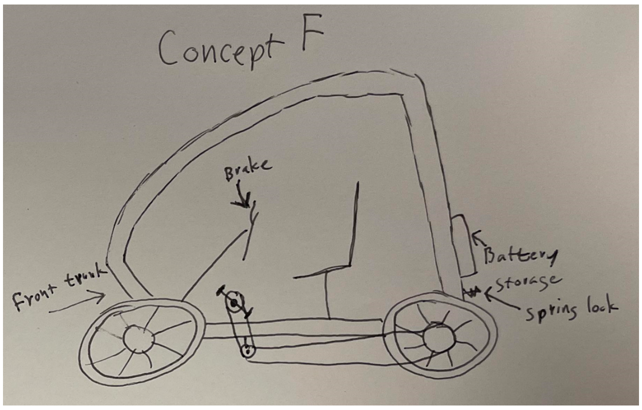
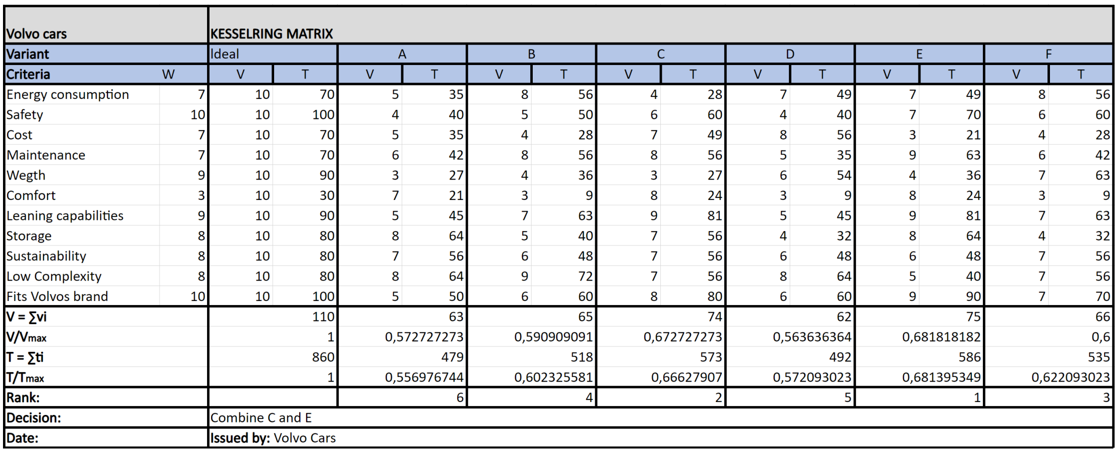


Figure 4.11: Concept F

4.3 Concept Evaluation

The result of the concept evaluation is presented here. Matrices used for generating concepts are presented and the concepts generated are described.

4.3.1 Kesselring Matrix



Volvo cars		**KESSELRING MATRIX**													
Variant		Ideal		A		B		C		D		E		F	
Criteria	W	V	T	V	T	V	T	V	T	V	T	V	T	V	T
Energy consumption	7	10	70	5	35	8	56	4	28	7	49	7	49	8	56
Safety	10	10	100	4	40	5	50	6	60	4	40	7	70	6	60
Cost	7	10	70	5	35	4	28	7	49	8	56	3	21	4	28
Maintenance	7	10	70	6	42	8	56	8	56	5	35	9	63	6	42
Wegth	9	10	90	3	27	4	36	3	27	6	54	4	36	7	63
Comfort	3	10	30	7	21	3	9	8	24	3	9	8	24	3	9
Leaning capabilities	9	10	90	5	45	7	63	9	81	5	45	9	81	7	63
Storage	8	10	80	8	64	5	40	7	56	4	32	8	64	4	32
Sustainability	8	10	80	7	56	6	48	7	56	6	48	6	48	7	56
Low Complexity	8	10	80	8	64	9	72	7	56	8	64	5	40	7	56
Fits Volvos brand	10	10	100	5	50	6	60	8	80	6	60	9	90	7	70
V = ∑vi			110		63		65		74		62		75		66
V/Vmax			1		0,572727273		0,590909091		0,672727273		0,563636364		0,681818182		0,6
T = ∑ti			860		479		518		573		492		586		535
T/Tmax			1		0,556976744		0,602325581		0,66627907		0,572093023		0,681395349		0,622093023
Rank:					6		4		2		5		1		3
Decision:		Combine C and E													
Date:		**Issued by:** Volvo Cars													

Figure 4.12: Kesselring matrix

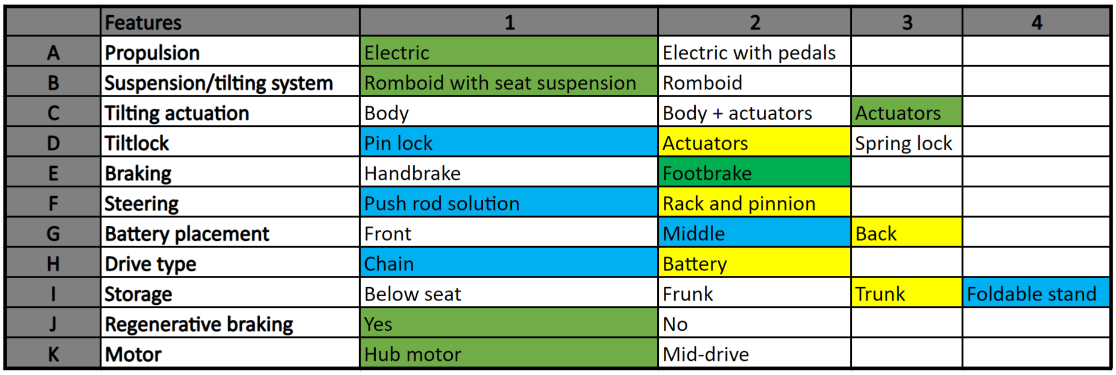
Since C and E scored highly it was decided to combine them into one concept that has a higher score than both and pursue that concept. The criteria and weight were used for the following reasons.

- **Energy consumption:** Since battery is limited keeping energy consumption low benefits the range. Battery life is a major aspect in a vehicle like this.
- **Safety:** Core value for Volvo therefore it was considered a 10 in importance.
- **Cost:** Keeping cost low was important in order to keep profit margins high. It was not the main focus of this project but still has to be kept in mind and that's why its importance was 7.
- **Maintenance:** This vehicle was designed to allow a pleasant owning experience having maintenance issues makes the owning experience worse but it was not a main factor for this project therefore it was weighted at 7.
- **Weight:** Lower weight gives it better range, decreases wear on components and makes the vehicle safer if anything were to happen. For those reasons it was considered the weight of 9
- **Comfort:** Comfort is an important factor to look at in vehicles since it offers purchasing power therefore it was considered in this matrix. In this vehicle comfort was not essential since future iterations will provide the comfort needed therefore it has a weight of 3.
- **Leaning capabilities:** One of the biggest factors for this vehicle to work therefore the leaning capabilities were essential and deciding for how the vehicle will perform therefore its weighted at 9.
- **Storage:** Possibilities of storing groceries and other luggage on this vehicle. Since this vehicle was made for small trips as grocery shopping storage for items has to exist and this was weighted at 8.
- **Sustainability:** Effect on the environment what affects this was materials used, manufacturing process and the recyclability of material used. This was weighted at 8 since its important but not a main priority.
- **Low complexity:** Low complexity guarantees reduced risk of error, ease of maintenance, lowers cost and leads to easier assembly. Important factors but not central to this project it was therefore given the weight 8.
- **Fits Volvos brand:** Focus of Volvos Cars should be taken into consideration by giving people the option towards future mobility solutions. Therefore it was considered very important to follow Volvos brand and it was given the weight of 10.

Since two concepts had similar scores in the Kesselring matrix we decided to combine the solutions. The process of how the concepts were combined will be presented in the next section.

4.3.2 Combining Concepts

The concepts C and E were chosen to be combined since they both score high in the kesselring matrix. The green represents whats shared in both concepts, yellow is for whats unique for concept C and blue is for whats unique in concept E.



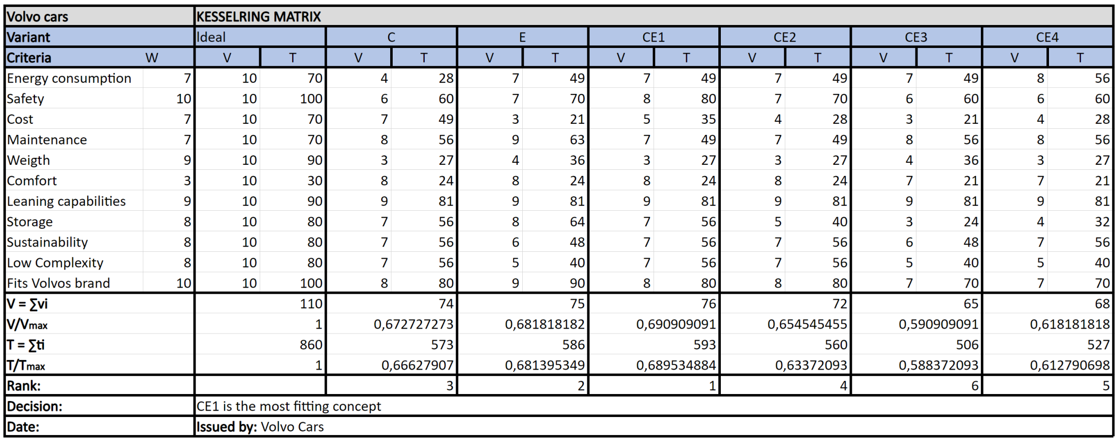
	Features	1	2	3	4
A	Propulsion	Electric	Electric with pedals		
B	Suspension/tilting system	Romboid with seat suspension	Romboid		
C	Tilting actuation	Body	Body + actuators	Actuators	
D	Tiltlock	Pin lock	Actuators	Spring lock	
E	Braking	Handbrake	Footbrake		
F	Steering	Push rod solution	Rack and pinnion		
G	Battery placement	Front	Middle	Back	
H	Drive type	Chain	Battery		
I	Storage	Below seat	Frunk	Trunk	Foldable stand
J	Regenerative braking	Yes	No		
K	Motor	Hub motor	Mid-drive		

Figure 4.13: Morphological matrix combined

4 new concepts called CE1, CE2, CE3 and CE4 were created where row D, F, G, H and I were changed in different permutations since they were not shared in concept C and E. The new concepts combinations in the morphological matrix are presented below. What is shared in all concepts is that vehicle has electric propulsion and its tilting system is a romboid with seat suspension where actuators are used for the tilting actuation. Braking is done with a foot pedal in all concepts, regenerative braking and hub motors are used in all concepts too.

- **Concept CE1:** This concept has a pin lock to lock the tilting at standstill it uses a rack and pinion solution for the steering. The battery was placed in the middle of the vehicle and its drive type was a battery. The main storage is found in the trunk.
  It consists of the combination: A1, B1, C3, D1, E1, F2, G2, H2, I3, J1, K1
- **Concept CE2:** This concepts tilt was locked with the help of the actuators its steering solution was a push rod solution. The battery was placed in the middle of the vehicle and the drive type was battery. A foldable stand at the back of the vehicle was the main area of storage.
  It consists of the combination: A1, B1, C3, D2, E1, F1, G2, H2, I4, J1, K1
- **Concept CE3:** A spring lock was used in this concept for locking the tilting at standstill for the steering a rack and pinion solution was used and the battery was placed in the front. The drive type was a chain and the storage option was below the seat.
  It consists of the combination: A1, B1, C3, D3, E1, F2, G1, H1, I1, J1, K1
- **Concept CE4:** The existing actuators are used to lock the tilt. The steering was solved with a push rod solution and the battery was placed in the front. A chain drive solution was used and the mains storage was in a front trunk.
  It consists of the combination: A1, B1, C3, D2, E1, F1, G1, H1, I2, J1, K1

The concepts were put in a new kesselring matrix explore which one would be the best possible combination and the score of C and E can be seen for comparison.



Volvo cars		KESSELRING MATRIX													
Variant		Ideal		C		E		CE1		CE2		CE3		CE4	
Criteria	W	V	T	V	T	V	T	V	T	V	T	V	T	V	T
Energy consumption	7	10	70	4	28	7	49	7	49	7	49	7	49	8	56
Safety	10	10	100	6	60	7	70	8	80	7	70	6	60	6	60
Cost	7	10	70	7	49	3	21	5	35	4	28	3	21	4	28
Maintenance	7	10	70	8	56	9	63	7	49	7	49	8	56	8	56
Weigth	9	10	90	3	27	4	36	3	27	3	27	4	36	3	27
Comfort	3	10	30	8	24	8	24	8	24	8	24	7	21	7	21
Leaning capabilities	9	10	90	9	81	9	81	9	81	9	81	9	81	9	81
Storage	8	10	80	7	56	8	64	7	56	5	40	3	24	4	32
Sustainability	8	10	80	7	56	6	48	7	56	7	56	6	48	7	56
Low Complexity	8	10	80	7	56	5	40	7	56	7	56	5	40	5	40
Fits Volvos brand	10	10	100	8	80	9	90	8	80	8	80	7	70	7	70
V = ∑vi		110		74		75		76		72		65		68	
V/Vmax		1		0,672727273		0,681818182		0,690909091		0,654545455		0,590909091		0,618181818	
T = ∑ti		860		573		586		593		560		506		527	
T/Tmax		1		0,66627907		0,681395349		0,689534884		0,63372093		0,588372093		0,612790698	
Rank:				3		2		1		4		6		5	
Decision:		CE1 is the most fitting concept													
Date:		**Issued by:** Volvo Cars													

Figure 4.14: Kesselring matrix combined

The score difference between concepts were not big but between the new combinations CE1, CE2, CE3 and CE4 a difference can be seen where CE1 was the clear winner. Although CE1 was not miles ahead of concept C and E the conclusion that it was better than both can still be drawn since its a combination of both concepts strengths therefore it was decided to go through with this concept.

4.4 Concept Development and Validation

The result of the concept development and validation conducted are presented here

4.4.1 LEGO Prototype

Ackerman steering, camber angle and caster angle were not consider during construction of the LEGO. First the tilting mechanism was constructed a simplified version of the double wishbone was the initial tilting mechanism explored with LEGO. A problem with this construction was that it would not stay in place as wanted since both sides move independently and there had to be a construction to prevent this. The romboid solution was made with LEGO and compared to the previous design. The romboid had no issues with the tilting and was the only design explored further with LEGO.

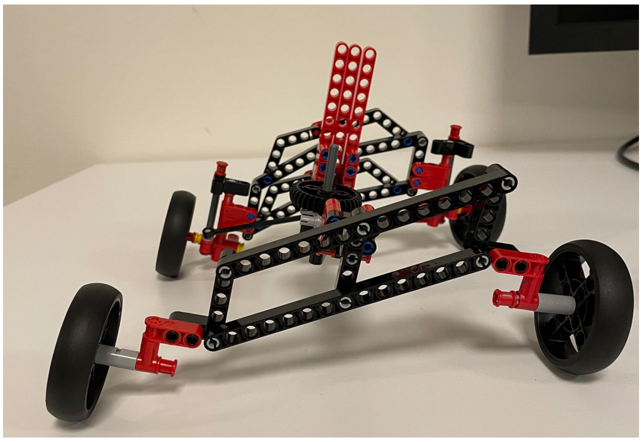


Figure 4.15: Romboid LEGO model

A steering mechanism was added to this construction where a simple push rod mechanism that was connected to a T-shaped component that could be rotated. This steering mechanism had issues and was therefore modified so that the T-shaped part was removed and the steering rods were connected to a cogwheel.

Figure 4.16: First steering mechanism for the LEGO model

This solution worked properly but the turning radius was very high. To solve this issue a rack and pinion construction was made with the LEGO. This solution also suffered some defects where the steering rods would fall out of place and the wheel would be stuck in an awkward angle. This solution was further improved until this issue was not present anymore.

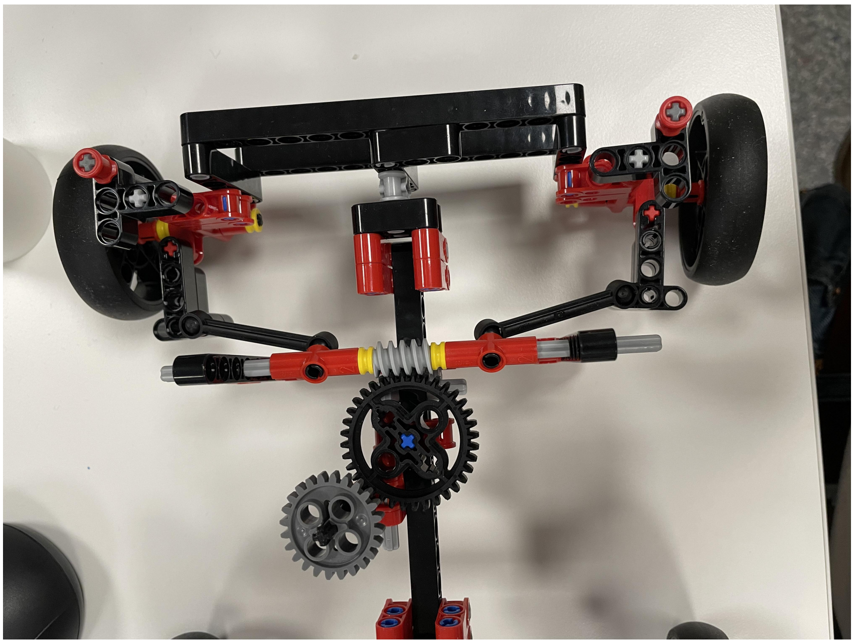


Figure 4.17: Final steering mechanism for the LEGO model

A pin lock was constructed and place in the back where tilting could be locked in place when turning a specific cogwheel when the vehicle was standing upright.

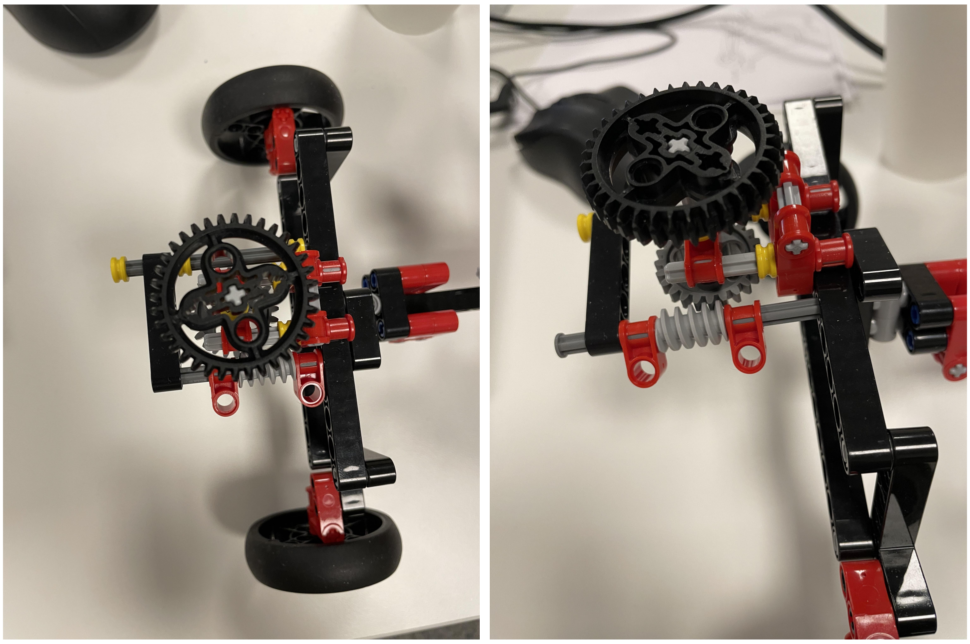
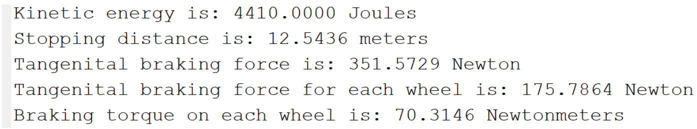


Figure 4.18: Tilt lock mechanism for the LEGO model

4.4.2 Brake

A brake that fits the vehicle can be found with these calculations. If further requirements are found they can also be added to the calculations in order to find better suited brakes. From the calculations performed in (Oertel, Neuburger, & Sabo, 2010) it was also concluded that these values are well within range to use regular bike braking equipment.



```
Kinetic energy is: 4410.0000 Joules
Stopping distance is: 12.5436 meters
Tangenital braking force is: 351.5729 Newton
Tangenital braking force for each wheel is: 175.7864 Newton
Braking torque on each wheel is: 70.3146 Newtonmeters
```

Figure 4.19: Results from calculations used for dimensioning of brakes

4.4.3 Linear Actuator

The calculations carried out resulted in having set requirements for the actuator. This requirements ensure that the actuator fulfills it purpose as intended. These criteria were used as a framework for finding an appropriate hydraulic linear actuator since it was decided to use a hydraulic cylinder for the tilting mechanism. For other types of linear actuator the requirements may vary. These numbers were optimised for the specific case in this project.

Unit:	**Amount:**	**Description:**
Force	4500 N	Minimum force the actuator has to be capable to lift
Time	1 Second	Longest possible time it should take for full extension of the actuator
Minimum piston area	8 cm^2	Minimum area allowed for the linear actuator if its hydraulic
Minimum cylinder bore	3 cm	Minimum bore diameter accepted for the linear actuator if its hydraulic
Retracted length	350 mm	Length of the linear actuator when it is fully retracted
Stroke length	152 mm	Length of the linear actuator stroke. This means the actuator can be anywhere between 350 - 502 millimeters when in use

Table 4.1: Requirements for linear actuator

These requirements calculated must be fulfilled for a hydraulic cylinder to be use in this NTV. If the construction is changed these requirements will also change. A hydraulic cylinder from the company Hytec Hydraulik (Hytec Hydraulik, 2023) was chosen. It follows all requirements and was 355 mm which was close to the sought out distance of 350 mm and the stroke length was 200 mm which was not a problem since 152 mm was the minimum required stroke length for a working geometry.

4.4.4 Hydraulic System

Combined with choosing the hydraulic cylinder a hydraulic system was developed. The parameters of the cylinder were used as input and a working pressure was chosen then the required displacement was calculated. From these requirements a hydraulic power pack was found that fits the requirement and the working pressure and displacement can be changed if needed. A potential hydraulic system was created. Containing the hydraulic cylinders a, the hydraulic power pack, a relief valve, a check valve and two directional 4-way 3 position control valves with tandom valves.

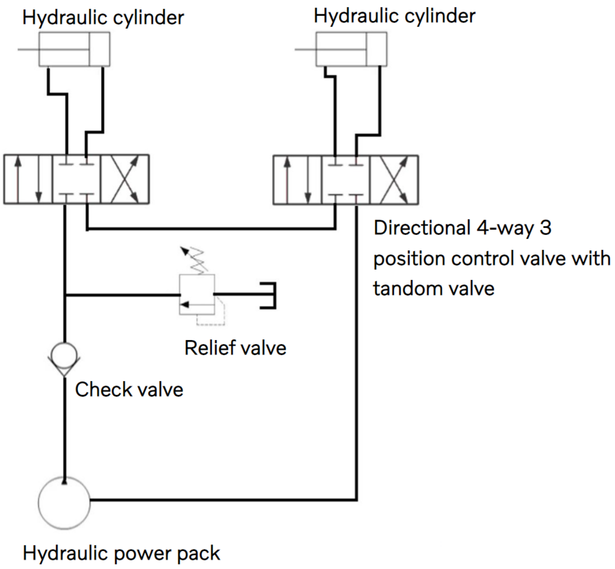


Figure 4.20: Hydraulic system created

One of the limitations for this thesis was to not go in to detail level on smaller issues therefore it was assumed that a hydraulic fluid of 850 kg/m^3 was used but not which one. Another issue with choosing hydraulic fluid was the working temperatures, if the working temperature was not in the right range use in winter cases can have huge issues. What was discovered and is aligned with research was that the hydraulic system consumes a lot of energy and was relatively complex compared to the rest of the vehicle. The only way to reduce this energy consumption was to have a smart control system that reduces the use of the hydraulics as much as possible as efficient tilting control is believed to be very important for the success of NTV:s (Tang & Khajepour, 2019). There was a high power consumption therefore two batteries were decided to use for powering this hydraulic system. The hydraulic system had to be incorporated into the driving cycle to research how the range would be affected.

Time when tilting system is active	Max driving time
20%	1 hour 36 minutes
40%	48 minutes
60%	32 minutes

Table 4.2: Usage cycle of hydraulic system

As seen from the calculations about the driving cycle using the hydraulic system as few times as possible extends the possible usage time. These calculations assume a 90% efficiency from the system. A normal bike ride can be anywhere from 5 minutes to 2 hours depending on the purpose of the travel. Average 2 way commuting time in Europe is 35-45 minutes (Giménez-Nadal, Molina Chueca, & Velilla, 2020). This usage cycle of the hydraulic system is short in terms of safety margin although commuting would be possible with this kind of hydraulic system it would require charging batteries everyday or after every travel. The biggest problem with a hydraulic system is the small adjustments that are made during usage (Tang & Khajepour, 2019) therefore a tilting system that does not require frequent small adjustments is needed.

4.4.5 Drive Cycle

For both the hydraulics and propulsion the batteries PowerTube 750 from Bosch were chosen for their light weight and easy fit in a NTV. Using the specific user case as constructed below different possible ranges were discovered. It was assumed that two batteries are used to reach this range and a weight of 170 kg are assumed for the vehicle in these calculations. If any variables are changed the range is changed. In the best case scenario (downhill 70 % of the time and a vehicle weight of 170 kg) a range of 150 km can be reached and in the worst case scenario a range of 30 km (70 % uphill and a vehicle weight of 230 kg). Therefore more realistic scenarios have to be considered to find out a possible range for this type of vehicle. Driving cycles were created since no standard exists at the time of writing for use in these types of calculations as there are in the case of a car. Following a similar approach to (Sun, Wen, Yang, & Li, 2020) where the driving cycle was split in to four different stages idle speed, acceleration, deceleration and uniform speed. For this case the driving cycle was split into standstill, driving on flat surface, driving uphill, driving downhill and time spent accelerating. Based on this, three scenarios were created one with a lot of stops and accelerations with a lot of uphill which will be called uphill. One case with average amount of uphill and downhill and a medium range of stops and accelerations which will be called average and one case with a lot of flat and a decent amount of downhill which will be called easy.

	Case 1 (uphill):	**Case 2 (average):**	**Case 3 (easy):**
Time standstill:	1%	5%	0%
Time flat:	15%	30%	50%
Time uphill:	59%	39%	27%
Time downhill:	14%	20%	20%
Time in acceleration:	11%	6%	3%
Amount of accelerations:	80	45	25
Calculated range:	53 km	68 km	108 km

Table 4.3: Drive cycles created for NTV

A strong dependence on the driving case was found in these calculations. What was most prevalent was that the amount of accelerations was a big factor to the range. This implies that a well planned infrastructure where not a lot of stops are necessary would be not only beneficial for time saving of the users of the NTV but also energy efficient. Which in its turn would save a lot of resources if the battery was charged fewer times and has a longer life cycle. This vehicles range was very dependent on the infrastructure was what the results show, mostly on stops and starts. The time spent uphill also requires a lot of battery power and takes away from the range but not as much as the accelerations. The reason for accelerations using so much energy was that the NTV was allowed to use more than 250 watts during short bursts and since the vehicle was heavy, more than 250 watt was needed for starting the vehicle from full stop. Adding many accelerations means that this power consumption peak was more frequent thus more energy was consumed.

5

Final Concept

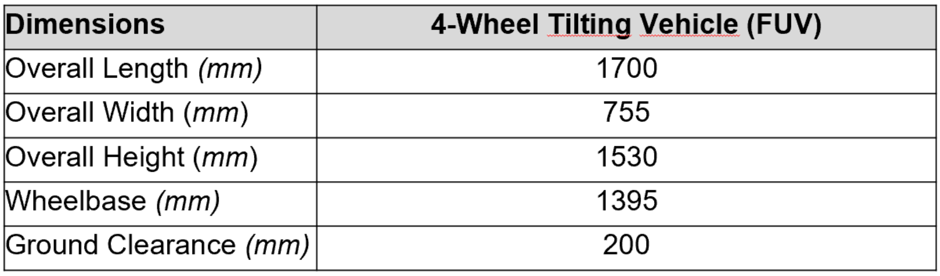
In the following chapter the final concept is shown in detail as a summary of the concept. Technical dimensions are presented, followed by positioning of the components. The platform is presented in the form of CAD geometries using CATIA V5 and each components are motivated. Lastly, the final concept is assembled and evaluated based on the results from the previous chapter.

5.1 Concept description

The final concept consists of design of suspension and steering components for the platform of NTV:s. The 3D CAD model of the vehicle includes rudimentary details of the vehicle top-hat were also produced during designing the concept in order to support feasibility judgement and verification. The concept's overall layout, geometry, and functionality are explained, emphasizing the innovative aspects that address the identified challenges and requirements of the final concept. Some of the important CAD requirements for the components were producing light weight parts, basic mechanism, minimizing the number of movable parts, offer better packaging solutions and cost efficient.

5.2 Dimensions of final concept

In order to begin the design phase, dimensions were established based on the combination of bicycle lane dimension and footprint of the vehicle itself. The footprint of the vehicle consists of overall length, track width and ride height of the vehicle. An acceptable footprint was determined based on bicycle lane regulations, that means the vehicle should not be wider than a standard bicycle and not longer than a cargo bike. The weight distribution of front and rear axle was calculated based on number of components and subsystems of the platform from the designed CAD parts. This includes the suspension system, steering mechanism, Wheels incorporated with disc rotors on the front and hub motor on rear, removable batteries. The weight of the vehicle was calculated to be around 150 kgs which includes the weight of the rider, small bags and small packages. The wheel size for front and rear were chosen to be 21 inch rounded tyre profile with tyre width of 80 mm. This offers better stability and traction while cornering.



Dimensions	4-Wheel Tilting Vehicle (FUV)
Overall Length *(mm)*	1700
Overall Width (*mm*)	755
Overall Height (*mm*)	1530
Wheelbase *(mm)*	1395
Ground Clearance *(mm)*	200

Figure 5.1: Vehicle Dimensions

5.3 Platform (geometry and components)

Platform consists of Suspension system, steering mechanism, braking system, wheel assembly and drivetrain components. The suspension concept chosen from the previous chapter is the Rhomboid Suspension model. The suspension model was designed for both front and rear part of NTV:s which consist of Knuckles, Control arms, Wheel Hubs, Actuators, ball joints and screw joints as shown in (). The suspension system is responsible for supporting the vehicle's weight, absorbing road shocks, providing stability and comfort to the user. Suspension geometry was designed based on the track width of the vehicle and track at ground i.e, ground clearance. Tilting suspension requires ball joint movement which was attached to the Upper and Lower position of Knuckle and Control Arm. This allows the suspension mechanism to slide or tilt left and right. The upper and lower control arms were attached with an actuator which was joined with screw joints. The actuator controls the movement of the control arms which in turn slides the knuckle left and right.

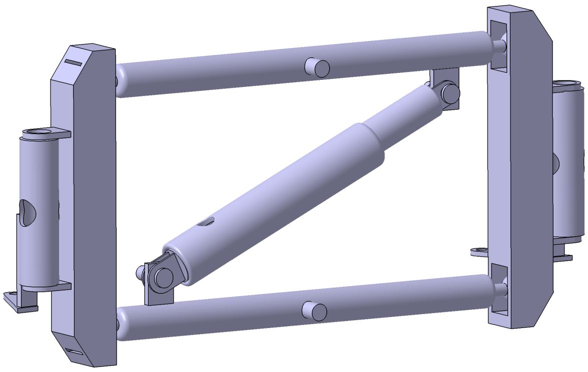


Figure 5.2: Romboid suspension assembly

From the previous chapter, the steering mechanism chosen was the Ackerman Steering layout which enables the rider to control the direction of the NTV. It includes components such as the steering column, rack and pinion (or other steering mechanisms), and steering knuckles as shown in figure 5.2. Based on the driver's input from the steering column, the steering input is converted into tilting motion which is controlled by the hydraulic actuator on the front suspension. The design of the Ackerman Steering Mechanism was based on calculation with respect to desired steering ratio, tilt angle and turning radius. The steering medium is not a wheel in this case, since this vehicle is similar in size to a bicycle or a moped.

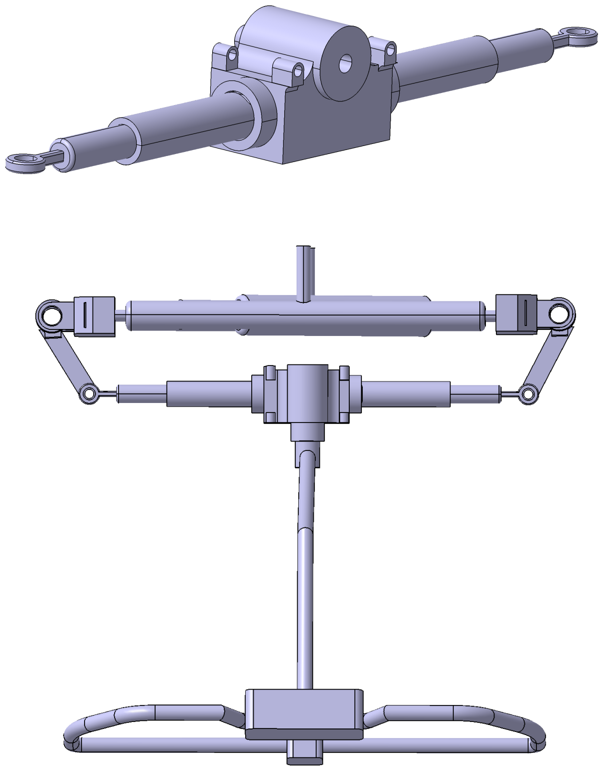


Figure 5.3: Rack and Pinion attached to Ackerman steering mechanism

The wheel assembly consists of two disc brakes assembled on the front wheels and two hub motors in-built on the rear wheels. The brake assembly consists of disc rotors, brake pads and brake callipers as shown in (). Hub Motors propels the vehicle by transmitting power to the rear wheels. Swappable batteries attached on the vehicle tophat to provide as power source for the hub motors. Other functional components such as hydraulic pump and ECU controller were placed on the floor of the vehicle frame. This offers a better packaging solution for the suspensions to be attached to the frame of the vehicle.

5.4 Final Assembly Concept

The final assembly concept brings together these components to create a cohesive and a functional platform layout for the narrow tilting vehicle (NTV). The assembly process ensures proper integration, alignment, and functionality of the subsystems. This involves comprehensive checks and tests to ensure the proper functioning and alignment of the subsystems. Using manipulation and constraints given for the subsystems, the components were positioned and connected using CATIA's assembly constraints and mating features. This ensures accurate alignment and allows for the simulation of suspension travel and articulation.

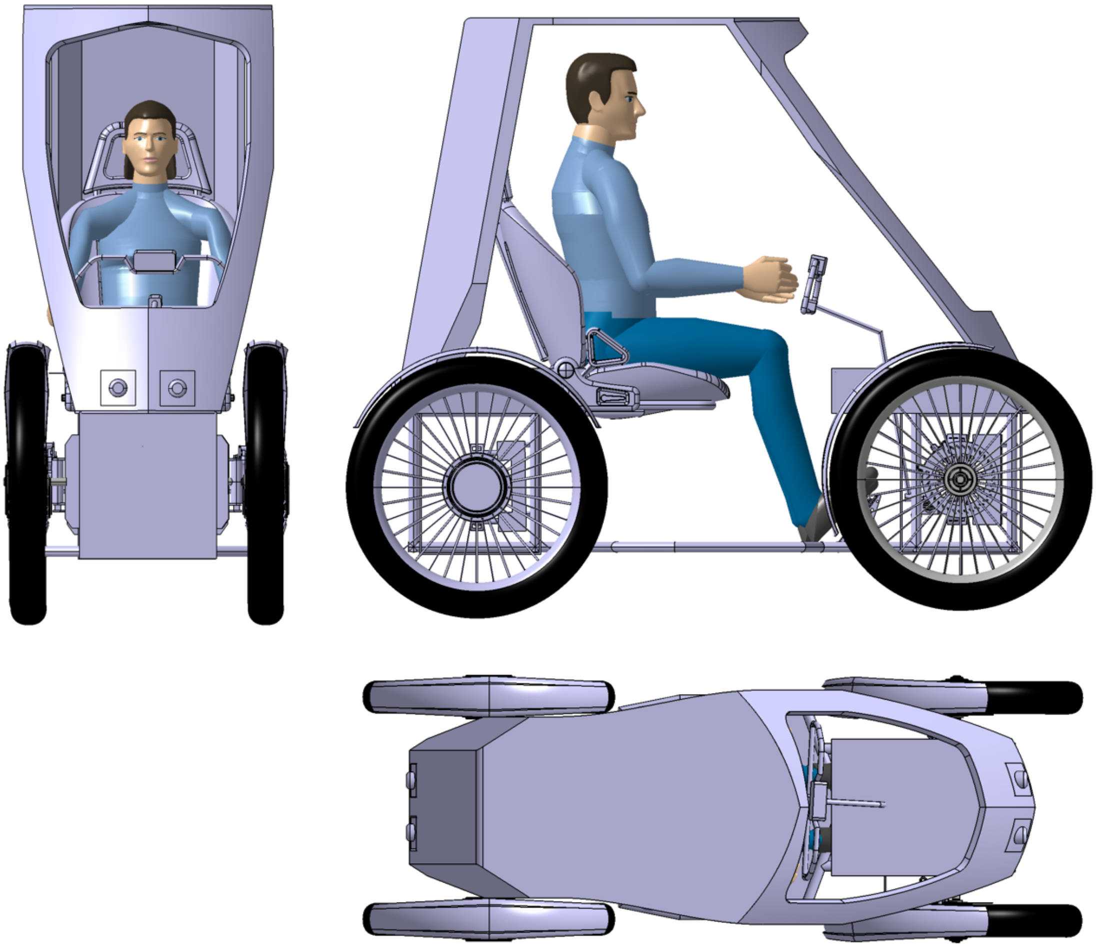


Figure 5.4: Front view, side view and top view of the final concept

The material chosen for the suspension components was Aluminium. The Aluminium has good properties to withstand strength and service life. There was also an aesthetic aspect as the rest of the vehicle frame is a mix of Aluminium and plastic body i.e polypropylene which gives a better quality in surface finish. Once the materials were determined, the weight of each component could be taken from the CAD model. This determines the weight of the fully assembled vehicle.

5.5 Tilting of Final Assembly Concept

The tilting suspension is connected by a tilting mechanism fitted with two ball bearings which is in-built inside the tilting mechanism. The tilting mechanism is connected to the frame of the platform in order for the body to tilt on both sides. The actuators extends to different lengths for the suspension to tilt the entire body of the vehicle. The outer diameter of the ball bearings are 14 mm, which can withstand up-to 20 degrees of tilt angle at higher and lower speeds while cornering.

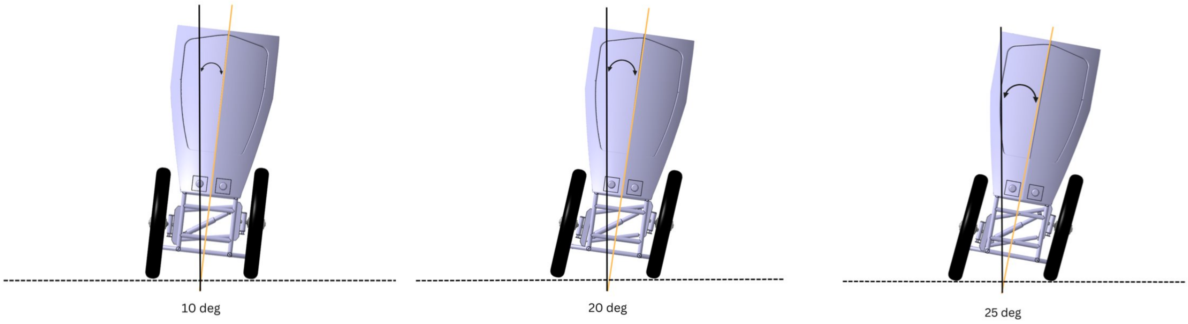


Figure 5.5: Tilting of 3 different angles

From figure 5.5, three different angles are compared to find the maximum tilt angle and maximum length of the actuator to extend. Under 10 degrees, the vehicle seems to be safe and balanced while performing initial tilt. At 20 degrees, the body tilts along with the suspension. The knuckle is tilted by the extended liner actuator by means of steering input to tilt the vehicle. The wheel width is 80 mm, in which the tires are able to make contact with the road surface. While cornering at 25 degrees, the actuator extends to a maximum length of 505 mm to tilt left and retracts back up-to length of 198 mm to tilt right. Having a maximum tilt angle of 25 degrees provides enough tilting at bike lanes and also for lane maneuvering. This provides a safe and balanced tilting motion at 25 km/h and a turning radius up-to 2.5 mm is achieved.

6
Discussion

This chapter discusses the result of this project.

6.1 Overall Result

Limitations were very important to involve for this project since it meant that not all problems had to be solved. Focus was put on the tilting part since its unique to this project and an important key for future mobility opportunities. The challenges when developing a tilting mechanism is what was found during this project.

Following the product development process was something that we were used to in our education and doing that for a complex product as this was a challenge since constant prioritisation had to be made with where to focus. The concept generation stage had to be adapted to our specific case since tilting was the main priority and a overview of the whole vehicle also had to be done which turned in to interesting compromises. Deciding on the right tilting mechanism turned into many discussion and in the end the least technical complex tilting solution was the one decided to explore to fit the time frame for the project. Making an evaluation matrix for a complete vehicle would turn into 1000 different areas of the NTV being investigated, to keep this possible for the time limit a few areas got extra focus in this project and main focus was spent on the tilting. Using a LEGO prototype turned out very useful for discussing and deciding which tilting mechanism to go with since it gave a feel for the design and the design could be researched a bit more thoroughly. The braking calculations should be further optimised to find the best fitting kind of brake for this purpose since it was found that regular bike brakes can be used.

Finding the right linear actuator turned out to be more complex than planned for. Many calculations had to be made and a lot of assumptions were made about the vehicle before a final design existed which limited our future design options. Realising that electrical actuators could not be used and switching over to a hydraulic system also turned out to be a very time consuming task. The hydraulic system had to be overdimensioned to ensure proper functionality which has downsides as high weight, high power consumption and a big physical size which is hard to fit in a small vehicle in an efficient way. The hydraulic system could be further improved in many ways to increase efficiency and time constraints was the reason why this was not further investigated. A conclusion found in early literature search that NTV:s used a lot of energy was also a conclusion we could draw from our results which is most likely the cause for these kinds of vehicles to not be as popular as they could be. Focusing on this issue is the most important for future development of these kinds of vehicles.

The driving cycle is very dependent on the amount of accelerations meaning that the infrastructure is what decides the range. This is very interested since future infrastructure is created so that bike stops are avoided. NTV:s in future cities have a lot of potential but also all the possible electric vehicles that will be allowed to drive on the bike lane. C40 and other recommendations for future infrastructure almost ensures that we will see a future where vehicles like this NTV have a higher possibility of succeeding.

6.2 Purpose, Goals, Considerations and Limitations

A goal for this project was to have this vehicle classified as a bike in the future which we found out to be somewhat of a challenge. Different regulations apply for different geographical areas and they differ on small points. Regulations are constantly changed when new technologies are presented. Is this one of those cases? The current regulations don't have a classification for this kind of vehicle meaning it would fall under another bike class or vehicle class where it does not belong. For the future we would like to see these types of vehicle have its own bike class to avoid confusion with the existing bike types.
A small scale model was created with LEGO and a virtual model was created although it was found during the projects process that using simulations and various programs that we have no experience in would be to time consuming therefore calculations were used to verify the design.
The safety of this vehicle was investigated and the main focus was on the tilting mechanism safety was prioritised therefore other safety areas were not always taken into consideration and are left for future research to involve.
Having strict limitations allowed this project to focus in the most important part which was the tilting mechanism. Being aware of the relatively short time frame for a project like this allowed the project to be planned in a way where prioritisation and decision had to be made to not lose time. This happened with the decision to settle for a less complex suspension geometry. The platform was the main focus of the project and that was a very important consideration to make since it allowed for this project to have a clear goal.

6.3 Research Questions

The research questions will be answered in this section.

How was a simple tilting four wheeled vehicle constructed?
In this project the tilting mechanism romboid was chosen and the product development process by (Ulrich & Eppinger, 2016) was used as a guideline. Along with matrices a general concept was chosen to go through with. In this concept the tilting mechanism was developed on a detail level. Calculations were done to find out exact dimensions and requirement to allow this tilting mechanism to function as intended. A driving cycle needs to be developed to calculate the theoretical range of the vehicle. A virtual model needs to be developed to assure that all components fit as planned.

Which were the important factors that have to be taken in to consideration when constructing an urban tilting vehicle?
Constructing a NTV is very dependent on the tilting mechanism it was very important to choose the right one for the case where its used. Many other parts of vehicle construction were well researched and therefore a lot of information was available and guidelines exist. This does not exist to the same extend with tilting vehicles. Creating a realistic driving cycle was important to know how the vehicle will work in its intended use. Prototyping was important since problems that don't exist in the virtual model can appear and can then be dealt with appropriately.

What were the biggest challenges when constructing a tilting vehicle?
Energy consumption in the hydraulic system. When this factor is minimised products like in this project can be introduced on larger scale if the solution is economically viable.

6.4 Requirements

The initial requirements were fulfilled. Ergonomics was not investigated deeply and could be further investigated and improved. A requirement that was harder to fulfill was that a vehicle like this has to be fun to drive. A big selling point would be this meaning that from a design point it should look attractive but also the feeling when driving should be different from what you are able to get from other vehicles on the bike lane. In this part of the products development the feel when driving was hard to determine so focus was put on making it attractive for the eye when viewing it.

6.5 Future Work

Continuing improving on the current design and researching the safety is what has to be done in future research about NTV:s like this. The hydraulic system can be made much more effective and less energy consuming, resources needs to be invested in those areas in future projects. Adding an accumulator is something that could be done to improve the design and efficiency for the hydraulics. Looking in to what the effect would be of using 4 actuators that work for every tire individually instead of 2 actuators is something that needs to be investigated. Evaluating if other actuator types can be used is also something that needs to be investigated. Electrical actuators have a trade of between power and strength perhaps a strong slow electrical actuator connected to a lever is a possible solution that would save energy and allow for the speeds needed in a NTV. How big would the interest in a vehicle like this on the current market be is also an important question that needs to be researched in future work.

Besides that, other questions that we see as necessary to be addressed regarding the topic are: How will this vehicle coexist with other vehicles on the bike lane? Is it welcome there? In that sense, we see that it is possible that conflicts might arise between regular bicycles and a vehicle like this sharing the bike lane, since non-electric bikes travel at lower speeds. Consequently, NTV drivers would want to overtake cyclists, causing initially surprises and maybe frustrations. In that sense, future work and research needs to be done to understand the implications of having this type of vehicle on the bike lanes.

7

Conclusion

A concept for a NTV that could be used in urban environments was created. The main focus was on the tilting mechanism and ensuring that it would work as intended. The tilting mechanism was verified in calculations and simulations. It was verified with a LEGO prototype but not a physical prototype similar to the final concept developed. A virtual prototype was developed with components modeled after their real size and the tilting mechanism was verified in the virtual prototype. Constructing a complete vehicle with the time constraints was a constant challenge in this project making it important to prioritise certain aspects. The primary focus was on completing the tilting mechanism.

The product development process was tailored for the development of this NTV. This caused the development process to be very dependent on the platform and several other important areas connected to the top hat were not investigated as aerodynamics, strength of materials and DFMA. The concept generation was adapted to be centered around the tilting mechanism and may have led this project in a certain direction than what could have been it a whole vehicle was considered in every step of the product development process.

Choosing a suitable electric linear actuator and the switch from electrical actuators to hydraulic turned out to be more complex and a longer process than expected. The hydraulic system had to be overdimensioned to establish proper functionality, this resulted in drawbacks such as increased weight, power consumption, and physical size. The result of this was that the hydraulic system was very energy consuming which is mentioned in (Tang & Khajepour, 2019) to counter this energy efficient tilting control has to be implemented. If this issue is resolved in a cost efficient way NTV:s will become much more viable in today's market.

When calculating the driving cycle of an NTV as in this project it was discovered that the infrastructure plays a big role in the range and feasibility. As future infrastructure develops and starts prioritising bike lanes there is potential for this type of vehicle to be successful and have a very generous range. A goal in this project was to get the vehicle classified as a bike in the future and it was found that this is possible if there is a new bike class added to the regulations that takes these types of NTV:s into consideration. The current regulations don't have a classification for this kind of vehicle meaning it would fall under another bike class or vehicle class where it does not belong.

The developed vehicle met many initial requirements and further improvement are needed for certain areas such as optimising the hydraulic system, exploring different actuator types and evaluating how an NTV would interact with other vehicles, cyclist, people and VRU:s The design should be aimed towards creating a vehicle that allows for a unique and exiting riding experience.

In conclusion, a concept for a NTV was developed with the main focus being on the tilting mechanism. However future work should aim towards improving the design, enhancing safety aspects, reducing energy consumption, and evaluating market interest and acceptance of NTV:s on bike lanes.

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