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# Exploratory Concept Analysis of Urban Mobility

Master's thesis in Product Development

ARVINTH KUMAR KUMARAVEL  
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DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

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CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden 2023  
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MASTER'S THESIS 2023

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Master's Thesis 2023  
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Disclaimer: Please note that the visuals included in this document are intended to merely illustrate development efforts by Volvo Cars and are not indicative of exact capabilities or applications of the technology onboard current or future Volvo Cars. Any future offering from Volvo Cars may materially deviate from what is illustrated in this document.

Cover: A rendering of the complete concept vehicle developed.

Typeset in L<sup>A</sup>T<sub>E</sub>X  
Printed by Chalmers digitaltryck  
Gothenburg, Sweden 2023

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## **Abstract**

Urban mobility is one of the fields under rapid development due to the movement of society towards sustainability and green transport. Drive experience and comfort of the user plays a vital role in the development of these vehicles. This project looks into the future focusing on the development of an urban mobility solution which could act as an alternative for cars inside the city. The standard product development process was opted starting with generation of requirement specifications and function analysis. Concept generation was done following that, with the help of ideas generated through innovative methods and final selection of concepts were performed using elimination matrices. The result of the project is a virtual prototype of a three wheeled electric trike concept with the ability to tilt the front part of the vehicle to improve the user feel. Verification of the concept was also done with the help of Finite Element Analysis (FEA) to make sure that the solution was robust enough for usage.

Keywords: Urban mobility, delta trike, electric trike, tilt, lean



# Acknowledgements

Throughout the course of this project, a lot of people have been really supportive and we would like to thank everyone.

We would like to extend our gratitude towards our supervisors Sladjana Strbac, Dag Aronson and Jan Nilsson at Volvo Cars who have helped us a lot along the way. We are very thankful for all their effort which helped us achieve a better understanding of the project and the deliverables.

We are thankful to our fellow thesis mates at Volvo Cars who had always provided us with improvement ideas all along the project. We would also like to thank the other officials at Volvo Cars who have given their time to us amidst their tight schedule.

Finally, we are grateful to our academic supervisor Fjollë Novakazi and examiner Gauti Asbjörnsson at Chalmers University of Technology. Their ideas and feedback from an experienced point of view helped us overcome a lot of struggles in the course of the project. We would also like to extend our gratitude towards the professors at the Vehicle Dynamics department who have given us their thoughts and material to support the proceedings of the project.

Arvinth Kumar Kumaravel & Hugo Löfgren, Gothenburg, June 2023



# Nomenclature

Below is the nomenclature of parameters that have been used throughout this thesis.

## Parameters

$R_\theta$	Gradient resistance force
$R_R$	Rolling resistance force
$R_A$	Aerodynamic drag force
$R_I$	Inertia resistance force
$V_{Vehicle}$	Velocity of vehicle
$V_{wind}$	Velocity of wind
$M_{Vehicle}$	Mass of vehicle
$g$	Acceleration due to gravity
$\alpha$	Angle of inclination of road
$C_{RR}$	Coefficient of rolling resistance
$\rho$	Density of air
$A_F$	Frontal area of vehicle
$C_d$	Drag coefficient
$a$	Acceleration of vehicle
$K_e$	Kinetic energy
$S_D$	Stopping distance
$T_W$	Braking torque
$F_t$	Tangential force on wheel
$BF_t$	Tangential braking force
$m$	Mass of the vehicle



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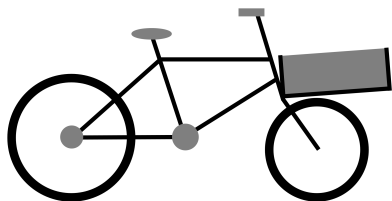


# 1

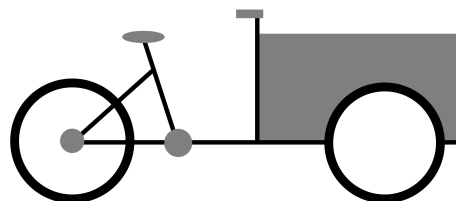
## Introduction

As cities are changing and thus the behavior of people, new needs are emerging to improve the quality of life and efficiency while doing everyday things. A number of cities are becoming more people-oriented by banning cars and providing better opportunities for walking, cycling, or using public transport (Glazener & Khreis, 2019). Some cities are adopting a '15-minute city' approach where the goal is to simplify everyday activities like buying groceries, by creating changes that in many ways benefit pedestrians and cyclists. For example, in Buenos Aires where one of the largest car-free zones in the world has been created to benefit walking and cycling infrastructure. Milan is using new plans for road infrastructure and sustainable urban mobility and also lowering the speed limit to 30 km/h for a majority of the city's streets (C40 Cities Climate Leadership Group, 2022). In Barcelona, the introduction of the Superblock program is meant to limit traffic within cities to increase green space, reduce noise pollution and a number of different benefits. The project will also add 300 km of bike lanes and is expected to reduce the amount of traffic by 21% (C40, 2016) (C40, 2018). Recently, the EU Commission announced the 100 cities which will be a part of the Cities Mission. The goal is to make the cities smart and climate neutral by 2030. The plan involves different types of changes, including more sustainable urban mobility, and expansion of cycling infrastructure (European Commission, 2022). This means road users need to find alternative ways of transportation.

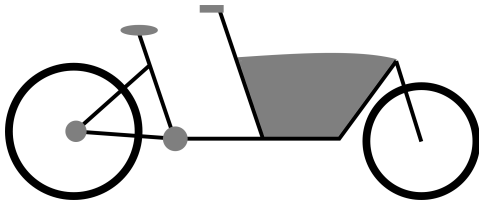
Popular modes of transport for urban contexts include bikes and e-scooters. These options work well for the purpose but cannot handle a lot of cargo. Some of the more typical vehicles with the ability to carry cargo include cycle trucks (Figure 1.1), front-load trikes (Figure 1.2), long-john bikes (Figure 1.3), and rear-load trikes (Figure 1.4). Front-load and rear-load tricycles are also known as a tadpole and delta trikes respectively.



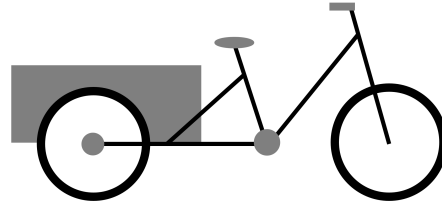
**Figure 1.1:** Cycle truck.



**Figure 1.2:** Front-load trike.



**Figure 1.3:** Long-john bike.



**Figure 1.4:** Rear-load trike.

The main problem with two-wheeled vehicles, like the long-john and the cycle truck is the instability, especially when carrying heavier loads. Because of this, a popular vehicle is the three-wheeled cargo trike. However, because of the three wheels, the rider is unable to lean when turning which gives a high lateral acceleration, which means an uncomfortable ride. It also increases the risk of toppling over in higher-speed corners since the center of gravity cannot efficiently be moved towards the center of the turning circle, as opposed to a normal bike where the user transfers the center of gravity by leaning. Products combining these functionalities also exist, for example, the Alpine Tilt Trike (Alpine Electric Bikes, n.d.), Butchers & Bicycles Mk1-E (Butchers & Bicycles, n.d.), Babboe E-carve (Babboe, n.d.), Cube Trike Hybrid (CUBE, n.d.). These all combine the stability of three wheels with creative tilting systems to get the best of both worlds.

This development opens up new opportunities on the market where bikes and other similar micro-mobility vehicles now have started to see a rise in popularity (Sutton, 2022). There is a need for making short urban trips with the ability to also carry around cargo or children with you, in a speedy and safe manner.

### 1.1 Aim and Research Questions

The aim of this master's thesis was to design and develop a concept of an urban mobility vehicle for short-distance trips, with a focus on the rider's safety and vehicle dynamics.

In order to set a direction for the project and clearly define the main points for completion, a set of research questions stemming from the aims of the project were created:

- How can the dynamic behaviour of the vehicle be verified?
- How can a natural feel be established when tilting the front part of the vehicle?
- How can the inertia be centered to allow for self-balancing in a standstill position?
- In what specific conditions should the self-balancing system be activated?
- How can the drive be transferred from the pedals to the rear axle?
- How can a modular cargo space be designed to allow for the transportation of both children and cargo?
- How can adequate safety be achieved for a child riding in the cargo space?
- How can the weight of the vehicle be minimized?

## 1.2 Project Setting

The background for the project lies in new emerging needs opening up new markets and Volvo Cars desires to also be a part of this in the future. Volvo Cars is a car manufacturer originating from Gothenburg, Sweden, consisting of 41 000 employees around the world (2021). Their main target is the premium segment for cars where they produce SUVs, sedans and station wagons (Volvo Cars, n.d.). However, in order to stay competitive in the market and address sustainability goals, the Future Mobility Lab at Volvo Cars want to investigate the opportunity for the development of a vehicle competing in the lightweight micro-mobility area. The Future Mobility Lab is part of the Open Innovation Arena department and tries to identify upcoming market trends early through research work. The vehicle should help fulfill Volvo Cars' ambition of helping people achieve personal, sustainable, and safe mobility in urban environments. Therefore, the project goal was to develop and design a concept of an urban mobility vehicle for Volvo Cars according to their demands and wishes for the product. Other car manufacturers like BMW are also looking into the development of similar vehicles as the need for it is increasing a lot.

The specific deliverables of the project were as follows:

- Requirements specification.
- Verification of vehicle dynamics.
- Complete high-level concept.
- Verification of the vehicle frame's structural integrity.
- 3D drawings of the concept.

## 1.3 Delimitations

A lot of factors were taken into consideration and studied during the course of the project but not everything that is related to the product. A set of limitations which includes the areas which are not going to be looked upon were created from the development previously done on the project:

- The vehicle will not be designed for rural commuting or inter-city travelling.
- The vehicle will also not be designed for extensive trip-sharing or heavy cargo haulage.
- The vehicle is not intended to be used on highways, rural/high-speed roads or in terrain.
- The vehicle will be rear-wheel drive, no investigation will be done on which wheels to put the propulsion in.
- The vehicle's wheel configuration will consist of one wheel in the front and two wheels in the back.



# 2

## Topic Research

In the initial stages of the project, research was done on what others had already done within this area. Previous literature on the subject, existing products and patents were looked into which is described in this chapter.

### 2.1 Related Work

A study at KU Leuven tried to develop a cargo vehicle for last-mile parcel delivery and ended up designing a trike with a delta wheel configuration along with a tilting axis. The main purpose of the vehicle is hauling cargo which requires a big cargo area capable of carrying an EU pallet. The study performed tests with different configurations of the tilting axis, varying the height and longitudinal angle of the axis position. The study showed that the height of the axis might influence the stability of the vehicle at higher speeds. A higher position proved less stable and a lower position more stable. The angle proved to also have an effect on the stability of the vehicle. As a forward leaning angle makes the rear wheels turn outwards, the turning radius is reduced but also vehicle becomes less stable. With a backward leaning angle, the rear wheels will turn inwards, making the turning radius larger but also resulting in a more stable vehicle. A horizontal angle made the vehicle feel more like a normal bike. In general, a low-positioned tilt axis with a slight forwards tilt was the preferred configuration. (D'Hondt, Juwet, Demeester, & Slaets, 2022)

In a different study, the same vehicle's handling qualities were tested against four other types of traditional cargo vehicles. It provided some strengths and weaknesses with the way the vehicle was constructed. The tilting showed that the lateral acceleration felt by the rider was significantly lower than the other vehicles, giving a more comfortable ride. A weakness was the width of the vehicle causing trouble in lane changes and slalom riding. The width simply made it impossible to maneuver around the circuit properly. Another problem was the braking power not being enough from only regenerative braking as it has poor efficiency at lower speeds. The paper states that reducing the wheelbase to create a smaller turning radius and also reducing the width of the vehicle could help the vehicle with maneuverability. And including mechanical brakes or motors with a higher maximum braking torque could help with braking distance. (D'Hondt, Degryse, Demeester, Slaets, & Juwet, 2022)

In a paper from Chalmers University of Technology, a tadpole-configured trike is evaluated against a conventional bike and an e-bike using physical tests. The trike

proved to be the most stable from the start until 10-12 km/h. Up to 20 km/h the three vehicles then behaved similarly. The e-trike was the best at braking but was worse at maneuvering. The steering was also confusing for the participants and required some getting used to. Something that has to be improved was the maximum steering angle, to allow for better slalom maneuvers. The parameters measured were steering angle, roll rate, speed and time. Steering rate and roll rate were combined into  $R^2$  of linear fit between steering rate and roll rate to indicate balancing skill. They were also combined into time delay between roll and steering rate to measure stability. (Rasch, Dozza, & Håland, 2016)

An investigation regarding the setup of the tilt axis height and front wheel size of a tilting delta trike has been done at the University of Padua. The height was altered by using a customizable four-bar linkage system allowing for tests of the dynamics response from the trike. The main parameters compared were specific roll which gives a ratio between the roll angle and steering torque, and the phase displacement between roll angle and steering torque which gives how much the rider has to anticipate the steering torque for the required roll angle. The results showed that at a lower height, vehicles in general became more stable and less handier. The vehicle required bigger steering angles and yaw angles and also more torque to be put into the steering. The rider did not have to anticipate the steering torque as much. Increasing the front wheel diameter led to bigger steering, roll and yaw angles, and also a higher steering torque. Essentially led to the vehicle becoming less handy. (Cossalter, Ruffo, & Agostinetti, 2005)

## 2.2 Market Study

Once the existing literature was studied, there was a need to do research on the existing products in the market. The explanations of how the existing problem has been solved by other products along with the benchmarking information have been provided in this chapter.

### 2.2.1 Tilting Trikes

Searches on the internet for similar products garnered a number of results. The most representative examples found were the Cube Trike Hybrid (CUBE, n.d.), Alpine Electric Tilt Trike (Alpine Electric Bikes, n.d.), Pashley Alecs (Pashley, n.d.), DHL Chariot (DHL, n.d.), Fulpra (Fulpra, n.d.) and Honda (Masaki, 1987). These are all based on a three-wheel rear-load configuration constructed of two frames which are rotatably connected to each other, allowing for bike dynamics for the rider while also having the stability and cargo capacity of a trike. Each of them has solved the issue using a different solution, some more simple and others more complex.

The Alpine Electric Tilt Trike has used simple solutions for the different functions. It tilts by connecting the front and rear with two bearings. The front and rear are also connected with a spring rod which is there to resist the tilting motion. This assists the rider with keeping the balance. It also uses a tilt lock mechanism

which locks the front upright, to act like a normal trike. This is activated using a lever on the handlebars which pushes a rod into a hole to lock the front in place. Another problem with trikes is that the rear wheels need to drive the trike while also having the ability to go at different speeds to avoid slipping and make turning easier. This is solved by only putting the drive into one of the rear wheels, and having the other one spin freely. One issue that could be spotted with the Alpine trike was that tilting the trike would have the chain drive's two sprockets misalign with each other. This could cause wear on the chain and should probably be avoided.

The Cube Trike Hybrid uses more technical solutions for its systems. To allow its rear wheels to spin at different speeds it uses a differential in the rear axle. This solves the problem while still also putting the drive in both rear wheels, which is preferred when compared to the Alpine trike. It also involves a solution to always keep the chain drive sprockets aligned. The rear sprocket is rotatably mounted on the rear axle using what could be described as a fixed spherical bearing. Both the inner and outer rings of the bearing rotate along their central axis together, but the outer ring is able to tilt independently. This allows the sprocket to still propel the rear axle, while also tilting with the chain. These two solutions fix some of the problems with the Alpine Trike, but they also introduce a lot more mechanical complexity to the vehicle.

The Pashley Alecs also does not use any solution for aligning the chain drive sprockets. It puts drive into both rear wheels but it is unclear how this is done from the patent.

The trikes from Pashley, Fulpra and DHL are more oriented to purely cargo transport and thus have a larger cargo area than what is required by trikes aimed for personal use. The Cube and Alpine trikes are most representative of what is being sought after from this project. The trikes with data available have been compared in a benchmark in Table 2.1.

**Table 2.1:** Benchmark of tilting trikes.

Trike	Cube Trike Hybrid (CUBE, n.d.)	Alpine Electric Tilt Trike (Alpine Electric Bikes, n.d.)	Pashley Alecs (Pashley, n.d.)
Length (mm)	N/A	1700	2400
Width (mm)	N/A	655	800
Weight (kg)	54,2	37,75	85
Front wheel size (in)	24	20	24
Rear wheel size (in)	20	20	
Battery capacity (Wh)	750	468	814
Cargo weight capacity (kg)	60	N/A	100
Rider weight capacity (kg)	125	150	N/A
Drivetrain	Hybrid w/ chain	Hybrid w/chain	Hybrid w/ chain

### 2.2.2 Cargo Bikes

To acquire an overview of cargo space in cargo bikes on the market an already existing benchmark made by Cargobikemag was used (Anders, 2017), shown in Table 2.2.

**Table 2.2:** Benchmark of cargo space in cargo bikes.

Cargo bike	Type	Length (mm)	Width (mm)	Max cargo load (kg)
<b>Urban Arrow Family</b>	Long john	650	520	125 + rider
<b>Bullitt</b>	Long john	710	440	180 incl. rider
<b>Reise &amp; Müller Packster 60</b>	Long john	600	670	200 incl. rider
<b>Reise &amp; Müller Load</b>	Long john	570	470	200 incl. rider
<b>Workcycles Kr8</b>	Long john	690	480	80 + rider
<b>Babboe City Mountain</b>	Long john	660	530	80 + rider
<b>Elride Cargo</b>	Long john	700	500	90 + rider
<b>Douze 60</b>	Long john	580	470	200 incl. rider
<b>Triobike Cargo</b>	Long john	720	470	200 incl. rider
<b>Christianiabike Light</b>	Tadpole	890	620	100 + rider
<b>Butchers &amp; Bicycles Mk1-E</b>	Tadpole	700	60	100 + rider
<b>Livelo #1</b>	Tadpole	600	520	N/A
<b>Babboe Carve</b>	Tadpole	820	500	80 + rider
<b>Babboe Big</b>	Tadpole	815	585	100 + rider
<b>Elride Cargo 3</b>	Tadpole	900	640	150 + rider

### 2.2.3 Bike Trailers

A benchmark of different bike trailers was also done to scope the different solutions as the sizing is important to get right for the ride experience of the passengers. The benchmark is presented in Tables 2.3.

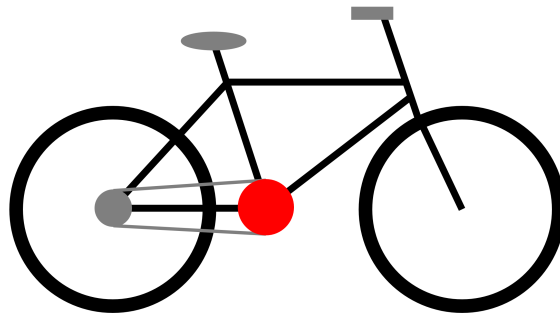
**Table 2.3:** Benchmark of bike trailers.

<b>Trailer</b>	<b>Hamax Out-back</b> (Hamax, n.d.-a)	<b>Hamax Traveller</b> (Hamax, n.d.-b)	<b>Hamax Avenida</b> (Hamax, n.d.-c)	<b>Nordic Roll Cruiser</b> (Bäst i test, n.d.)
Length (mm)	1090	1015	1020	N/A
Width (mm)	860	780	780	790
Seat height (mm)	650	660	630	N/A
Shoulder width (mm)	600	560	560	N/A
Passenger load capacity (kg)	40	47	45	45
Max weight per passenger (kg)	22	22	22	18
Max passenger height (mm)	1170	1170	1170	N/A
Min passenger age (years)	0.5	0.5	0.5	1.5
<b>Trailer</b>	<b>Thule Chariot Cross 2</b> (Thule, n.d.-b)	<b>Thule Chariot Lite 2</b> (Thule, n.d.-c)	<b>Thule Chariot Cab 2</b> (Thule, n.d.-a)	<b>Thos Hushovd Kid Racer Twin</b> (Bäst i test, n.d.)
Length (mm)	N/A	N/A	N/A	1080
Width (mm)	800	800	800	860
Seat height (mm)	680	680	710	N/A
Shoulder width (mm)	570	570	570	640
Passenger load capacity (kg)	45	45	45	60
Max weight per passenger (kg)	22	22	22	21
Max passenger height (mm)	1110	1110	1110	1000
Min passenger age (years)	1	1	1	N/A

## 2.2.4 Drivetrains

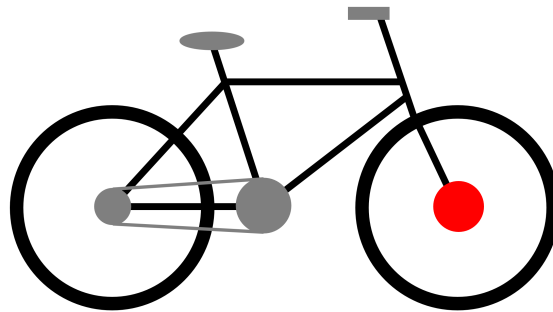
There exist three different types of common drivetrain systems for e-bikes. Mid-drive motors are mounted together with the front crankset of the bike, with the pedals being attached directly to the motor, shown as red in Figure 2.1. Torque sensors can sense the amount of power being produced by the rider and then tell the motor how much power to apply. Since the mid-drive motor is directly incorporated into the existing drivetrain, it just adds the power which is then transferred in the chain or belt to the rear wheel. This also means it can take advantage of the already installed gears of the bike. Using torque sensors gives the rider a natural feel since power is only being added depending on how much power the rider is putting in

themselves. Mid-drive motors however are more complex and expensive. (Where The Road Forks, 2023) (Cavallari, 2022)



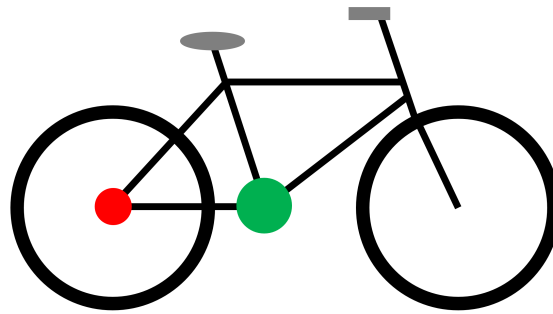
**Figure 2.1:** Mid drive motor setup.

Hub motors are a cheaper option which is attached directly to the wheels of the bike, shown in Figure 2.2. When given power, they directly give torque to the wheel. Most hub motors use cadence sensors to know when the user is pedaling. They then give a continuous amount of power to the motor as long as the rider is pedaling. The amount of assistance can usually be adjusted by the rider to a comfortable level. Some higher-end hub motors have cadence sensors that also measure the speed of pedaling, and then adjust the amount of assistance with regard to this. Hub motors are cheaper and simpler. (Where The Road Forks, 2023) (Cavallari, 2022)



**Figure 2.2:** Hub motor setup.

Series hybrid drivetrains are uncommon in comparison to the previously mentioned options. They are powered solely by the electric motors of the bike without directly using the mechanical power of the user. Instead, the mechanical power is converted into electricity using a generator attached to the pedals. This is shown in Figure 2.3 with red as the motor and green as the generator. The electricity can then be used to charge the batteries of the bike or power the motors. These types of systems use hub motors for propulsion of the wheels (Toll, 2023). The efficiency of these drivetrains is a drawback as some power is lost, about 5% loss for one system is mentioned by Evans (2022).



**Figure 2.3:** Series hybrid drivetrain.

## 2.3 Patent Analysis

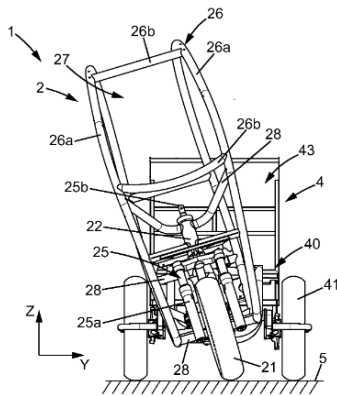
Google Patents (Google, n.d.) and Espacenet (Espacenet, n.d.) were the main sources for the patent search which was done to identify the existing and emerging technologies in order to get inspiration and solutions to solve the problems. Several keywords such as 'tilt', 'trike', 'lean', etc., were used in order to explore the available patents and around 183 patents showed up in Espacenet. A lot of different types of patents were available which were both in the mature and emerging stages of development. In addition, Patsnap (Patsnap, n.d.) which was accessible at Volvo Cars was also used for the patent search process. A set of keywords were gathered, and a short description was prepared which was provided to the Patsnap search engine as input and it resulted in 340 patents. A list could be compiled of the ones that had the most relevancy with regard to the project after going through all the patents. It was done manually as the keywords used were very similar to another concept called NTV (Narrow Tilting Vehicle) and they started overlapping. These patents are shown in Table 2.4.

The patents included several other concepts such as the ones for narrow tilting vehicles and three-wheeled motorbikes, which were filtered out and the ones which were related to this project were selected. The patent search was mainly targeted towards the tilting mechanism and lean resistance requirements of the vehicle as they were the complex parts of the project which had to be figured out. Moreover, the technology readiness level (TRL) is also provided for each of the patents in order to get an idea of the maturity level of the proposed particular technology. The filtered ones had a few technologies which were kind of similar, the ones having completely different solutions have been explained below.

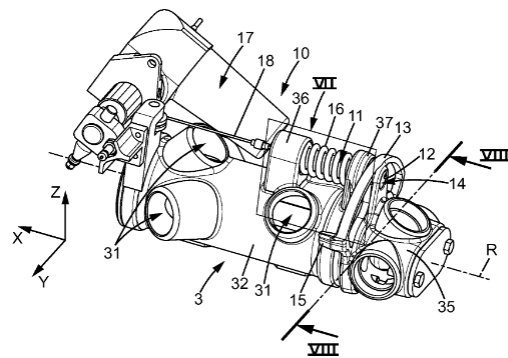
**Table 2.4:** Patents found in the patent analysis.

SN	Patent Name	Patent Number	Technology Involved	TRL
1	Tricycle	WO2011121211A1	Rotating joint around a roll axis, joint lock control system (Gerard, 2011)	4
2	Electric tricycle with roll	WO2019025898A1	Swivel mechanism along an inclined axis (Antoine, 2019)	5
3	Vehicle tilting system and tricycle	CN106809323A	Tilting system consisting of arc shaped track assembly and sliding base assembly (Su-Yuen, 2017)	5
4	A utility vehicle	EP4074586A1	Radial and axially loadable bearing structure, hybrid propulsion using pedal and motor (Harald, 2022)	6
5	Tiltable mobility vehicle	WO2022223562A1	Two ball and socket joints for pivotable front part (Christphe, 2022)	2
6	Tiltable electric tricycle	US9731785B1	Spring damper system for keeping the system upright (Yongbiao, 2017)	3
7	Tricycle	US5240267A	Caliper assembly for connecting front and back halves, biasing arrangement for providing lean resistance (Peter, 1993)	
8	Tricycle for passenger and cargo transport	WO2019162714A1	Dual bearing tilt arrangement, power transmission with universal joint (Zoltan, 2019)	
9	Tricycle tilting device	CN101559803A	Pin lock with switch arrangement, spring rod structure for lean resistance (Haraguchi, 2009)	9
10	Tiltable tricycle	US4678053A	Elliptical housing with rubber bodies for lean resistance (Masaki, 1987)	9
11	Vehicle	EP4098531A1	Rear bearing arrangement for tilt and spring system for lean resistance (Adrian, 2022)	9
12	Oscillation righting mechanism of tricycle	JP3479946B2	Oscillation righting mechanism for lean resistance (Toyoyuki, 2003)	9
13	Coupling mechanism for a vehicle body	US11338879B2	Coupling mechanism with spring attachment for lean resistance (Chyuan-Yow, 2022)	5
14	Tricycle	WO2019125138A1	Tilt mechanism inclined downwards (Hubertus, 2019)	4
15	Tricycle with wheelchair platform	US20120175856A1	Dual cam arrangement for lean resistance (Robert, 2012a)	4
16	Tricycle	JP1983067588A	Fork arrangement for lean resistance (Robert, 2012b)	

Patent 1 in Table 2.4 is regarding a vehicle that has a simple rotating joint with bearings between the front and rear halves of the vehicle that allows the front part to tilt in order to provide the user with a feel of driving a normal bike as shown in Figure 2.4 (Gerard, 2011). Also, to prevent instability during low speeds, a joint lock mechanism as shown in Figure 2.5 (Gerard, 2011) with a control system provided. The control system engages the locking mechanism such that until a threshold speed, the tilting feature is locked such that the vehicle is stable and once that speed is reached the lock is released and the user is allowed to tilt the front part of the vehicle.

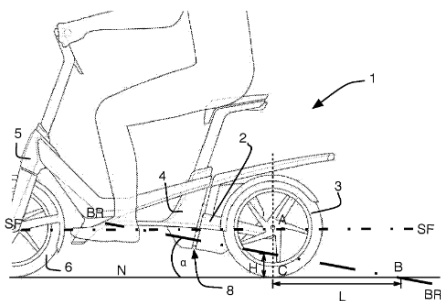


**Figure 2.4:** Tilting trike.

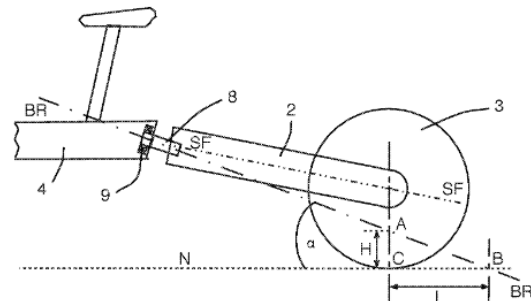


**Figure 2.5:** Joint lock mechanism.

Patent 2 in Table 2.4 used a similar tilt mechanism but the difference was that the roll axis was tilted upwards at an angle with respect to the ground as shown in Figure 2.6 (Antoine, 2019). They made interesting claims that the angle between the roll axis and the ground should be around  $5^\circ$  to  $10^\circ$  and preferably  $7^\circ$  for optimum conditions. In addition, the distance between the roll axis and the axis passing through centre of rotation of the rear wheels should be less than 0,05 m. Also, the distance L between B and C which is shown in Figure 2.7 (Antoine, 2019) should be less than 0,5 m.

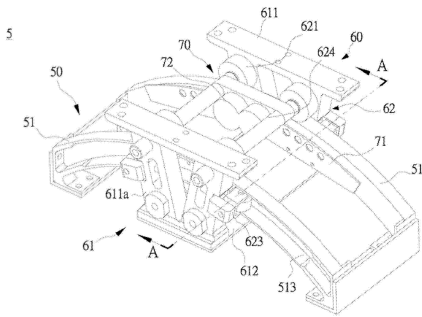


**Figure 2.6:** Electric cycle with roll motion.

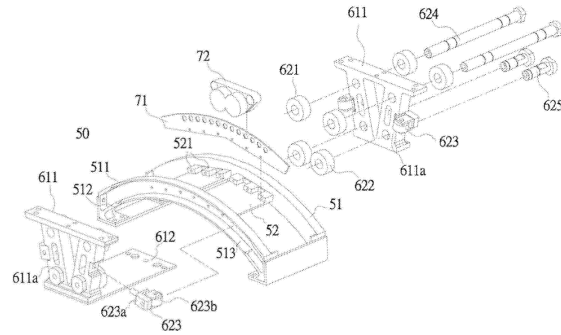


**Figure 2.7:** Distance between roll axis and wheel centre.

Patent 3 in Table 2.4 used a bigger setup consisting of a track and a carriage assembly which has an arcuate motion as shown in Figure 2.8 (Su-Yuen, 2017) in order to allow the front part of the vehicle to tilt. The purpose of this setup was to move the centre of the roll axis rotation down below to the level of the ground or even below the ground according to needs to improve the user control. A disassembled view of the carriage assembly is shown in Figure 2.9 (Su-Yuen, 2017).

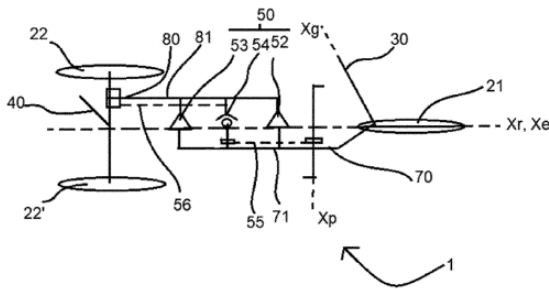


**Figure 2.8:** Vehicle tilting system.

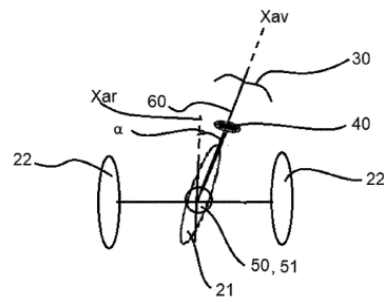


**Figure 2.9:** Exploded view of vehicle tilting system.

Patent 5 in Table 2.4 proposed an interesting solution for the tilt where ball and socket joints have been used to provide the degree of freedom. As one ball joint will allow all the rotational degrees of freedom, two joints have been used with a universal joint between them as shown in Figure 2.10 (Christphe, 2022) for power transmission. The front view of the vehicle in the tilted condition is shown in Figure 2.11 (Christphe, 2022). This was just a simple idea of the concept though, for which none of the developments could be found.

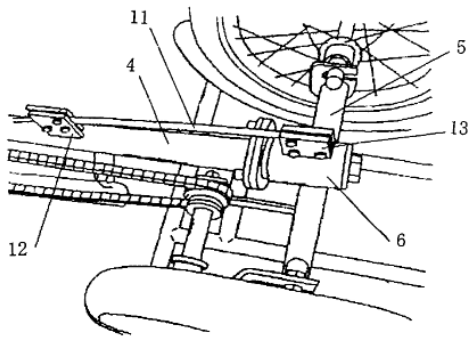


**Figure 2.10:** Tiltable mobility vehicle.

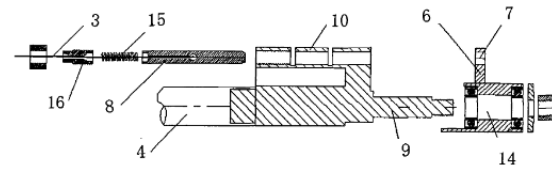


**Figure 2.11:** Dual ball joint structure.

Patent 9 in Table 2.4 is similar to the Alpine Electric Tilt Trike where they have tried to solve the tilt and lean resistance problems with simple low-weight structures such as the spring rod and pin lock structures respectively as shown in Figures 2.12 (Haraguchi, 2009) and 2.13 (Haraguchi, 2009). The pin lock was controllable with the help of a switch provided on the handlebar by the user. Though it does not provide a detailed or sophisticated solution, it was enough to solve the existing problem and the product has also been developed and exists on the market.

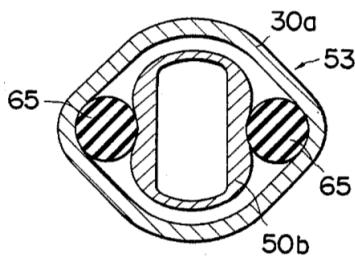


**Figure 2.12:** Spring rod structure.

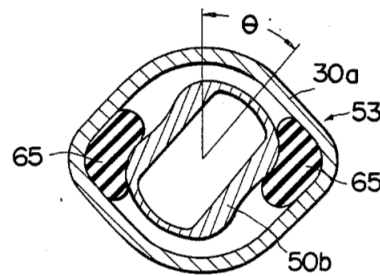


**Figure 2.13:** Pin lock with switch.

In patent 10 of Table 2.4, Honda had proposed an interesting solution to solve the lean resistance problem which was relatively simple as well as very effective. The system has an elliptical housing with rubber bodies as shown in Figure 2.14 (Masaki, 1987) which resists the rotatory motion of the shaft, and the amount of resistance increases with the angle of tilt. Figure 2.15 (Masaki, 1987) shows the tilted position where the rubber bodies are in a compressed position.

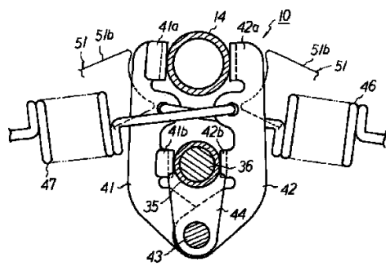


**Figure 2.14:** Elliptical housing at upright state.

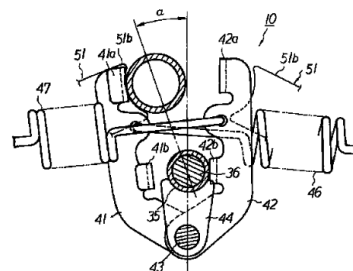


**Figure 2.15:** Elliptical housing at tilt state.

In patent 12 of Table 2.4, Yamaha had proposed an oscillation righting mechanism with the help of a damping system as shown in Figures 2.17 (Toyoyuki, 2003) and 2.16 (Toyoyuki, 2003) to provide the lean resistance effect. It provides a constrained pivotal effect when the vehicle tilts so that the amount of resistance increases with the amount of tilt.



**Figure 2.16:** Oscillation righting mechanism at upright state.



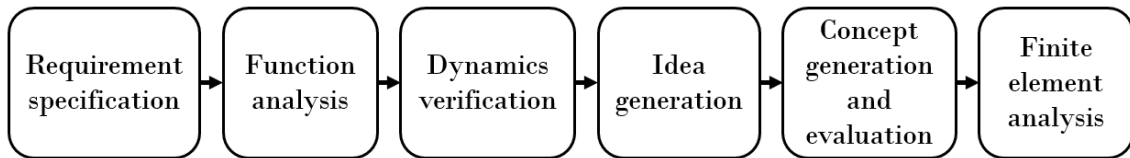
**Figure 2.17:** Oscillation righting mechanism at tilt state.



# 3

## Methodology

A standard product development process has been followed throughout the project involving the development of a virtual model of a working concept. This process was loosely based on Ulrich, Eppinger & Yang (2020). The process that was roughly followed is shown in Figure 3.1. The process was not entirely step-by-step but instead, a more iterative process where sometimes a skip backward was needed.



**Figure 3.1:** Project steps.

The following sections describe the methods used during the different steps of the project.

### 3.1 Requirement Specification

A structured requirement specification was created in an organized manner from the set of requirements which was provided by Volvo Cars. The list of requirements along with their verification and assessment methods are listed in Section 4.1.

### 3.2 Function Analysis

Prior to the idea generation process there existed a need to map out the different subfunctions that the vehicle should carry out. Various subfunctions relating to the whole functionality of the vehicle were identified in order to include all the aspects of the features that are to be added. Three different methods such as the process flowchart (Lucidchart, n.d.), function-means tree (L, Almfelt, personal communication, January 17, 2022) and function tree (Parrot, n.d.) were considered at the start to proceed with the process.

Since the project deals with the development of a product involving different subsystems for different subfunctions there is not really a flow of the process involved. To be exact, there is no step-by-step structure where the latter step completely depends upon the inputs from the previous step. Due to this reason, the process flowchart

did not seem to fit well to identify the subfunctions and was ruled out.

In the next step, the function-means tree was investigated, where the function identification is driven with the help of the generation of a few different solutions for each function. As the function-means tree includes solutions already at an early stage, the tree can become quite complex if everything was to be included. This not only happens for the main function levels but on all sublevels too which reduces the opportunity to explore the different solutions if the tree size is to be kept at a reasonable level. Due to this reason, the function-means tree was not feasible for the process either. Finally, the function tree method seemed to be a good fit for this project and was used to map out all the subfunctions.

## 3.3 Dynamics Verification

Before the generation and selection of concepts, there was a need to research the tilt mechanism. As the tilting mechanism of the vehicle was one of the most important subsystems among all, a good understanding of its effect and how it could be affected by the selection of its solution was required.

The first approach tested for the problem of verifying the vehicle dynamics was creating simulations in multibody physics software, where the goal was to have a simple model run on a short test track with measurements of forces and accelerations being taken. Research was done on which software seemed most appropriate for the purpose and a decision was made to first try MSC Adams View (Hexagon, n.d.) since similar research already exists using this software (Persson, Ekström, Ekström, & Papadopoulos, 2021) (Barbagallo, Sequenzia, Oliveri, & Cammarata, 2016). An attempt was also done using the Simscape toolbox in Matlab (MathWorks, n.d.) after consulting with an author of Persson et al. (2021). After working with both software for a period of time it was apparent that the instability of having a tilting mechanism would create problems for the simulation. The simulation would require a control system in order to help the vehicle stay upright and also follow a pre-determined track. A path-following model using a PID controller was created in Adams View but the vehicle was not able to balance itself hence this was not usable for the project. The development of a control system to keep the vehicle's balance would have used up too much of the available time for the project and it was decided that other approaches had to be explored. Later, the problem was solved with the use of CATIA by creating a simple CAD (Computer aided design) model and measuring dimensions regarding the movement of parts at different case situations as explained in Section 4.3.

## 3.4 Idea Generation

In order to proceed with the concept generation process, solutions for each subfunction were generated first with the help of different creative methods such as brainstorming (Halme, n.d.), negative brainstorming and biomimicry. This was

done to increase the chances of coming up with different and innovative solutions at the end by using a larger design space. The methods used led to improved creativity and the ability to think outside the box.

For the brainstorming session, the participants tried to come up with solutions for each subfunction identified, and no thought was given to whether the generated solution will fit this project or not at this stage of the process. To get a varied perspective, a few fellow thesis students working in the same department at Volvo Cars were invited to participate in the idea generation session which proved to be very helpful. Random and even crazy ideas were included having the view that they may somehow prove to be useful in the later stages of the project.

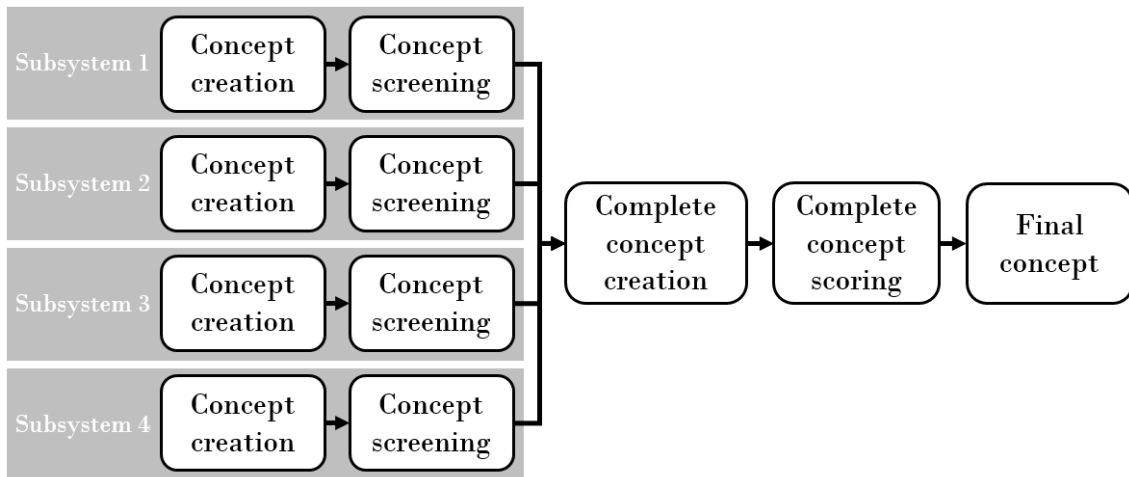
In order to increase the size of the solution set, negative brainstorming was also performed which resulted in the generation of multiple solutions for each of the subfunctions (Universaldesignguide, n.d.). A series of processes were followed in this negative brainstorming method, where negating the subfunctions was the first step. Each of the subfunctions was rephrased such that it provided a negative meaning, for example, the subfunction *Protection from splash* was re-written as *No protection from splash*. Next, a solution for solving the negated subfunction was generated. Following that, one of the facts that made the generated idea bad was thought of and noted down. Finally, the good things about the bad facts were identified and a good idea was generated in order to solve the purpose of the particular subfunction.

Thirdly, to derive something creative from the surrounding environment and nature, biomimicry research was opted for. It included a different source of knowledge compared to the previous methods. An online platform called Asknature (Institute, 2021) containing large sources of information about the technologies developed from the existing natural beings was made use of to carry out this process.

### 3.5 Concept Generation and Evaluation

Once the position of the tilt mechanism was fixed, the next step was to start the concept generation process by combining the variety of ideas that were available from the previous step. The process is shown in Figure 3.2.

Since there was a lot of different subfunctions to cover for the whole vehicle, it was soon decided that combining solutions for all subfunctions one concept at a time would not be efficient and would introduce a risk of not exploring all the best concept combinations. It was instead decided to split the system up into four subsystems, which each were explored individually. These four subsystems were; *Drive train*, *Cargo box*, *Tilting mechanism*, and *Remaining functions*. Since these subsystems do not have big synergies between them, it was more beneficial to find the most optimal solutions for each one of them, and then combine those to find the final concept combination.



**Figure 3.2:** Steps taken during concept generation and evaluation.

To create concepts for each subsystem, morphological matrices, or concept combination tables (Ulrich et al., 2020), was created to combine the different solutions. With the help of the morphological matrices, random combinations were tried out and combined to generate different concepts with big variations.

With the generated concepts, the next step was to proceed with the evaluation of their credibility and selection of useful concepts to proceed with the development. One way of doing that is by rating each of the concepts based on different criteria and finding out which concept fulfills the needs. But it was very important to compare the concepts between each other to identify which part of the concepts made it effective. Having a comparison seemed more useful because the generated concepts will not be proceeded with till the end as it is and there will be a lot of merging of attributes from different concepts. Keeping that in mind, identification of the solutions leading to an improved idea was given the first preference and Pugh concept selection (Ulrich et al., 2020) was used in order to evaluate the existing concepts. The method involves taking one of the concepts as a reference and ranking the other concepts +,- or 0 meaning better, worse or the same level respective to the reference concept. This resulted in some concepts being eliminated and some progressing. The concepts from each subsystem that progressed were then combined with the other subsystems to create five full concepts, again using a morphological matrix.

To compare the final concepts more in-depth, a Kesselring matrix, or concept scoring matrix (Ulrich et al., 2020), was used to give the concepts weighted scores. This acted as an indicator of which concept(s) could be the winning ones. The categories are based on the requirements specification. When a category was run through in the matrix, a medium-performing concept was chosen to act as a reference and was given a score of 3. The other concepts were then scored based on this reference to give them an accurate score. Choosing a new reference for every category assures that the scores are distributed fairly across the board. If e.g. only one concept acted as a reference for all categories, there might be a number of points to other concepts

if the reference concept performs well in a category, but still is given a 3 because it is the reference.

### **3.6 Finite Element Analysis**

Finally, the structural integrity of the developed model was verified with the help of finite element simulations carried out using Ansys Mechanical (Ansys, n.d.). The main concentration was given to the front and the rear frames as they were the main load-carrying components of the vehicle. Different types of simulations such as a strength test and buckling analysis were performed and the results of all the simulations are explained in Section 4.7.



# 4

## Concept Development

This chapter presents the work done to develop a concept for the project. All methods and their respective results are presented and discussed.

### 4.1 Requirement Specification

A list of requirements mainly based on Volvo Cars already existing requirements was created. The regulatory aspects were also included in the requirements and based on The Swedish Transports Agency's list of requirements on bikes (Transportstyrelsen, n.d.) since Volvo Cars want the vehicle to fall under these. This removes the need for registering and insuring the vehicle in addition to not needing a license to drive it. Regarding the regulatory requirements on reflectors, different EU countries have different laws on this. Since this part is easily customizable by the user it was not considered to adjust it for each specific country. The regulation on motor power and speed is the same in all EU countries and treats the vehicle the same as a normal bike (EUR-lex, 2020). The specifications list includes all the aspects needed for the design of the whole vehicle with the highest priority given to safety consisting of the most number of requirements. These results, including a description of criteria, justification and verification are presented in Tables 4.1 and 4.2.

The figure on the rider weight is based on Hanson, Sperling, Gard, Ipsen, & Olivares Vergara (2009), where it is stated that a 95th percentile male is 100 kg. The weight limit for the cargo space as well as the max weight of the vehicle is based on previously mentioned benchmarks. All the requirements were not finalized at this point in time and there was a possibility to change some of those based on the final results of the project.

**Table 4.1:** Requirement specification.

Criteria	R No.	Requirement	Justification	Verification
<b>Safety</b>	R1	3 wheels	Address balance issues	Assessment
	R2	Form factor that is highly visible	Improve visibility	Engineering assessment
	R3	Excellent visibility	Improve visibility	Engineering assessment
	R4	Capable of emergency braking	Avoid accident	Prototype testing
	R5	Centering of inertia	Self balancing	Simulation
	R6	Handling that allows for looking over the shoulder and other pro-SA actions	Safe riding	Simulation
	R7	Handling that allows for safe swerving	Safe riding	Simulation
	R8	Suitable for accident-prone frail users	Safe riding	Assessment
	R9	Format that allows for safe and stable ingress/egress	Avoid fall	Prototype testing
	R10	Wheel configuration that prevents accidents related to curbs, rails, gravel, leaves, or potholes	Avoid fall	Engineering assessment
	R11	Tilt-lock mechanism	Provide non-tilting ride option	Prototype testing
	R12	Red rear light	Regulation	Assessment
	R13	White or yellow front light	Regulation	Assessment
	R14	Red reflector in rear	Regulation	Assessment
	R15	White reflector in front	Regulation	Assessment
	R16	White or yellow reflectors on sides	Regulation	Assessment
	R17	Has brakes	Regulation	Assessment
	R18	Has a bell	Regulation	Assessment
	R19	Can handle rider weight of 100kg	95th percentile male data	Finite element analysis
	R20	Can handle cargo weight of 60kg (total max 40kg for children)	Benchmark data	Finite element analysis
<b>Dimensions</b>	R1	Overall length is 2155 mm	Minimize footprint & vehicle dynamics	CAD
	R2	Rear overhang is 382 mm	Minimize footprint	CAD
	R3	Wheelbase is 1430 mm	Vehicle dynamics	CAD
	R4	Front WCL to SRP is 852 mm	Comfort	CAD
	R5	Vehicle height-body is 1000 mm	Comfort	CAD
	R6	SRP front to ground is 880 mm	Attractive design	CAD
	R7	Cowl height is 730 mm	Comfort	CAD
	R8	Vehicle width is 666 mm	Minimize footprint	CAD

**Table 4.2:** Requirement specification continued.

Criteria	R/D	Requirement	Justification	Verification
<b>Space &amp; mass</b>	R1	Fits at least 3 average-sized grocery bags	Provide maximum cargo space	Engineering assessment
	R2	Modular cargo space	Use for different applications	Engineering assessment
	R3	Can be parked on paved non-road infrastructure	Suitable to park anywhere	Prototype testing
	R4	Does not weigh more than a heavy bike (50kg)	Benchmark data	Engineering assessment
	R5	One main seat	Only one driver	Assessment
<b>Power</b>	R1	Top speed is 25 km/h	Regulation	Engineering assessment
	R2	Max rated motor power is 250 W	Regulation	Assessment
	R3	Combination of mechanical and electrical drive	Easy propulsion	Engineering assessment
	R4	Easily replaceable battery	Ease of repair	Engineering assessment
<b>Characteristics</b>	R1	Fun to drive	User attraction	Prototype testing/simulation
	R2	Adequate shelter	Improve safety	Assessment
	R3	Little maintenance	Ease of repair	Engineering assessment
	R4	Sustainable and durable lightweight materials	Improve sustainability	Engineering assessment
	R5	Suitable for bike lanes, mixed sidewalks	Conveniency	Assessment
	R6	Suitable for mixed local urban car roads	Conveniency	Assessment
<b>Durability</b>	R1	Lifecycle of the vehicle should be at least 5 years	Sustainability/user attraction	Fatigue analysis

## 4.2 Function Analysis

The function tree method was outlined as shown in Figure 4.1. It was performed on three different sublevels where *Provide mode of transportation* was the primary function that the vehicle has to deliver and 19 final level subfunctions were mapped out from that to include all the capabilities of the whole vehicle. Some of the subfunctions were overlapping with one or more higher-level functions but in order to avoid repetition, they were placed under the higher priority functions. For example, the subfunction *Allow for tilting of front part* could potentially be placed under *Provide adequate safety* or *Provide comfort*. As the safety function was of a higher priority it was chosen for branching it out.

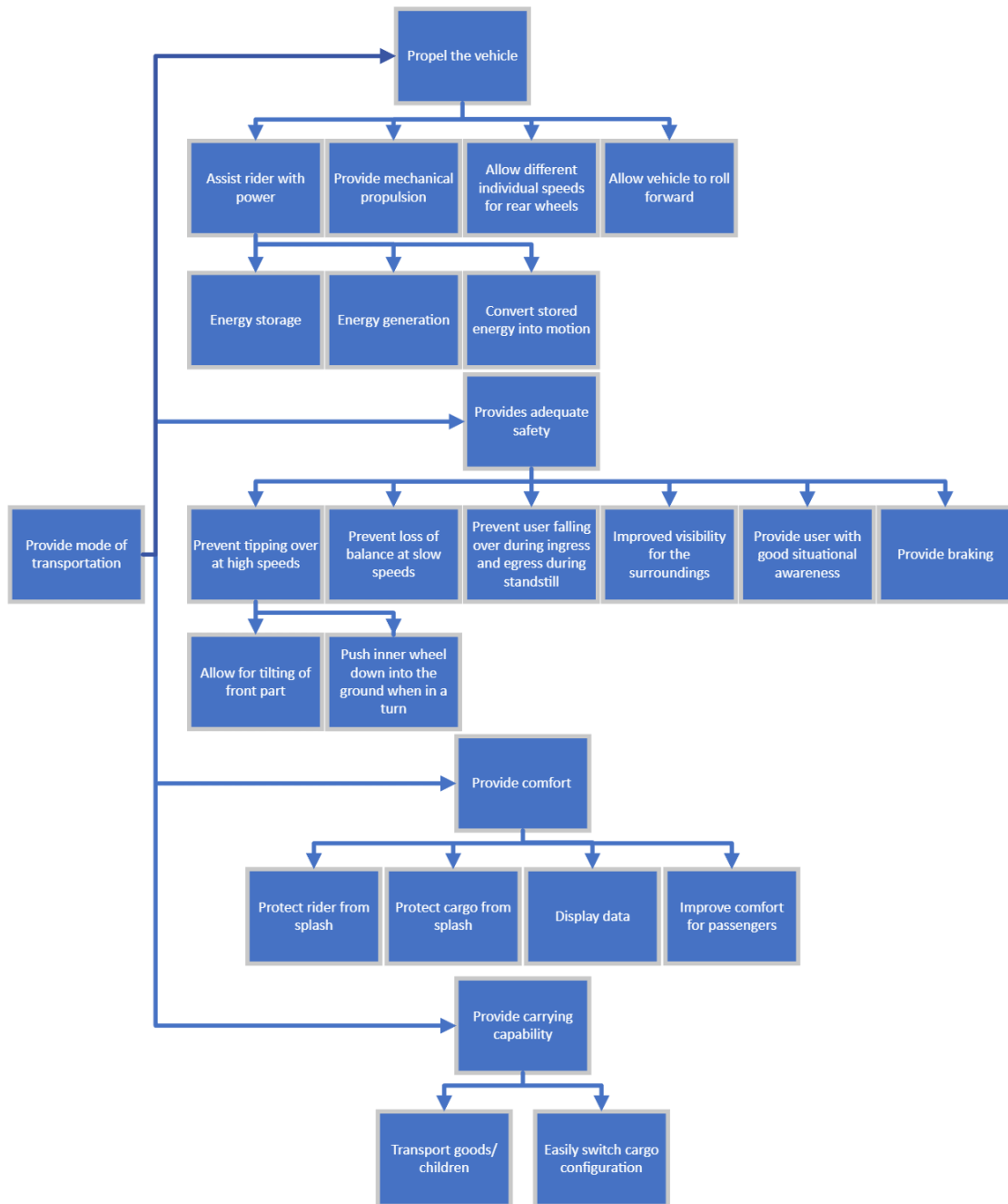


Figure 4.1: Function tree.

The 19 subfunctions at the lower level of the function tree are explained below and will be taken over to the next step of idea generation.

**1. Transport goods/children:** This subfunction refers to the ability of the vehicle to carry goods such as groceries or other materials as well as children that the user wishes to transport from one place to another.

- 2. Easily switch cargo configuration:** As the vehicle is capable of transporting goods and children, this subfunction refers to the ability to switch the cargo setup to incorporate both.
- 3. Protect rider from splash:** This subfunction involves the fact that the front part of the vehicle has to be protected somehow so that the rider is protected from the tire splash.
- 4. Protect cargo from splash:** This subfunction involves the fact that the rear part of the vehicle has to be protected somehow so that the goods or children getting transported do not get wet during the travel which will not be desirable.
- 5. Display data:** This subfunction elucidates the need for informing basic data related to the vehicle during the travel to the user to make them aware of the situation and riding conditions.
- 6. Improve comfort for passengers:** This subfunction describes the need to design the cargo seat for passengers such that it is comfortable to be seated on it.
- 7. Allow for tilting of front part:** This subfunction deals with the inclusion of the ability of the front part of the vehicle to tilt along the roll axis in order to improve the safety as well as improving the rideability and maneuverability of the vehicle.
- 8. Push inner wheel down into ground when in turn:** This subfunction refers to the concept of providing downward force on the inner wheel while taking a turn in order to prevent the toppling of the vehicle.
- 9. Prevent loss of balance at slow speed:** This subfunction refers to the ability of the vehicle to be in good balance when it is driven at slow speed as the tilting front part of the vehicle can cause instability.
- 10. Prevent user falling over during ingress and egress:** This subfunction describes the need for the vehicle to prevent the user from falling over during the time of boarding and getting down from the vehicle.
- 11. Improved visibility for the surrounding:** This subfunction includes the need for the vehicle to be clearly visible to other people in the roads so that they are well informed of the presence of this vehicle to avoid accidents.
- 12. Provide user with good situational awareness (SA):** This subfunction deals with the fact that the vehicle's design should allow improved visibility of what is happening in the surroundings to the user and also the present running conditions of the vehicle.

**13. Provide braking:** This subfunction refers to the ability of the vehicle to brake and provide a steady reduction in speeds for safety purposes.

**14. Energy storage:** This subfunction deals with the ability of the vehicle to store the energy in order to power the motor(s).

**15. Energy generation:** This subfunction includes the need for the vehicle to generate energy with the help of the manual power from the user in order to provide a hybrid source of propulsion (in case the chosen drivetrain requires it).

**16. Convert stored energy into motion:** This subfunction deals with the ability of the vehicle to convert the generated and stored energy into motion for propelling the vehicle forward.

**17. Provide mechanical propulsion:** This subfunction is to include the ability of the vehicle to provide some source for the user to manually power the vehicle, to be exact, to use that for the generation of power.

**18. Allow different individual speeds for rear wheels:** This subfunction refers to the ability of the rear wheels to have individual speeds to avoid slipping when the vehicle is taking a turn.

**19. Allow vehicle to roll forward:** This subfunction deals with the provision in the vehicle which allows it to roll forward when propelled.

### 4.3 Dynamics Verification

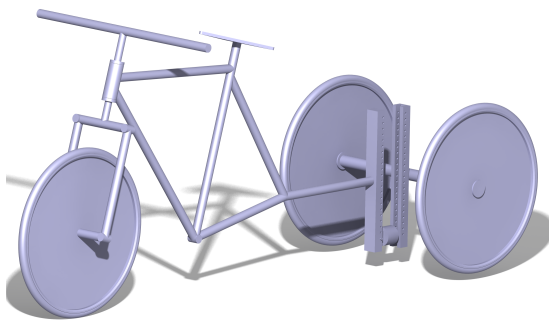
The method for verifying the dynamics was not given at the start of the project and this also had to be explored to find a solution that could be completed within a reasonable time frame. After a set of methods were tried out, it was decided to use previous research done on similar prototypes, and geometrical experiments on a simple CAD model of the vehicle.

In a normal bike, the axis of tilt remains on the ground connecting the two contact patches of the front and the rear wheel. The contact patch of the front wheel will also always be aligned with the central axis of the bike. The front contact patch will also always be aligned in the middle of a normal, rigid, trike. When introducing a tilting mechanism in a trike, the front wheel contact patch can move laterally in different magnitudes depending on how the tilting system is designed (D'Hondt, Juwet, et al., 2022). To get a better understanding of this phenomenon, an experiment similar to the one in D'Hondt, Juwet, et al. (2022) was conducted using CAD to understand how the geometry and placement of the tilting mechanism could influence the riding behaviour of the vehicle.

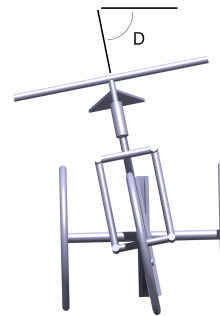
A simple CAD model as shown in Figure 4.2 of the vehicle was created in CATIA along with a hinge arrangement at the rear part in order to observe the movement

of the front wheel when the front part of the vehicle is tilted. Four main variables were considered in the test and a DOE (Design of Experiments) table was created in order to record results for varying conditions and their depictions are shown in Figures 4.3, 4.4 and 4.5. The variables were as follows:

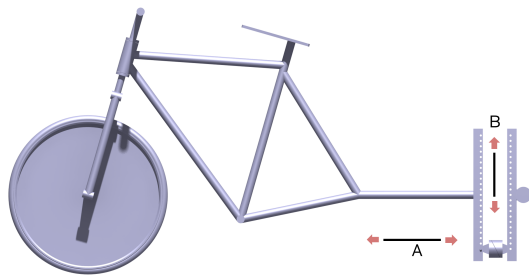
- Longitudinal distance (A) - The movement of the whole tilt setup front and back along the longitudinal direction of the vehicle.
- Vertical distance (B) - The movement of the hinge up and down along the vertical direction perpendicular to the ground.
- Inclination of tilt setup (C) - Angle of the tilt axis with respect to ground (horizontal, inclined upwards, inclined downwards).
- Angle of tilt (D) - The angle at which the front part of the vehicle is tilted (while taking a turn).



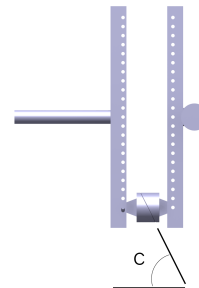
**Figure 4.2:** Simplified CAD model.



**Figure 4.3:** Angle of tilt.



**Figure 4.4:** Longitudinal and vertical distance.



**Figure 4.5:** Inclination of tilt setup.

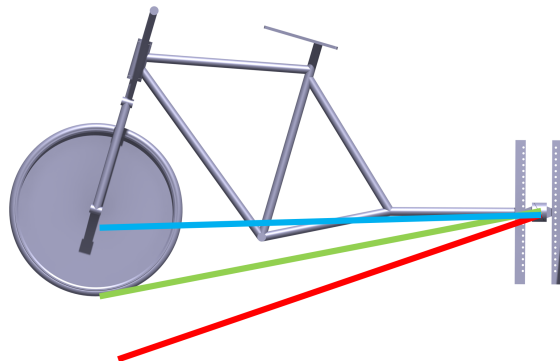
During the experiment, four different positions of the tilt setups were tried out. First, the setup was placed along the frame at the mid-height at a distance of 305 mm from the rolling axis of the rear wheels. Second, the setup was moved back and placed along the frame at mid-height at a distance of 105 from the rolling axis of the rear wheels. Third, the longitudinal distance (A) was kept the same as the second setup and the vertical distance (B) was changed to 95 mm from the ground. Fourth, the longitudinal distance (A) was kept the same again and the vertical distance (B) was changed to 495 mm from the ground. For all four setups the inclination of tilt setup (C) was varied ( $3^\circ$ ,  $7^\circ$ ,  $10^\circ$ ,  $12^\circ$ ,  $15^\circ$ ,  $17^\circ$ ) for both upward inclination and downward inclination. Also, the angle of tilt (D) was varied ( $10^\circ$ ,  $12^\circ$ ,  $15^\circ$ ,  $17^\circ$ ,  $20^\circ$ )

along with that. An example of the acquired data is shown for one setup.

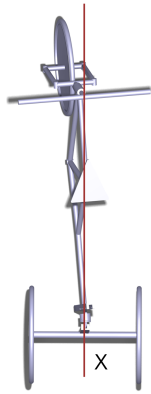
The experiment was performed such that the vehicle was taking a right turn. In the real-life scenario, the point of contact of the front wheel with the ground will slightly move forwards as the vehicle is being turned but an assumption was made that it stays in the same position throughout the turn for simplification of the model. This assumption is expected to be reasonable since this mentioned distance would be negligible. The offset distance is the distance between the contact point of the wheel with the ground and the central axis (X) between the rear wheels and having the offset distance as zero means that the behaviour is similar to a bike. Positive values are the distance values when the contact point moves to the left of the central axis and the negative values are the opposite where the contact point moves to the right of the central axis.

A few important inferences were made from D'Hondt, Juwet, et al. (2022) and from this experiment which played a big role in understanding the dynamic behaviour of the vehicle. This helped in the decision on where to fix the position of attachment of the tilt system on the vehicle. The inferences were as follows:

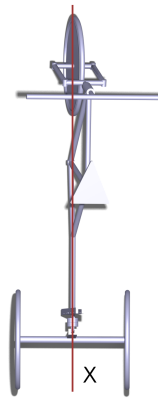
- When the angle of the tilt axis (C) makes the axis coincide with the contact patch of the front wheel, like the green line in Figure 4.6, there is zero lateral movement when leaning the frame to the side as shown in Figure 4.8. When the inclination of the tilt setup is upward the point of contact of the front wheel, like the blue line in Figure 4.6, the wheel moves to the left of the central axis (X) during a right turn as shown in Figure 4.7. When the inclination of the tilt setup is downwards the point of contact of the front wheel, like the red line in Figure 4.6, the wheel moves to the right of the central axis (X) during a right turn as shown in Figure 4.9. It was also shown that the amount of lateral movement increased with an increasing change in inclination angle.
- The longitudinal and height positioning of the tilt mechanism will also have an effect on the lateral movement, only because it changes where the tilt axis coincides with the ground. If the axis coincides in front of the front contact patch, the effect seen in Figure 4.7 will be had. If it coincides with the front contact patch, the opposite will happen seen in Figure 4.9.



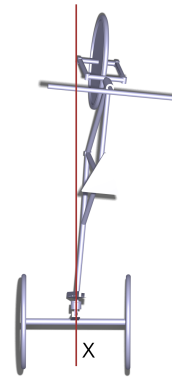
**Figure 4.6:** Examples of tilt angles tested.



**Figure 4.7:** Upward angle of tilt.



**Figure 4.8:** Tilt angle aligns with front wheel contact patch.



**Figure 4.9:** Downward angle of tilt.

This was just a static experiment through which the rider's comfort could not be quantified. So, a reference was acquired from D'Hondt, Juwet, et al. (2022) who have also performed a similar experiment by making a physical prototype which proved that the users found it more comfortable with a slight downwards inclination angle. Thus it is believed that the best design is to have the tilt axis coincide with the front contact patch. An added benefit of having this specific angle is that the rear frame will always stay horizontal. If the angle was higher or lower, the rear frame will start tilting backwards or forwards respectively. This could become an issue if you have cargo on the frame. The weight could make leaning the front frame more difficult.

Having the inclination angle forwards might make the rider feel as if he/she is leaning forwards while riding. To minimize this potential effect it is also believed that it is better to have the tilting mechanism as close to the ground as possible to make the inclination angle as small as possible, while still coinciding with the front contact patch.

Also, another factor which involves the load-taking capability of the tilt system was considered with respect to its position. The higher the bending moment due to the user weight will act on the system if it is in the front part of the vehicle. To counteract this problem and to lessen the load the tilt system has to be moved to the back of the vehicle, most likely close to the center of the rear wheels. Combining all these findings the decision was made to have the tilt system at the lower back part of the vehicle with a small downward inclination angle to coincide with the front contact patch.

## 4.4 Idea Generation

The useful results from all the idea generation processes are given in Tables 4.3 and 4.4. Some of the ideas which cannot be directly understood from the list have been given a detailed explanation with images in Appendix A.

**Table 4.3:** Idea generation results.

Subfunction	Solution(s)
Transport goods/children	<ul style="list-style-type: none"> <li>• Different boxes</li> <li>• Same box with foldable seats</li> <li>• Same box with removable seats</li> </ul>
Easily switch cargo configuration	<ul style="list-style-type: none"> <li>• Clasps</li> <li>• Rail</li> <li>• Thumbscrews</li> <li>• Beetle fastener</li> <li>• Bolts</li> </ul>
Improve comfort for passengers	<ul style="list-style-type: none"> <li>• Springs in seat</li> <li>• Suspension in frame</li> <li>• No suspension</li> </ul>
Allow for tilting of front part	<ul style="list-style-type: none"> <li>• Tubes attached with bearings</li> <li>• Four bar linkage</li> <li>• Rail</li> <li>• Cup rack</li> <li>• Flat bearings without tubes</li> </ul>
Push inner wheel down into the ground when in a turn	<ul style="list-style-type: none"> <li>• Two springs on sides</li> <li>• Torsion spring around shaft</li> <li>• Spring lever</li> <li>• Neidhart spring</li> <li>• V-spring</li> </ul>
Prevent loss of balance at slow speeds	<ul style="list-style-type: none"> <li>• Pin spring system</li> <li>• Tilt brake</li> <li>• Sawtooth</li> </ul>
Protect rider from splash	<ul style="list-style-type: none"> <li>• Mud guard</li> </ul>
Protect cargo from splash	<ul style="list-style-type: none"> <li>• Glass protection</li> <li>• Mud guards</li> <li>• Rear wheels 'built into' cargo box</li> <li>• Front facing visor</li> </ul>
Display data	<ul style="list-style-type: none"> <li>• Digital display on handlebars</li> <li>• LED</li> <li>• Sound feedback</li> <li>• Haptic feedback</li> <li>• Phone integration</li> <li>• Display integrated in front light housing</li> <li>• Indicators on frame below handle</li> </ul>
Allow vehicle to roll forward	<ul style="list-style-type: none"> <li>• Airless tires</li> <li>• Air tires</li> </ul>
Provide user with good SA	<ul style="list-style-type: none"> <li>• Rear view mirror</li> <li>• Proximity alarm (light and sound)</li> <li>• Camera</li> </ul>

**Table 4.4:** Idea generation results continued.

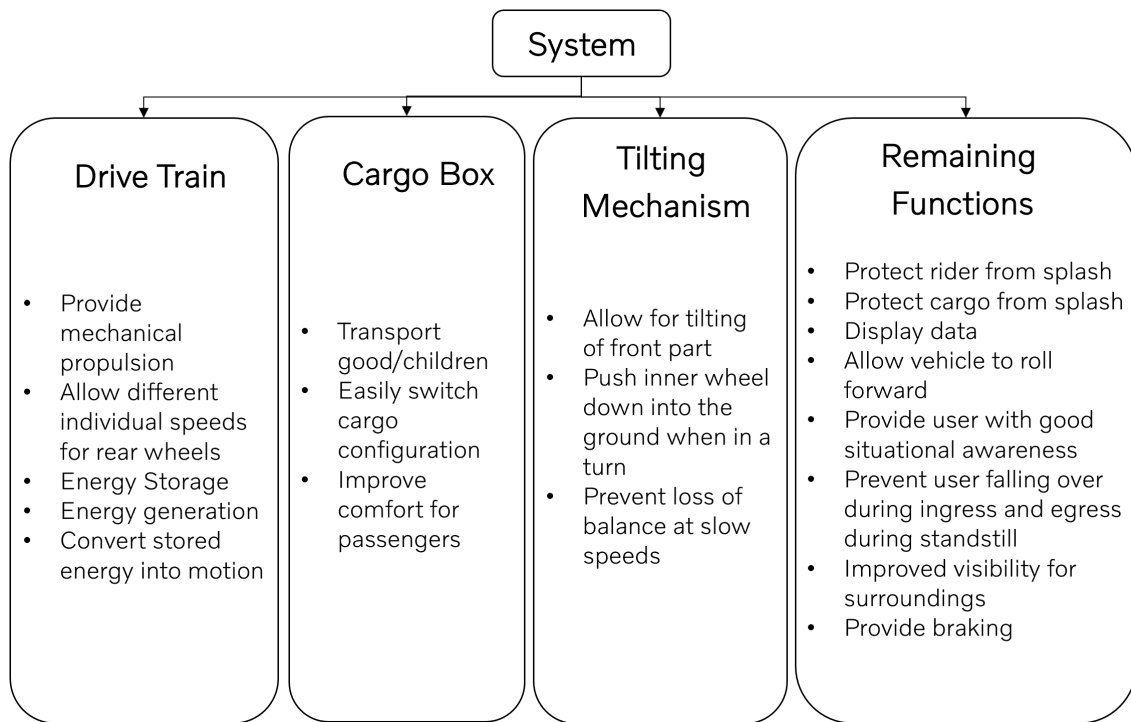
Subfunction	Solution(s)
Provide braking	<ul style="list-style-type: none"> <li>• Regenerative braking</li> <li>• Disc brake</li> <li>• Rim brake</li> <li>• Drum brake</li> <li>• Electromagnetic brake</li> </ul>
Prevent user falling over during ingress and egress during standstill	<ul style="list-style-type: none"> <li>• Bar less frame</li> <li>• Hand brake</li> </ul>
Energy storage	<ul style="list-style-type: none"> <li>• Battery</li> </ul>
Energy generation	<ul style="list-style-type: none"> <li>• Generator</li> </ul>
Convert stored energy into motion	<ul style="list-style-type: none"> <li>• Electric motor</li> </ul>
Provide mechanical propulsion	<ul style="list-style-type: none"> <li>• Chain drive</li> <li>• Belt drive</li> <li>• Pedals powering generator</li> </ul>
Allow different individual speeds for rear wheels	<ul style="list-style-type: none"> <li>• Hub motors</li> <li>• Differential</li> <li>• Motors connected with individual drivetrain</li> </ul>
Improved visibility for the surroundings	<ul style="list-style-type: none"> <li>• Front/rear lights</li> <li>• Reflectors</li> <li>• Bell</li> </ul>

## 4.5 Concept Generation and Evaluation

The different methods used in order to generate innovative concepts and the process of evaluating them at multiple levels have been discussed in this section. The explanation and reasoning behind the decisions taken at each step are also talked about in detail.

### 4.5.1 System Layout

The four main groups are namely drivetrain, cargo box, tilting mechanism and all the other remaining subfunctions as one group as shown in Figure 4.10. This segregation was done to make the process easier and to provide more concentration towards the specific subsystems while creating concepts. At the same time, the synergies between different subsystems were also important. They were listed out clearly before starting the process and were included in the whole discussion when generating subsystem-level concepts.



**Figure 4.10:** Function classification for system layout.

### 4.5.2 Concept Selection for Drive Train System

A morphological matrix was not used in the case of the choice of the solutions for the drive train system. The main reason was that there were only one or two ideas through which the subfunctions present in the system could be solved and there was not much need for a matrix as it will only result in the variations of the same concept. For example, the subfunctions *Energy storage* and *Energy generation* just had the solutions as *Battery* and *Generator* respectively.

The problem of mechanical propulsion could be solved either by having a chain drive similar to a normal bike or by having a generator fitted to the pedals and powering motors that could be fitted to the wheels. This decision was a bit hard to make because both the solutions were completely different and the optimal one for the current case had to be chosen. In order to make a sensible choice the advantages and disadvantages of both solutions were analysed and compared to each other.

The main advantage of using a chain drive was that it is more efficient compared to the electric drive and considering that the vehicle will take some load at the back the efficiency of the drive train plays a big role while travelling on slopes. Also, it has a simple construction without any wires and electrical components which makes it easily repairable. The biggest disadvantage of this system was that although the chain setup is pretty simple, in this particular case the front part of the vehicle had to tilt. This implied that the complete chain drive system had to tilt in a turn and that increased the complexity of the mechanical construction at so many levels. There was a need for a separate mechanical system to compensate for the tilt such

that the chain does not get dismounted from the sprocket every time the user takes a turn.

On the other hand, the advantage of the series hybrid drive train is that it eliminates the complexity while tilting because in this case it's just the wires that tilt along with the frame and they can be easily packaged inside the frame. So, having this solution eliminates the need for a separate mechanical system which has to support the drive system while tilting giving this a big upper hand over the other. In addition, the height of the base of the cargo box from the ground could be lowered while using this solution. This was because when a chain drive is used the sprockets at the front and the back have to be around the same level for effective transfer of power. Whereas in an electric drive, the frame could be just bent down a bit to lower the cargo box level and this acted as an added advantage. The disadvantage of this system is the efficiency, and when used without any extra source of power, it will need extra human effort to drive the vehicle. However, this problem can be easily solved by installing batteries in the vehicle which can be charged so that the pedaling effort could be used to charge the batteries on the way and the batteries can be used to directly power the vehicle. In case the battery charge runs out, the user is not stranded on the way and can still pedal back home.

Considering the advantages and disadvantages of both it was deduced that the electric drive system had better advantages and also the problems in it were easily solvable.

Finally, to solve the subfunction *Allow different individual speeds for rear wheels* the two main solutions were either using hub motors at the back wheels or a differential. Once the decision of using an electrical drive was made it seemed better to use hub motors at the back wheels which can have different controllers to solve the problem. Using a differential will still add up to mechanical complexity and so that idea was given up. One problem is that the system becomes too dependent on the electrical systems and controllers which demands the need for high-quality software increasing the cost of the vehicle. But the mechanical complexity factor was given a higher priority and the choice of using electric drive systems with hub motors was made.

### **4.5.3 Concept Selection for Cargo Box**

Unlike the selection of the drive train system, there existed multiple solutions in the case of cargo box selection. So a Pugh matrix was used in combination with a morphological matrix in order to evaluate the generated solution concepts. The steps followed using these two methods are explained in this section.

#### **4.5.3.1 Morphological Matrix for Cargo Box**

This morphological matrix was completely about the concepts for the cargo box taking the subfunctions *Transport goods/children*, *Easily switch cargo configuration* and *Improve comfort for passengers* into consideration as shown in Table 4.5. Initially,

cargo and children were supposed to be handled separately. Later, it was realized that there was not much use in having them separately and they were combined together. So, two main variations present in this matrix were that the vehicle was supposed to have different boxes for each purpose or the same box with modular fitting to solve the need.

Though the subfunctions were separated into groups there was still a big scope of concepts that could be generated from the matrix, but the aim was to keep the concepts diverse. Following that, seven concepts as shown in Table 4.5 were generated where the possible ideas were integrated with the two main variations mentioned above taking the synergies and compatibility into consideration. For example, the concept of having different boxes for goods and children can be fitted to the frame with the help of bolts or clasps and a rail setup could be used for fitting the modular chairs to the box. Each of the concepts was named after different materials instead of numbering them in order to easily recognize a specific concept.

**Table 4.5:** Morphological matrix for cargo box system.

<b>Function</b>	<b>Steel</b>	<b>Iron</b>	<b>Wood</b>	<b>Rubber</b>	<b>Gold</b>	<b>Silver</b>	<b>Platinum</b>
<b>Transport goods/ children</b>	Different boxes	Same box with foldable seats	Same box with removable seats	Different boxes	Same box with removable seats	Different boxes	Same box with removable seats
<b>Easily switch cargo configuration</b>	Clasps		Thumb screws	Beetle fastener	Bolts	Rail	Rail
<b>Improve comfort for passengers</b>	Springs in seat	Suspension in frame	Springs in seat	No suspension	Springs in seat	No suspension	Springs in seat

#### 4.5.3.2 Pugh Matrix for Cargo Box

Nine different criteria as shown in Table 4.6 were considered while ranking the concepts such that they covered all the aspects which make the vehicle better. Between the two main variations which were using different boxes or using the same box with modular fittings, it was found that having the same box the whole time was a much better option. That could be seen clearly in the concepts *Iron*, *Wood*, *Gold* and *Platinum* as shown in Table 4.6. This was decided by considering the fact that it takes longer time and more effort to change the whole box every time. For the same reason, the usage of a rail system proved better than the others for fitting modular seats into the box. In addition to that, both having springs on the seat or having suspension on the frame seemed to improve the comfort factor. In the end, the concept *Platinum* scored high but not only that was taken over to the next step but also the concepts *Gold* and *Wood* which had some potential to combine each other. There was a possibility to make more iterations to achieve convergence but

as the scores were very distinct, it was decided to proceed with just one iteration.

**Table 4.6:** Pugh matrix for cargo box system.

Criteria	Steel	Iron	Wood	Rubber	Gold	Silver	Platinum
Usability	0	+	+	0	+	0	+
Safety	0	+	+	-	+	+	+
Durability	0	-	0	0	0	0	0
Capacity	0	-	0	0	0	0	0
Number of parts	0	-	0	+	0	0	0
Comfort	0	+	0	-	0	-	0
Ease of manufacturing	0	-	0	+	0	+	0
Setup time	0	+	-	0	-	0	+
Cost	0	0	+	0	+	0	+
Sum +’s		4	3	2	3	2	4
Sum 0’s		1	5	5	5	5	5
Sum -’s		4	1	2	1	1	0
Net Score		0	2	0	2	1	4
Rank		4	2	4	2	3	1

#### 4.5.4 Concept Selection for Tilting Mechanism System

Similar to the selection of cargo box concepts, morphological and Pugh matrices were again used for the generation and selection of tilting mechanism concepts. The subfunctions considered and the base criteria on which they were evaluated are discussed in this section.

##### 4.5.4.1 Morphological Matrix for Tilting Mechanism System

This morphological matrix mainly deals with the different types of tilting mechanisms of the vehicle taking the subfunctions *Allow for tilting of front part*, *Push the inner wheel down into the ground when in a turn* and *Prevent loss of balance at slow speeds* as shown in the Table 4.7. The ideas generated to solve this were inspired by different patents, other tilt systems in existing products or created by the team members of the project. As this system of the vehicle was very crucial compared to the previous system a bit more concepts summing up to nine were generated from the matrix. The concepts were named after food in order to avoid any confusion similar to the previous case. Also, compared to the previous system the variety of solution combinations was also more which accounted for more number of distinct concepts.

**Table 4.7:** Morphological matrix for tilting mechanism system.

Function	Sushi	Pancake	Meatball	Kebab	Pizza
Allow for tilting of front part	Tubes attached with bearings	Rail	Cup rack	Flat bearing without tubes	Flat bearings without tubes
Push the inner wheel down into the ground when in a turn	Two springs on sides	Two springs on sides		Torsion spring around shaft	Two springs on sides
Prevent loss of balance at slow speeds	Tilt brake	Tilt brake	Tilt brake	Pin spring system	Pin spring system
Function	Butter Chicken	Taco	Crepe	Carbonara	
Allow for tilting of front part	Four bar linkage	Tubes attached with bearings	Tubes attached with bearings	Flat bearings without tubes	
Push the inner wheel down into the ground when in a turn	Two springs on sides	Neidhart spring	V-spring	Spring lever	
Prevent loss of balance at slow speeds	Pin spring system	Pin spring system	Sawtooth	Sawtooth	

#### 4.5.4.2 Pugh Matrix for Tilting Mechanism System

Comparatively, it was a bit hard to carry out the evaluation of the tilting systems as they were working mechanical systems and not so easy to visualize their performance. But due to the constriction on time and resources for the project, a few more criteria which apply to this case were added and the evaluation process was performed as usual.

Based on the previous research that was done, the solutions such as the *Four bar linkage* and *Rail* would perform the best in terms of tilting because these solutions push down the axis of tilt to the ground level exactly similar to a bike. The issue was that both these solutions take up a large amount of weight and space in the vehicle which was not desirable and therefore they were not given that much preference. Also, the *Cup rack* solution had a bit of mechanical complexity and the whole behaviour of the tilt will be affected by having that in place, so those concepts had a lower scoring. Solutions having the bearing had a better score at performance as well as the weight so they seemed more desirable.

Considering the mechanism to push down the inner wheel, the solutions were mostly

related to having springs. The variation was just the type of springs and type of attachments in the vehicle. In addition, for preventing loss of balance at slow speed the solution *Tilt brake* which is nothing but a modified disc brake attached proved to be bad as it has the ability to lock the vehicle at any tilted position. This could cause the vehicle to lock in an unusual position leading to problems while driving. In the end, the concepts *Kebab*, *Pizza* and *Carbonara* scored the highest and along with them the concept *Taco* was also taken to the next step. In total, four concepts were proceeded with and there was a distinct difference in the scoring compared to the other concepts as shown in the Table 4.8.

**Table 4.8:** Pugh matrix for tilting mechanism system.

Criteria	Sushi	Pan-cake	Meat ball	Kebab	Pizza	Butter Chicken	Taco	Crepe	Carbonara
Usability	0	0	0	+	+	+	+	+	+
Safety	0	-	0	+	+	-	+	0	+
Durability	0	0	+	0	0	0	0	0	0
Ride feel	0	+	0	0	0	+	0	0	0
Number of parts	0	-	-	+	+	-	0	-	+
Ease of manufacturing	0	-	-	+	+	+	-	-	+
Weight	0	-	0	0	0	0	+	0	0
Space required	0	-	-	0	0	-	+	0	0
Cost	0	-	-	0	0	0	-	0	0
Sum +'s		1	1	4	4	3	4	1	4
Sum 0's		2	4	5	5	3	3	6	5
Sum -'s		6	4	0	0	3	2	2	0
Net Score		-5	-3	4	4	0	2	-1	4
Rank	3	6	5	1	1	3	2	4	1

#### 4.5.5 Concept Selection for Remaining Subfunctions

The use of morphological and Pugh matrices in combination proved to be a very good method considering the concept generation selection for the previous two systems. So, the same strategy was followed for proceeding with the remaining subfunctions too.

##### 4.5.5.1 Morphological Matrix for Remaining Subfunctions

Considering the remaining subfunctions, only half of them which were *Protect rider from splash*, *Protect cargo from splash*, *Display data*, *Allowing vehicle to roll forward*, *Provide user with good situational awareness* and *Provide braking* were used in the morphological matrix to generate new concepts as shown in the Table 4.9. The remaining two subfunctions such as *Prevent user falling over during ingress and egress during standstill* and *Improved visibility for surroundings* had only one solution or was very obvious to choose so they were not included in this matrix. Six

different concepts were generated in total and were named after fruits to recognize them easily.

**Table 4.9:** Morphological matrix for remaining functions.

Criteria	Apple	Orange	Pear	Watermelon	Grape	Pineapple
<b>Protect rider from splash</b>	Mud Guards	Mud Guards	Mud Guards	Mud Guards	Mud Guards	Mud Guards
<b>Protect cargo from splash</b>	Glass protection	Rear wheels 'built into' cargo box	Front facing visor	Glass protection	Front facing visor	Mud Guards
<b>Display data</b>	Digital display on handlebars	Digital display on handlebars + Sound feedback + Haptic feedback	Display integrated in front light housing	Phone integration + Sound feedback + Haptic feedback	LED	Indicators on frame below handle
<b>Allowing vehicle to roll forward</b>	Airless tire	Air tires	Air tires	Airless tire	Air tires	Airless tire
<b>Provide user with good SA</b>	Rear view mirror	Rear view mirror	Camera	Camera		Proximity alarm (light and sound)
<b>Provide braking</b>	Regenerative braking + Disc brake	Regenerative braking + Disc brake	Regenerative braking + Rim brake	Regenerative braking + Electro magnetic brake	Regenerative braking + Rim brake	Regenerative braking + Drum brake

#### 4.5.5.2 Pugh Matrix for Remaining Subfunctions

Similar to the previous Pugh matrices a comparison was made and the ideas making a particular concept stand out were identified. In the case for *Protect cargo from splash* as shown in Table 4.10 it was visible that using the built-in mudguards into the rear wheels was better as they had a good effect on the looks of the vehicle and also improved safety because the hands of the children will not get in contact with the wheels. Using a simple visor also seemed better instead of using glass as it weighed heavier and was not so easy to maintain. Looking into the tires, as the vehicle did not have any kind of separate suspension systems, the comfort could be provided better only by the use of air tires instead of airless tires.

For the subfunction *Provide user with good situational awareness* the usage of camera or proximity alarms could work well but they seemed a bit advanced as the user themselves can easily look at the rear part of the vehicle. So, the usage of rearview mirrors was a simple and cheap solution that could fit well. In addition, the usage of

disc brakes appeared to be very effective from the research done on different types of brakes. The rim brakes were a bit more simple construction but considering the weight of the vehicle and the load that it will carry at the back, usage of disc brakes seemed to be a better fit. When all these patterns were identified, it was obvious that the concepts *Orange* and *Grape* scored the highest with a higher margin compared to the others. As the above-mentioned points were shared equally between the two concepts the best ideas were taken from them and a new concept was created combining both right away.

**Table 4.10:** Pugh matrix for remaining functions.

Criteria	Apple	Orange	Pear	Watermelon	Grape	Pineapple
Useability	0	0	0	+	-	0
Safety	0	+	-	0	-	0
Durability	0	+	-	0	+	-
Number of parts	0	0	0	-	+	0
Comfort	0	+	+	0	+	-
Ease of manufacturing	0	-	-	-	+	-
Cost	0	-	-	-	+	-
Sum +'s		3	1	1	5	0
Sum 0's		2	2	3	0	3
Sum -'s		2	4	3	2	4
Net Score		1	-3	-2	3	-4
Rank	3	2	5	4	1	6

## 4.6 Detailed Concept Generation and Evaluation

At this point, several distinct concepts were generated for different systems and were evaluated with the help of Pugh matrices. Then, there was a need for creating a combination of those which results in complete vehicle concepts. As the functions were split up in the previous steps, the process of creating complete concepts became a bit simplified. The methods used for the generation and evaluation of complete concepts along with justifications are discussed in this section.

### 4.6.1 Morphological Matrix for Complete Concept Generation

For the complete concept generation, a morphological matrix was used in order to combine the several system concepts. A few of the solutions were fixed already. For example, the ones for the drivetrain system were decided prior so those were fixed for all the concept variations when used in the matrix. The subfunctions for which the solutions were fixed before proceeding with the matrix are *Prevent user falling over during ingress and egress during standstill*, *Energy storage*, *Energy generation*, *Convert stored energy into motion*, *Allow different individual speeds for rear wheels*, *Improved visibility for the surroundings* and *Provide mechanical propulsion*.

In total, five different complete concepts were generated with the help of the matrix, and they were named randomly after different cities to differentiate them from each

#### 4. Concept Development

other as shown in Tables 4.11 and 4.12. To avoid the generation of all the possibilities from the matrix concepts were formed on different themes such as expensive (Stockholm), mid-range (San Diego), cheap (Berlin), ideal (Delhi), and eco-friendly (Auckland). Though they were of different themes, it was possible that not all solutions from a concept would be kept. It was kept in mind to combine the most effective ones from different concepts. Following all concepts are presented.

**Table 4.11:** Morphological matrix for complete concept generation.

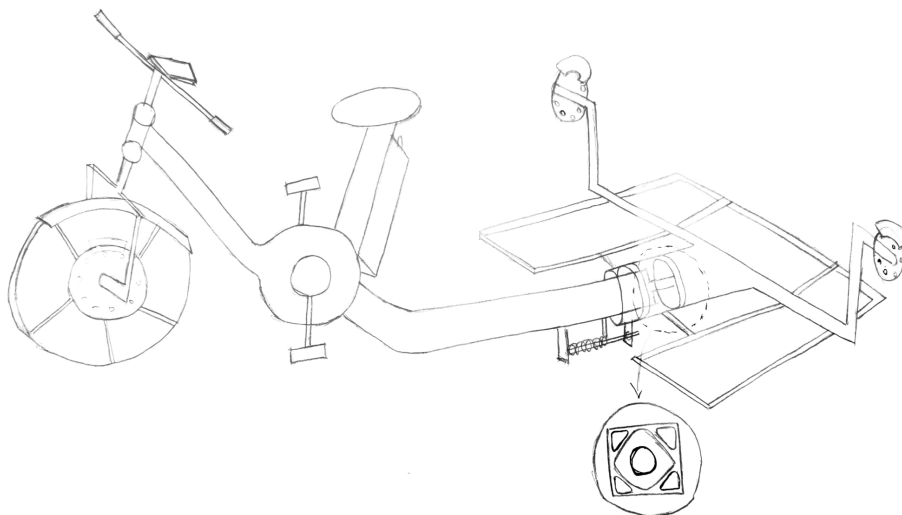
Criteria	Stockholm	Berlin	San Diego	Delhi	Auckland
<b>Cargo</b>	Same box with removable seats	Same box with removable seats	Same box with removable seats	Same box with removable seats	Same box with removable seats
<b>Easily switch cargo setup</b>	Rail	Thumbscrews	Bolts	Rail	Bolts
<b>Suspension</b>	Springs in seat	Springs in seat	Springs in seat	Springs in seat	Springs in seat
<b>Tilting mechanism</b>	Tubes attached with bearings	Flat bearings without tubes	Flat bearing without tubes	Tubes attached with bearings	Flat bearings without tubes
<b>Resisting mechanism</b>	Neidhart spring	Spring lever	Torsion spring around shaft	Neidhart spring	Two springs on sides
<b>Tilt lock mechanism</b>	Pin spring system	Sawtooth	Pin spring system	Pin spring system	Pin spring system
<b>Protect rider from splash</b>	Mud guards	Mud guards	Mud guards	Mud guards	Mud guards
<b>Protect cargo from splash</b>	Rear wheels 'built into' cargo box	Front facing visor	Rear wheels 'built into' cargo box	Rear wheels 'built into' cargo box	Front facing visor
<b>Display data</b>	Digital display on handlebars + Sound feedback + Haptic feedback	LED	Digital display on handlebars	Digital display on handlebars	LED
<b>Allowing vehicle to roll forward</b>	Air tires	Air tires	Air tires	Air tires	Air tires
<b>Provide user with good SA</b>	Rear view mirror				
<b>Provide braking</b>	Regenerative braking + Disc brake	Regenerative braking + Rim brake	Regenerative braking + Disc brake	Regenerative braking + Disc brake	Regenerative braking + Rim brake
<b>Prevent user falling over during ingress and egress during standstill</b>	Bar less frame + hand brake	Bar less frame + hand brake	Bar less frame + hand brake	Bar less frame + hand brake	Bar less frame + hand brake

**Table 4.12:** Morphological matrix for complete concept generation continued.

Criteria	Stockholm	Berlin	San Diego	Delhi	Auckland
<b>Energy storage</b>	Battery	Battery	Battery	Battery	Battery
<b>Energy generation</b>	Generator	Generator	Generator	Generator	Generator
<b>Convert stored energy into motion</b>	Electric motor	Electric motor	Electric motor	Electric motor	Electric motor
<b>Provide mechanical propulsion</b>	Pedals powering generator	Pedals powering generator	Pedals powering generator	Pedals powering generator	Pedals powering generator
<b>Allow different individual speeds for rear wheels</b>	Motors connected with individual drivetrain	Motors connected with individual drivetrain	Motors connected with individual drivetrain	Motors connected with individual drivetrain	Motors connected with individual drivetrain
<b>Improved visibility for the surroundings</b>	Front/rear lights + Reflectors + Bell	Front/rear lights + Reflectors + Bell	Front/rear lights + Reflectors + Bell	Front/rear lights + Reflectors + Bell	Front/rear lights + Reflectors + Bell

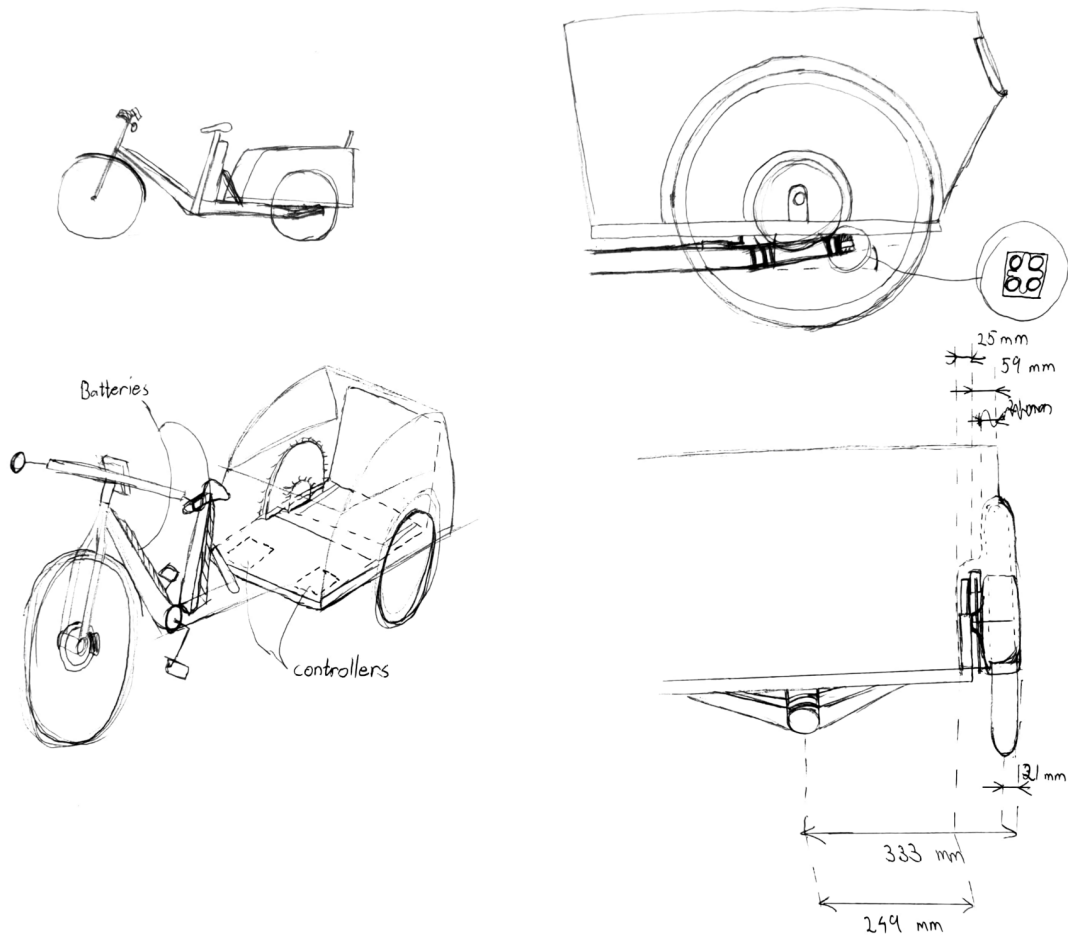
#### 4.6.1.1 Concept Delhi

The Delhi concept was designed to be the most ideal concept, utilizing a good mix of solutions that were not too advanced, but also skipping the cheapest options. The result is shown in Figure 4.11. The batteries are mounted in the front frame, one in the main bar connecting the mid bracket with the front fork, and one in the seat post bar. It also uses a U-shape design for the rear frame where the center of the rear wheels will be above the bottom of the cargo platform. This should allow for a lower center of gravity.

**Figure 4.11:** A sketch of the Delhi concept vehicle.

### 4.6.1.2 Concept Stockholm

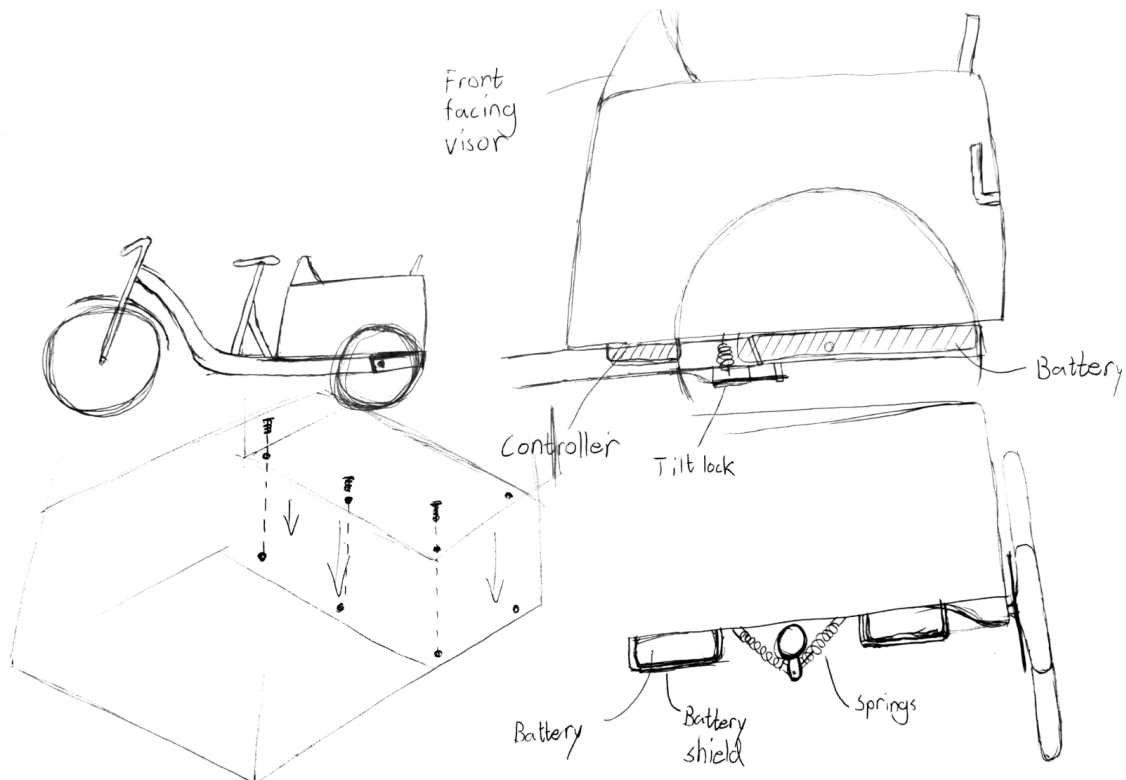
The Stockholm concept, as shown in Figure 4.12, is similar to the Delhi concept, only that it has slightly more advanced components such as haptic and sound feedback for the rider to give information not only on the display of the vehicle. The batteries are also mounted in the frame, and it also uses the same U-shaped rear frame to keep the center of gravity low.



**Figure 4.12:** A sketch of the Stockholm concept vehicle.

#### 4.6.1.3 Concept Auckland

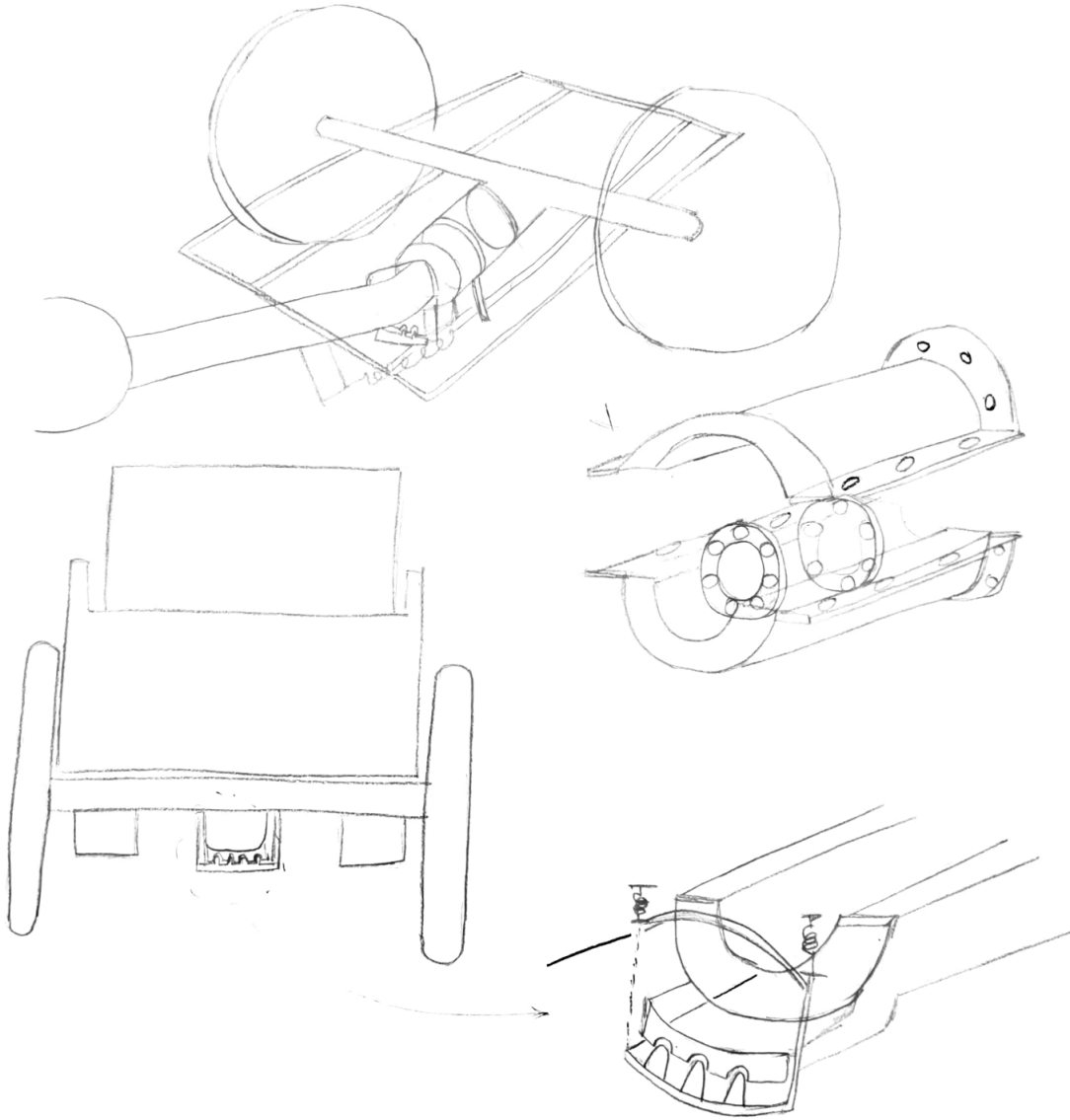
The idea behind the Auckland concept was to reduce electronics use and thus become a bit less damaging for the environment and simpler. This concept has the batteries assembled underneath the rear frame, shown in Figure 4.13. This should help reduce the center of gravity of the vehicle slightly compared to having them in the front frame. It also does not use a U-shaped frame in the rear and instead has the bottom of the cargo platform mounted parallel to the center of the rear wheels which makes the cargo platform sit a little higher.



**Figure 4.13:** A sketch of the Auckland concept vehicle.

#### 4.6.1.4 Concept Berlin

The Berlin concept was made to be as cheap and simple as possible and thus has less advanced solutions. It is also the only concept using the sawtooth tilt lock mechanism as shown in Figure 4.14. The concept has its batteries mounted underneath the front frame and no U-shaped frame.



**Figure 4.14:** A sketch of the Berlin concept vehicle.

#### 4.6.1.5 Concept San Diego

Lastly, the San Diego concept was designed as a middle ground in terms of advanced solutions to include as much in the spectrum as possible for the concept selection stage. The batteries of this one are mounted in the front frame similar to the Stockholm and Delhi concepts. It also uses a U-shaped rear frame as shown in Figure 4.15 to lower the center of gravity.

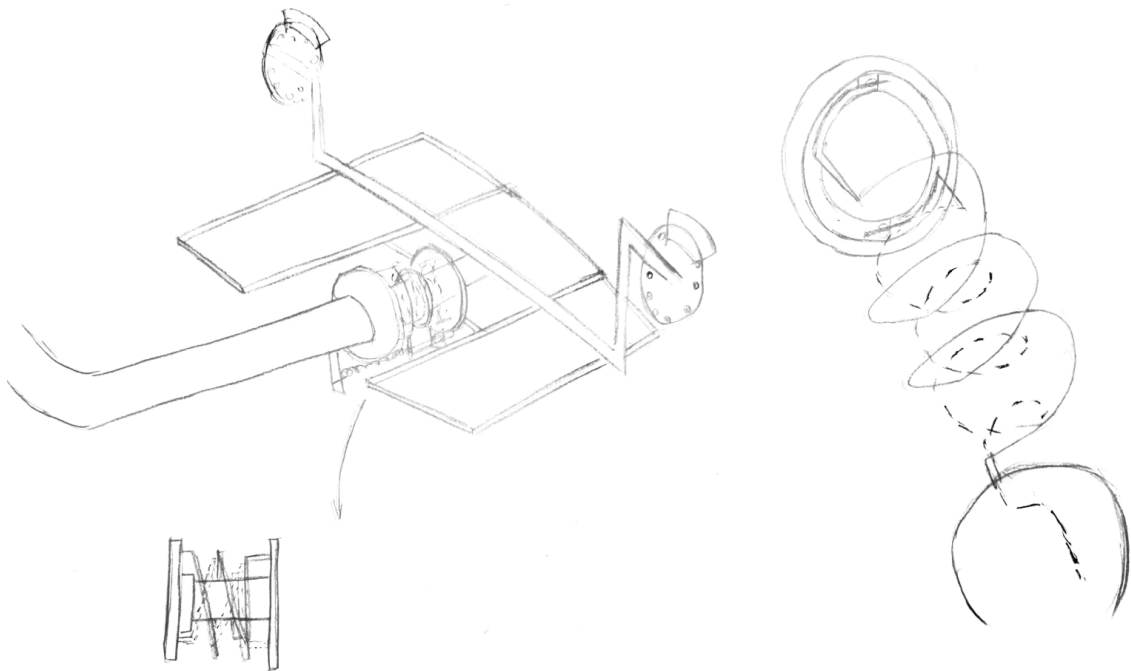


Figure 4.15: A sketch of the San Diego concept vehicle.

#### 4.6.2 Kesselring Matrix for Evaluation of Complete Concepts

To compare the concepts, nine different main categories were used for evaluation, with respective subcategories:

- Functionality
- Usability
- Safety
- Ergonomics
- Electronics placement
- Mobility
- Durability
- Capacity
- Other

The results from the Kesselring matrix are shown in Tables 4.13 and 4.14.

The matrix showed that Stockholm and Delhi were the top-scoring concepts, with scores of 3,29 and 3,27. Compared to the rest of the concepts, the scores are not

**Table 4.13:** Kesselring matrix for the complete concepts.

Selection Criteria	Weight	Stockholm (expensive)			Berlin (cheap)			San Diego (mid-range)		
		Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	
<b>Functionality</b>	<b>18,0%</b>		<b>0,53</b>		<b>0,51</b>		<b>0,44</b>		<b>0,44</b>	
Lightweight	4,0%	2	0,08		0,12	4	0,16		0,16	
Sustainable (material use, amount of electronics etc)	4,0%	3	0,12	3	0,12	3	0,12		0,12	
Sturdiness (Construction)	7,0%	3	0,21	3	0,21	1	0,07		0,07	
Display useful information (speed, battery level, etc.)	3,0%	4	0,12	2	0,06	3	0,09		0,09	
<b>Useability</b>	<b>9,0%</b>		<b>0,32</b>		<b>0,27</b>		<b>0,11</b>		<b>0,11</b>	
Easy to clean/wipe off	2,0%	2	0,04	3	0,06	2	0,04		0,04	
Ease of fitting chairs in cargo box	7,0%	4	0,28	3	0,21	1	0,07		0,07	
<b>Safety</b>	<b>16,0%</b>		<b>0,58</b>		<b>0,59</b>		<b>0,58</b>		<b>0,58</b>	
Protects from weather	2,0%	4	0,08	3	0,06	4	0,08		0,08	
Protects from rolling over	5,0%	3	0,15	3	0,15	3	0,15		0,15	
Protects from falling over	5,0%	3	0,15	2	0,1	3	0,15		0,15	
Braking power	4,0%	5	0,2	2	0,08	5	0,2		0,2	
<b>Ergonomics</b>	<b>12,0%</b>		<b>0,47</b>		<b>0,29</b>		<b>0,47</b>		<b>0,47</b>	
Battery placement (ease of switching)	7,0%	5	0,35	2	0,14	5	0,35		0,35	
Sufficient space for child seats	3,0%	2	0,06	3	0,09	2	0,06		0,06	
Reachability (Handles, controls...)	2,0%	3	0,06	3	0,06	3	0,06		0,06	
<b>Electronics placement</b>	<b>7,0%</b>		<b>0,26</b>		<b>0,23</b>		<b>0,31</b>		<b>0,31</b>	
Cabling (folds, length)	2,0%	3	0,06	4	0,08	3	0,06		0,06	
Shield sensitive parts	5,0%	4	0,2	3	0,15	5	0,25		0,25	
<b>Mobility</b>	<b>6,0%</b>		<b>0,22</b>		<b>0,26</b>		<b>0,18</b>		<b>0,18</b>	
Turning radius	2,0%	3	0,06	3	0,06	3	0,06		0,06	
Low center of gravity	4,0%	4	0,16	5	0,2	3	0,12		0,12	
<b>Durability</b>	<b>12,0%</b>		<b>0,28</b>		<b>0,36</b>		<b>0,24</b>		<b>0,24</b>	
Longevity	4,0%	2	0,08	2	0,08	2	0,08		0,08	
Ease of maintenance	4,0%	2	0,08	3	0,12	3	0,12		0,12	
Amount of maintenance	4,0%	3	0,12	4	0,16	1	0,04		0,04	
<b>Capacity</b>	<b>7,0%</b>		<b>0,28</b>		<b>0,21</b>		<b>0,28</b>		<b>0,28</b>	
Storage size	7,0%	4	0,28	3	0,21	4	0,28		0,28	
<b>Other</b>	<b>13,0%</b>		<b>0,35</b>		<b>0,39</b>		<b>0,37</b>		<b>0,37</b>	
Manufacturability	4,0%	2	0,08	3	0,12	2	0,08		0,08	
Appealing design	2,0%	4	0,08	3	0,06	4	0,08		0,08	
Cost	2,0%	2	0,04	3	0,06	3	0,06		0,06	
Number of moving parts	5,0%	3	0,15	3	0,15	3	0,15		0,15	
<b>Sum:</b>	<b>100%</b>		<b>3,29</b>		<b>2,91</b>		<b>2,98</b>		<b>2,98</b>	
<b>Rank:</b>			<b>1</b>		<b>2</b>		<b>2</b>		<b>2</b>	

Table 4.14: Kesseling matrix for the complete concepts continued.

Selection Criteria	Weight	Delhi (ideal)		Auckland (eco friendly)	
		Rating	Weighted Score	Rating	Weighted Score
<b>Functionality</b>	<b>18,0%</b>		<b>0,54</b>		<b>0,41</b>
Lightweight	4,0%	3	0,12	4	0,16
Sustainable (material use, amount of electronics etc)	4,0%	3	0,12	3	0,12
Sturdiness (Construction)	7,0%	3	0,21	1	0,07
Display useful information (speed, battery level, etc.)	3,0%	3	0,09	2	0,06
<b>Usability</b>	<b>9,0%</b>		<b>0,32</b>		<b>0,13</b>
Easy to clean/wipe off	2,0%	2	0,04	3	0,06
Ease of fitting chairs in cargo box	7,0%	4	0,28	1	0,07
<b>Safety</b>	<b>16,0%</b>		<b>0,58</b>		<b>0,44</b>
Protects from weather	2,0%	4	0,08	3	0,06
Protects from rolling over	5,0%	3	0,15	3	0,15
Protects from falling over	5,0%	3	0,15	3	0,15
Braking power	4,0%	5	0,2	2	0,08
<b>Ergonomics</b>	<b>12,0%</b>		<b>0,47</b>		<b>0,29</b>
Battery placement (ease of switching)	7,0%	5	0,35	2	0,14
Sufficient space for child seats	3,0%	2	0,06	3	0,09
Reachability (Handles, controls...)	2,0%	3	0,06	3	0,06
<b>Electronics placement</b>	<b>7,0%</b>		<b>0,31</b>		<b>0,23</b>
Cabling (folds, length)	2,0%	3	0,06	4	0,08
Shield sensitive parts	5,0%	5	0,25	3	0,15
<b>Mobility</b>	<b>6,0%</b>		<b>0,18</b>		<b>0,26</b>
Turning radius	2,0%	3	0,06	3	0,06
Low center of gravity	4,0%	3	0,12	5	0,2
<b>Durability</b>	<b>12,0%</b>		<b>0,28</b>		<b>0,36</b>
Longevity	4,0%	2	0,08	3	0,12
Ease of maintenance	4,0%	2	0,08	4	0,16
Amount of maintenance	4,0%	3	0,12	2	0,08
<b>Capacity</b>	<b>7,0%</b>		<b>0,28</b>		<b>0,21</b>
Storage size	7,0%	4	0,28	3	0,21
<b>Other</b>	<b>13,0%</b>		<b>0,31</b>		<b>0,47</b>
Manufacturability	4,0%	1	0,04	5	0,2
Appealing design	2,0%	4	0,08	3	0,06
Cost	2,0%	2	0,04	3	0,06
Number of moving parts	5,0%	3	0,15	3	0,15
<b>Sum:</b>	100%		<b>3,27</b>		<b>2,8</b>
<b>Rank:</b>			<b>1</b>		<b>3</b>

much higher but still prove that these might have an edge. A reason why the scores are similar that they are all based on the same sub-system solutions, as described in the previous Sections 4.6.1.1 and 4.6.1.2. This means that they all already have good solutions for the most vital sub-systems and only smaller variations are tested in the Kesselring matrix.

However, there are some bigger differences between the concepts in the matrix which showed what advantages and disadvantages each of the concepts had. A discussion follows below:

For *Sturdiness*, having a tilt mechanism with two bearings instead of only one gave a significantly higher score since it would be able to handle different loads better. With only one bearing, there is a risk of big bending moments in the bearing which could result in worse performance or even failure in this part.

For *Display useful information*, not having a display for useful information on the vehicle was deemed very bad in comparison to the other concepts.

For *Ease of fitting chairs in cargo box*, bolts gave the respective concepts a worse score since they would increase the time and effort it takes for mounting the chairs. Having a tool-less system would be much better.

When it comes to *Protects from falling over* the sawtooth system performs worse since it can lock in different positions than when being upright. It is better if the front frame can lock only in the upright position since that is where you usually want to be the most stable. You could question this though e.g. if the user is riding along a sideways incline, and the true upright position is actually tilting the front frame a bit to the side relative to the rear frame. However, it was deemed that this will generally not be an issue since it is a rare situation, and it would most likely be preferred to only have one possible position for the lock to activate. If the lock suddenly activates while the frame is leaning on flat ground, it could lead to an annoying experience.

For *Provide braking*, the superior mechanism is disc brakes combined with regenerative braking using hub motors. Disc brakes are generally more reliable than rim brakes since they produce more braking power and are less dependent on the weather. Rim brakes tend to lose more power in wet conditions. Also including regenerative braking is an obvious choice since the electric motors would already be installed and ready for this functionality.

Concerning *Battery placement*, some of the concepts had the batteries placed within the front frame, similar to a normal e-bike, and some had the batteries mounted underneath the rear frame. From an ergonomics perspective it was determined that having the batteries mounted in the front frame, it is much more convenient and easy to change or remove the batteries from the vehicle. The user would not have to bend down as much to reach them as they would have to if they were mounted

underneath the rear frame.

In *Cabling* the main concern regarded the placement of the batteries and how the rear frame was shaped. If the rear frame had a U-shape, extra cabling would be necessary to reach the hub motor connector. Thus batteries mounted in the front frame and a U-shaped rear frame would reduce the scoring of the concepts.

The *Shield sensitive parts* category looked at how well electronics were shielded from potential damage. For example, if running over a high obstacle, a battery mounted underneath the rear frame could get damaged. This led to these kinds of concepts scoring less here.

*Low center of gravity* was better for concepts where batteries and electronics were mounted at a lower height in the vehicle.

For *Amount of maintenance*, having the rear wheels "covered" by the cargo box could lead to more build-up of dust and dirt inside the wheel and disc rotor area, which could also be more difficult to remove. Also, one bearing was deemed worse since it will take an unfavorable load and thus might require replacing.

For *Cargo space* the only difference was if the concept had the rear wheels covered by the box, which if it did would mean a slightly higher volume of cargo space.

When looking at *Manufacturability*, a frame with embedded batteries would require more specialized equipment to be built and thus given a lower score. Also, neidhart springs are a fairly difficult component to assemble which also gives these concepts a lower score.

The final decision was to combine the Stockholm and Delhi concepts using the best parts of each for a final concept. The complete list of solutions is presented in Table 4.15. The design removes the haptic feedback and rear-view mirror, as they are seen as excessive for the purpose, but keeping the sound feedback since it can provide a good amount of information to the rider with little effort for designing it.

**Table 4.15:** Final concept configuration.

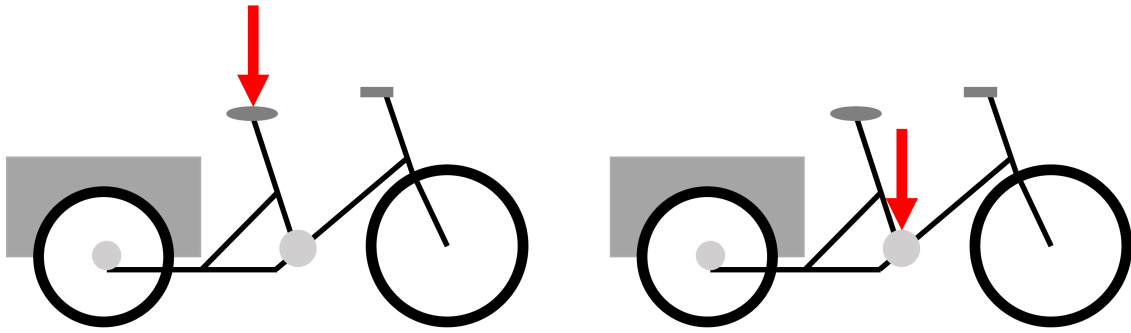
<b>Subfunction</b>	<b>Solution</b>
Transport goods/children	Same box with removable seats
Easily switch cargo configuration	Rail
Improve comfort for passengers	Springs in seat
Allow for tilting of front part	Tubes attached with bearings
Push inner wheel down into the ground when in a turn	Neidhart spring
Prevent loss of balance at slow speeds	Pin spring system
Protect rider from splash	Mud guards
Protect cargo from splash	Rear wheels 'built into' cargo box
Display data	Digital display on handlebars + Sound feedback
Allowing vehicle to roll forward	Air tires
Provide user with good SA	
Provide braking	Regenerative braking + Disc brake
Prevent user falling over during ingress and egress during standstill	Bar less frame + Hand brake
Energy storage	Battery
Energy generation	Generator
Convert stored energy into motion	Electric motor
Provide mechanical propulsion	Pedals powering generator
Allow different individual speeds for rear wheels	Motors connected with individual drivetrain
Improved visibility for the surroundings	Front/rear lights + Reflectors + Bell

## 4.7 Finite Element Analysis

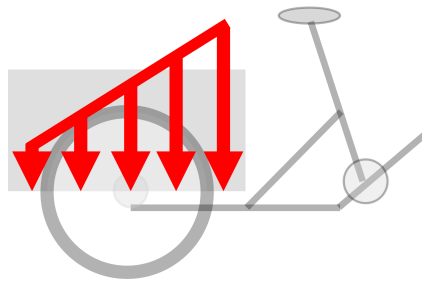
In order to verify the final concept's structural integrity, it was tested in different ways using Ansys.

### 4.7.1 Strength Analysis

The first case involved applying loads on the areas where the seats and pedals are attached. So a force of 1000 N was separately applied on the seating area and the pedals as shown in Figure 4.16. This load was applied considering the weight of the user to be a maximum of 100 kg. The rear frame was loaded using a uniformly varying load of 600 N as shown in Figure 4.17. This was done to simulate two children sitting in the front of the cargo space with some cargo also in the rear. The weight of the children was considered to be 40 kg and the extra cargo weight of 20 kg along with it.



**Figure 4.16:** Load cases for the front frame.



**Figure 4.17:** Load case for the rear frame.

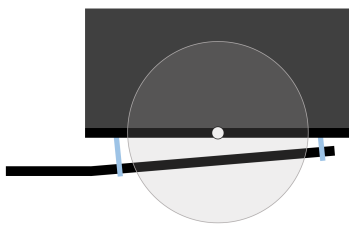
The second case considered the condition where the vehicle goes over a bump and that was simulated in the front frame using a load of 2400 N. This case was considered in the simulation to take the higher stress that would act on the vehicle due to the road irregularities into consideration (Maestrelli & Falsini, 2008). This load was 2,4 times that of the normal load used previously, so the load applied on the rear frame was also multiplied with this factor, which equates to 1 440 N. Those two loads were used alternatively to simulate the condition of the vehicle's front and rear wheels going over a bump separately. A separate test was also carried out only testing the rear frame. Again, a 1440 N load was applied downwards along with a 1000 N load on the bearing surface to take the load from the front frame into account. This test was just done to get more types of boundary conditions tested, to make sure the frame could handle them all.

## 4.7.2 Buckling Analysis

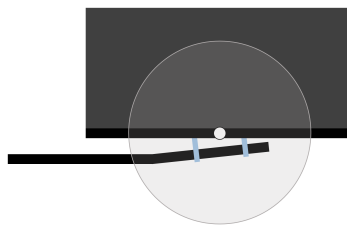
Once the strength test was completed, there was a need to make a buckling analysis as there were two support bars on the frame which could have the possibility of buckling when the load from the rider is applied on the vehicle. Again a force value of 2400 N was applied on the seat to consider the worst case of the vehicle going over a bump.

### 4.7.3 Finding the Optimal Placement of the Bearings

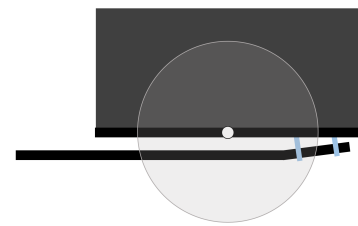
Depending on where the bearings are mounted and how the cargo load is distributed in the rear, the front frame can be affected in different ways. If they are placed in an unfavourable position with an uneven load, the front frame could experience a high bending force. To test this effect and find an optimal solution, three different bearing position setups were analyzed in Ansys. One tested having the bearings symmetrically placed around the wheel axis far apart, shown in Figure 4.18. One also had the bearings mounted symmetrically around the wheel axis, but closer together, shown in Figure 4.19. The last setup looked at having both bearings mounted closer to the rear of the vehicle, shown in Figure 4.20. For all tests, a triangle-distributed force on the cargo plate was applied equal to 600 N in addition to a force of 1000 N on the seat.



**Figure 4.18:** Far apart bearing placement.



**Figure 4.19:** Close bearing placement.



**Figure 4.20:** Rear bearing placement.

The benefit of having the bearings far apart would be to better distribute the forces of a potentially uneven load in the cargo box. Having this placement should lead to less leverage on the front frame bar and thus less mechanical stress. A drawback of this placement appears when aligning the bend of the front frame with the front wheel contact patch. Because of the front bearing being so close to the front of the box, it would have to be attached quite low to give enough space to also mount the rear bearing. This could either impact the ground clearance or force the cargo box to be higher off of the ground, both of which are not optimal. It can also give an awkward look to the vehicle with a bar hanging low to the ground.

The close bearing placement improves the height problem since the front frame bar can be more closely mounted to the rear frame. The potential drawback would be a higher bending moment in the front frame bar if the cargo is distributed unevenly.

The rear bearing placement has the added benefit of having the tilt mechanism mounted further back in the vehicle, which makes it possible to decrease the tilting angle slightly. As described previously this is what is sought after when designing this tilting mechanism for potentially better vehicle dynamics. The drawback of this would also be high bending moments on the front frame bar.

# 5

## Final Concept

This chapter includes detailed explanations of all the sub systems present in the final concept. The calculations and the reasoning behind the choice of the subsystems have also been presented.

### 5.1 Overview

An overall view of the concept while leaning is presented in Figures 5.1 and 5.2.



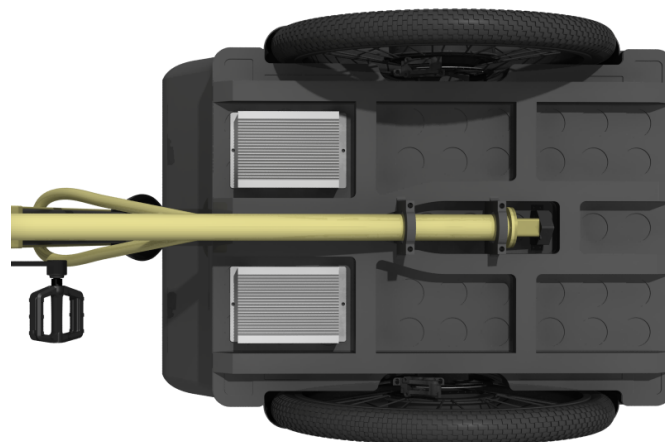
**Figure 5.1:** Isometric front view of the final concept.



**Figure 5.2:** Isometric rear view of the final concept.

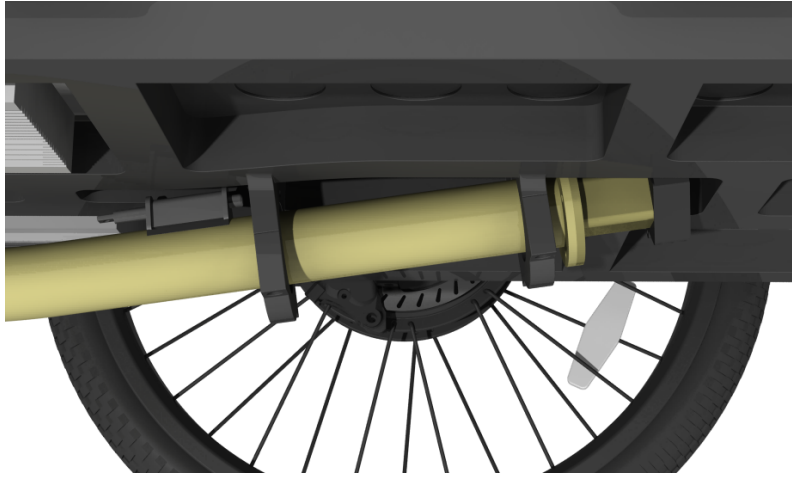
## 5.2 Tilt Mechanism

The design of the tilt mechanism is where the most time was spent on development to make the riding experience the best as explained previously. The system itself is constructed of several parts where different considerations had to be made to create a system that offers good vehicle dynamics, and good synergies between the different solutions. The underneath of the rear frame, where the tilt mechanism is positioned, is shown in Figure 5.3. In this figure, the placement of the motor controllers is also visible.



**Figure 5.3:** Underneath of the rear frame, showing the tilt mechanism.

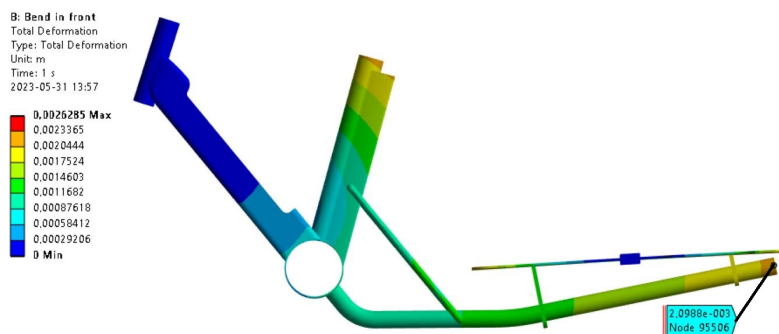
A side view of the tilting mechanism is also shown in Figure 5.4, where the two bearing mounts are shown, along with the pin spring system on the left side and the neidhart spring on the right.



**Figure 5.4:** Side view of the tilting mechanism.

### 5.2.1 Bearing Placement

From the analysis results it was found that the deformation values were 2 mm, 1,4 mm and 13 mm for far apart, close and rear placement respectively as shown in Figures 5.5, 5.6 and 5.7. The deformation values on the cargo plate were ignored as it was not the final design and so the deformation at the rear end of the front frame tube was considered. The stress values were around the same amounts in all three cases which accounted for a FoS (Factor of Safety) of more than two, so the deformation results were the deciding factor. Looking at the deformation results the close placement was the optimal positioning. It gives the mentioned benefits compared to the far-apart placement, without causing too much stress or deformation in the construction. The rear placement analysis showed that there would be a big deflection in the back part of the vehicle, and it was thus decided that this placement was not suitable.



**Figure 5.5:** Deformation results of far apart bearing placement.

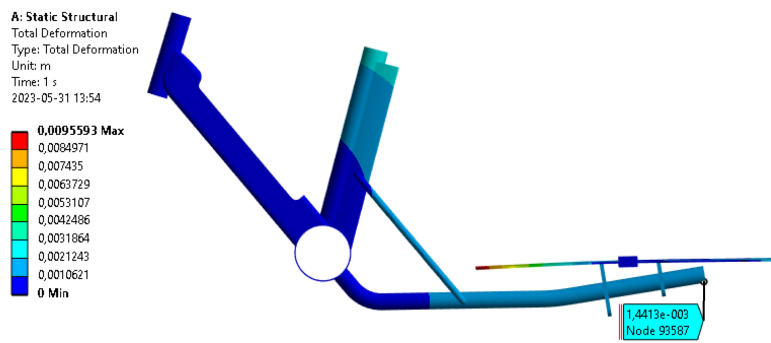


Figure 5.6: Deformation results of close bearing placement.

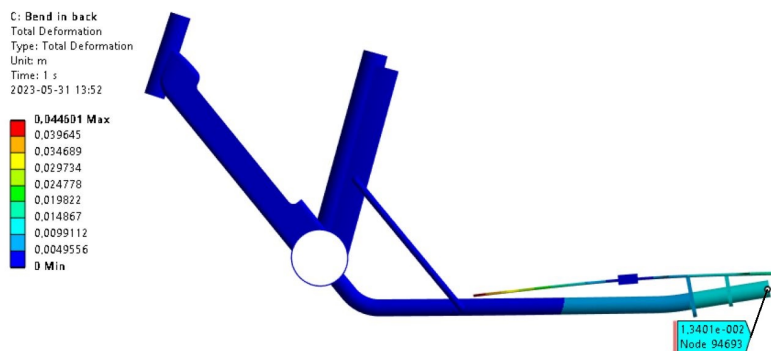
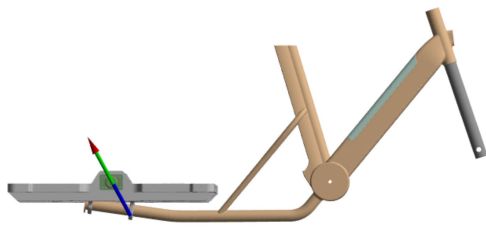


Figure 5.7: Deformation results of rear bearing placement.

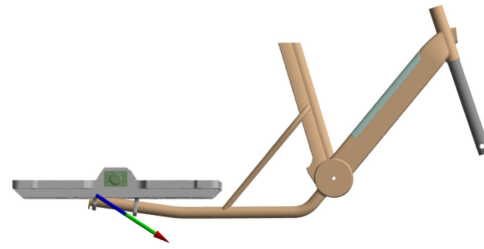
## 5.2.2 Bearing Selection

The two bearings situated on the rear are the main means of attachment of the rear frame to the front frame and they will be subjected to the loads from the cargo weight. In the close placement as discussed in Section 5.2.1 the two bearings are present at equal distances from the point of attachment of the wheel to the rear frame. This allows the wheel to take the maximum load forces from the cargo whereas there would still be some reaction forces acting on the bearing locations as the load on the rear frame will not always be uniformly distributed.

The approximate values of the reaction forces acting on the bearings were found with the help of FEM analysis. The force values were 558 N on the front bearing and 1456 N on the rear bearing and the direction of those forces are as shown in Figures 5.8 and 5.9. As most of the forces are taken by the wheels, the reaction force values on the bearings are comparatively lesser. From research it was found that ball bearings are normally good at withstanding large radial loads and are also capable of taking axial loads (Smb bearing, n.d.). So, ball bearings which can withstand these load values could be a good fit for this application.



**Figure 5.8:** Reaction force on front bearing.



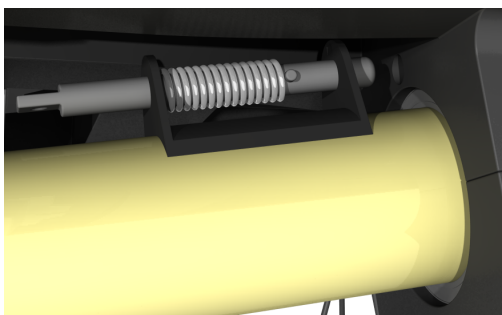
**Figure 5.9:** Reaction force on rear bearing.

### 5.2.3 Tilt Lock

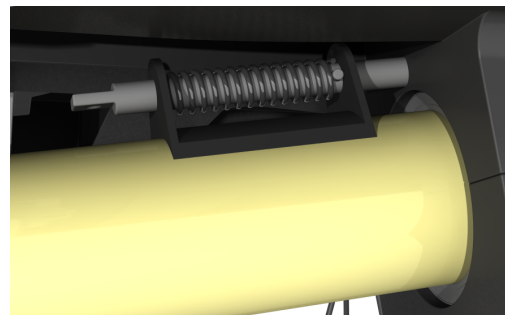
The tilt lock mechanism consists of two main parts. The lever, which is on the handle shown in Figure 5.10, and the locking system itself, which is shown without its cover in Figures 5.11 and 5.12. The two parts will be connected with a wire, similar to a braking wire. In normal operating conditions when the front frame is unlocked, the spring will be compressed by the pull of the wire, as shown in Figure 5.11. When pushed, the lever will release the wire letting the spring in the locking system decompress, which will push the locking pin into a hole in the bearing mount, as shown in Figure 5.12. When the lever is pulled, the wire will pull the pin backwards against the spring. When it is outside of the hole in the bearing mount, the lever will lock into position stopping the wire from being pulled away again, until the lever is pushed again.



**Figure 5.10:** Tilt lock lever.



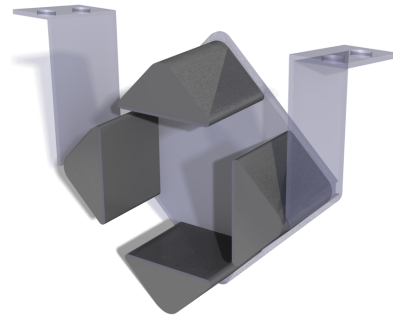
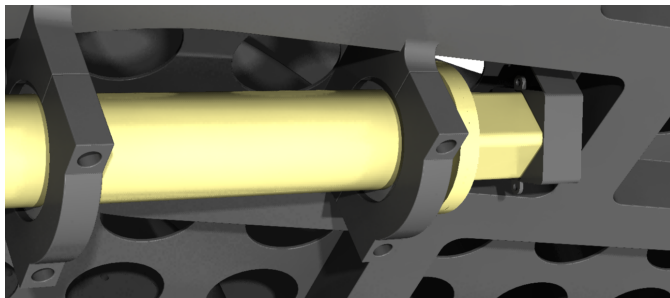
**Figure 5.11:** Tilt lock mechanism disengaged.



**Figure 5.12:** Tilt lock mechanism engaged.

### 5.2.4 Neidhart Resistance Spring

The neidhart resistance spring is mounted on the bottom of the rear frame where the front frame is inserted into it, shown in Figure 5.13. The front frame has a square-shaped extension mounted at the end which is inserted into the spring housing. When the front frame starts tilting, the four rubber elements seen in Figure 5.14 will resist this motion. This was a simple way of being able to use this system as a round-shaped end would not work with this. It also includes a full stop at an angle of  $25^\circ$  to stop the vehicle from falling over.



**Figure 5.13:** Neidhart spring from the front. **Figure 5.14:** See through view of the neidhart spring.

## 5.3 Front Frame

The front frame is one of the major load-carrying parts of the vehicle. The frame was designed first, and testing was done as discussed in Section 4.7 to refine the design in multiple iterations. The results showed that there were some areas on the front frame that required improvement to handle different types of loads that the vehicle might be exposed to.

One improvement that was made was to round the corners at the bottom of the battery slot to reduce stress concentrations in this area, shown in Figure 5.15. The second improvement that was done was changing the support arms that connect the support tube with the rear tube. These support arms used to be attached to the side of the rear tube, which caused them to bend. The change attached them to the top of the rear tube, as shown in Figure 5.16, making the arms mostly take compression loads instead, which helped solve this issue. The result of these changes made the frame have a FoS of 3.5 as shown in Figure 5.17.

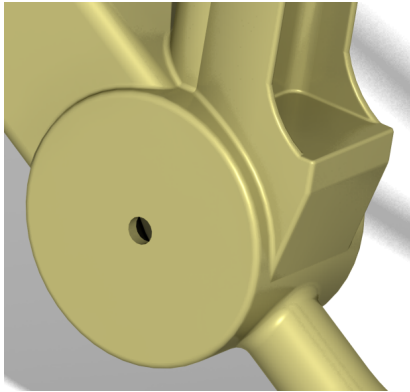


Figure 5.15: Battery fillet.

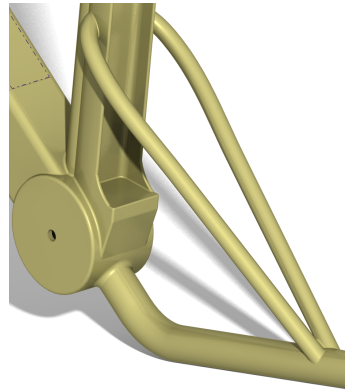


Figure 5.16: Support arms.

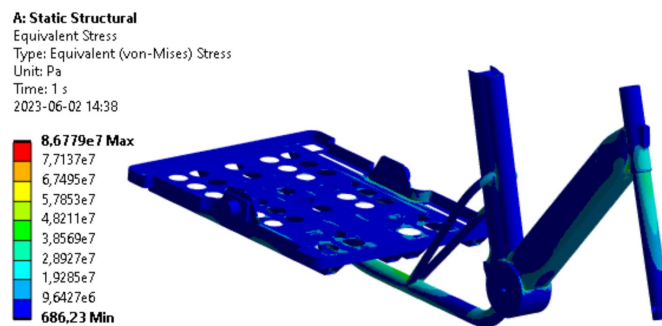


Figure 5.17: Stress on frame.

Considering the buckling analysis, eight different buckling modes were generated using the Eigenvalue buckling analysis in Ansys to consider different types of failure cases in the model. An example of one of the failure modes is shown in Figure 5.18. The lowest load multiplier value obtained from the simulation is 174,75. This means that the minimum load to be applied on the frame for the failure to occur is 421 800 N. This is a big load value, and this condition is impossible to act on the vehicle in the real-world conditions which conclude the fact the model will not buckle.

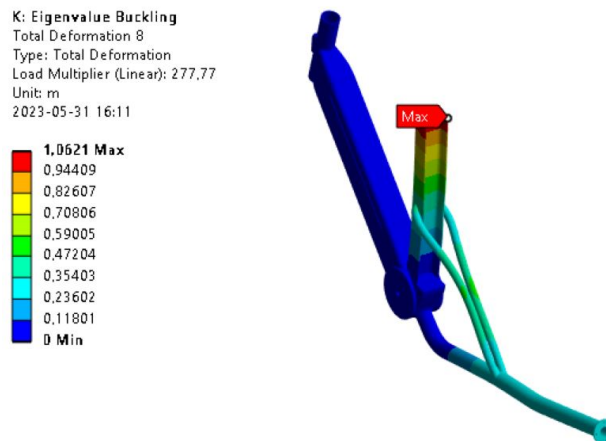


Figure 5.18: A buckling mode of the front frame.

## 5.4 Cargo Space

The cargo space makes up almost half of the vehicle at the rear part. Explanations and improvements made with the rear frame, seat size and the attachment of the seat to the cargo box are discussed in this section.

### 5.4.1 Cargo box

The cargo box is a single-layered container which is attached to the rear frame at the back using bolts. This box provides space for placing the cargo materials and also provides protection for the children who are sitting on the seat. There also exists a door in combination with the cargo box in order to make it easier for the children to get in and out. The door also makes the process of loading and unloading goods easier because in its absence the user has to lift materials over the box which is not so ergonomic.

### 5.4.2 Rear frame

The rear frame provides the base for carrying the load from the cargo at the back of the vehicle. After performing the set of analyses with different load conditions as specified in Section 4.7.1, changes were made iteratively to the design. After a few iterations, the problem areas of the design were identified, and the final design was fixed. The evolution of the design is shown in Figures 5.19, 5.20 and 5.21.



**Figure 5.19:** Rear frame iteration 1.



**Figure 5.20:** Rear frame iteration 2.



**Figure 5.21:** Rear frame iteration 3.

The first design was simple consisting of a plate (not shown in the figure) along with a frame and was created to test out the areas with higher stresses. Following

that, there was a need for weight reduction and the second design was created so that there is no need for the cargo plate. From the results of those, a final design development was made which, although it might not look like it, was 1,5 kg lighter than the first version, and was capable of withstanding the load. Instead of flat elements, it uses square, hollow, beam elements which seemed to have increased the strength of the construction while also reducing the weight. It was able to take even higher loads and the FoS is more than 2 which proves that the frame is perfectly safe to use. The stress values when the frame is completely loaded are as shown in Figure 5.22.

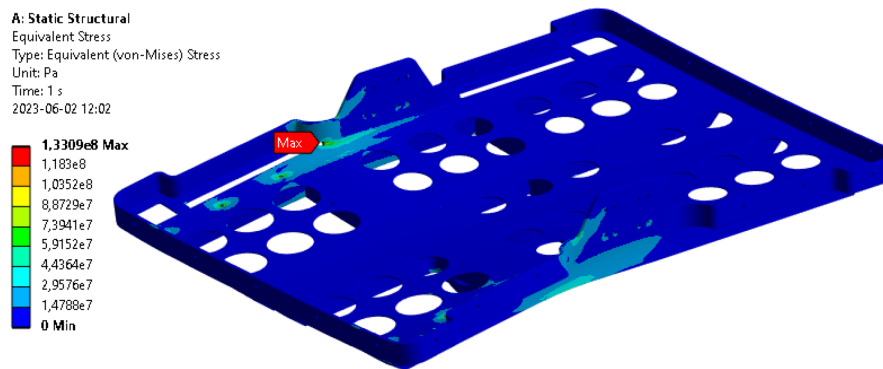


Figure 5.22: Stress values of rear frame.

### 5.4.3 Seat Size

The dimensions of the rear seat were decided after market research from Sections 2.2.2 and 2.2.3 combined with studies on the height of children. It was important to keep a narrow track width for the vehicle while still allowing two children to sit in the cargo space. This led to a decision to make the seat frame 500 mm wide which allowed the total width of the vehicle to be 704 mm, which was close enough to the specified 666 mm. The seat itself has space to be slightly wider as shown in Figure 5.23 which allows for a hip breadth of approximately 270 mm per child, which accounts for the 95th percentile of children who have a 112 cm standing height according to Castaing (2010). The height of the seat was made to be 350 mm with an extendable headrest which raises the total seat height to 600 mm. From this, the max seated height of the child was set at 650 mm since the important thing is that the back of the head would be in contact with the headrest. According to Castaing (2010) this would also include the 95th percentile of children with a 112 cm standing height. The limit for children's height was thus set at 112 cm. This would include the 50th percentile of both male and female five-year-olds. (Fryar, Carroll, Gu, Afful, & Ogden, 2021). It also stands close to the competition according to the benchmark in Section 2.2.2, where most height limits were set at 111 cm-117 cm.

### 5.4.4 Seat Attachment

The rail mechanism shown in Figure 5.25 used for attaching the seat works by mounting two rails with six bolts each in the bottom of the cargo box. The seat is

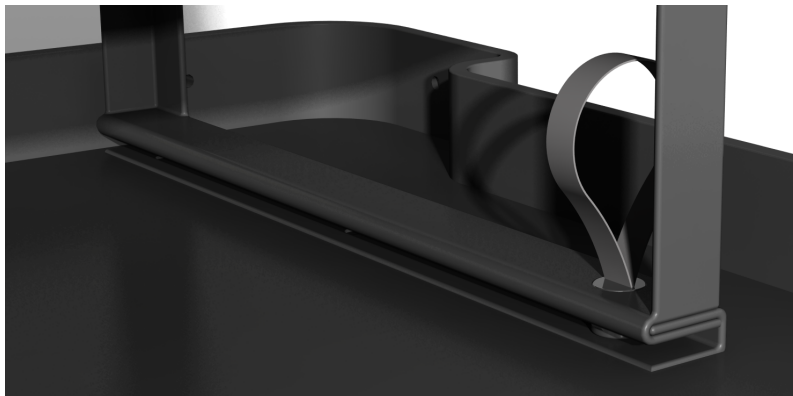


**Figure 5.23:** The rear seat in the cargo space (cargo door hidden).



**Figure 5.24:** Rear seat head rest extended to max height.

mounted to a metal frame which then slides into these rails. The rails will be able to take loads in all directions except for the direction in which the seat slides out. The load in this direction will not be high, it should only be loaded when the vehicle is accelerating forwards. To secure the seat frame in this direction as well, there is a hole in each side of the seat frame and rail where a pin is easily inserted to lock it in place. This will make the insertion and removal of the seat easy and seamless.



**Figure 5.25:** Rail mechanism with lock pin inserted.

## 5.5 Motor

As the vehicle is completely driven by electric power there was a need to calculate the needed motor power and battery capacity. The total power needed by the vehicle was calculated using Equation 5.1. A few simple assumptions were made for the simplification of the calculation, and they are as follows:

- No transmission efficiency loss in the electric drivetrain
- No wind blowing in any direction of the vehicle
- Velocity of the vehicle is constant and has zero acceleration

Power calculations were made for two different cases using the Equations 5.1, 5.2, 5.3, 5.4 and 5.5 (Miri, Fotouhi, & Ewin, 2021). The weight considerations used for the calculations include the rider, cargo and vehicle weights. The first case involves a situation where the vehicle travels on a plane surface with no slope at a speed of 25 km/h which is the legal limit. The second case involves the situation of the vehicle travelling uphill with an inclination of 15°.

$$P_{Wheels} = (R_{\theta} + R_R + R_A + R_I)V_{Vehicle} \quad (5.1)$$

where:

$$R_{\theta} = M_{Vehicle} * g * \sin\alpha \quad (5.2)$$

$$R_R = C_{RR} * M_{Vehicle} * g * \cos\alpha \quad (5.3)$$

$$R_A = 0,5(\rho * A_F * C_d * (V_{Vehicle} - V_{wind})^2) \quad (5.4)$$

$$R_I = \delta * M_{Vehicle} * a \quad (5.5)$$

The constant values considered in the calculation are,

$$\rho = 1,23kg/m^3; C_d = 1,2; a = 0,66m^2; C_{RR} = 0,005; g = 9,81m/s^2 \quad (5.6)$$

For case 1,

$$R_{\theta} = 180 * 9.81 * \sin(0) = 0N \quad (5.7)$$

$$R_R = 0,005 * 180 * 9,81 * \cos(0) = 8,829N \quad (5.8)$$

$$R_A = 0,5(1.23 * 0,66 * 1,2 * (6,944 - 0)^2) = 23,48N \quad (5.9)$$

$$R_I = 1,15 * 180 * 0 = 0N \quad (5.10)$$

$$P_{Wheels} = (31,328 * 0,165) * 42,08 = 224,43W \quad (5.11)$$

For case 2,

$$R_{\theta} = 180 * 9.81 * \sin(12) = 367,13N \quad (5.12)$$

$$R_R = 0,005 * 180 * 9,81 * \cos(12) = 8,63N \quad (5.13)$$

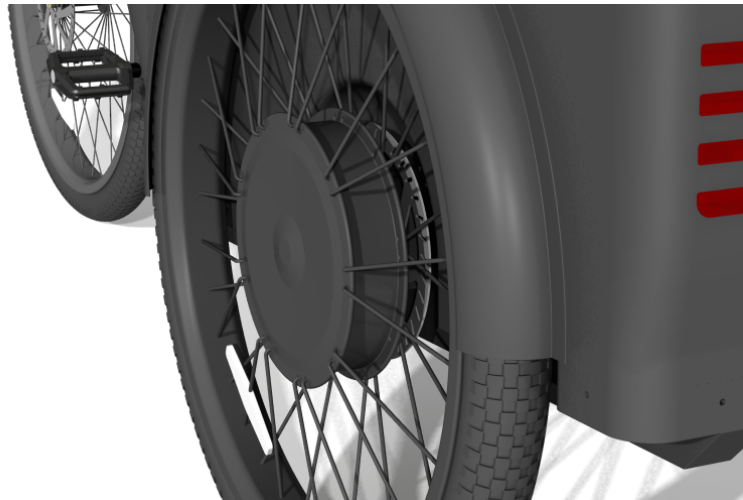
$$R_A = 0,5(1,23 * 0,66 * 1,2 * (2,778 - 0)^2) = 3,758N \quad (5.14)$$

$$R_I = 1,15 * 180 * 0 = 0N \quad (5.15)$$

$$P_{Wheels} = (379,52 * 0,165) * 16,835 = 1054W \quad (5.16)$$

According to the legal requirements the motors used on e-bikes should have a maximum power of 250 W and a maximum speed of 25 km/h without the assist from pedaling. So this speed value was used for the power calculation in the first case, and it shows that the vehicle needs less power than 250 W while travelling on a flat surface. So, there will be no problem regarding the power requirements in normal road conditions.

The problem of the power requirement comes into existence when the vehicle tries to go over a slope. The calculation for the second case shows that there is a need for a motor around 1000 W but according to the legal requirements, it's not possible to have one like that. Although a powerful motor like that is not allowed, a 250 W motor that can peak up to a larger power is allowed. So, it was found that a motor which can peak up to 1000 W could be a good fit for this case. The use of hub motors will be much better because it eliminates the need for extra space for the placement of the motors as shown in Figure 5.26.



**Figure 5.26:** Hub motor.

## 5.6 Battery

As there is a loss of efficiency when the vehicle is directly powered by the generator, there was a need for batteries to power up the system. Once the power requirement calculations were done, the next step was to calculate the battery capacity to power up the vehicle.

To consider the actual conditions, the calculations have to be performed by taking the acceleration details of the vehicle into consideration. But once again, it complicates the calculation a lot, so a simple consideration for calculation purposes was considered splitting into two cases again. The first case involves the case where the vehicle travels a distance of 40 km at a speed of 25 km/h. The second case is where the vehicle travels a distance of 10 km at a speed of 10 km/h. These cases were just an approximation of how much the vehicle could travel based on the ground conditions of Sweden. The power values from the motor power calculations were taken into consideration for this calculation too.

$$Time = Distancetravelled/Speedofthevehicle \quad (5.17)$$

For case 1,

$$Time = 40/25 = 1,6hours \quad (5.18)$$

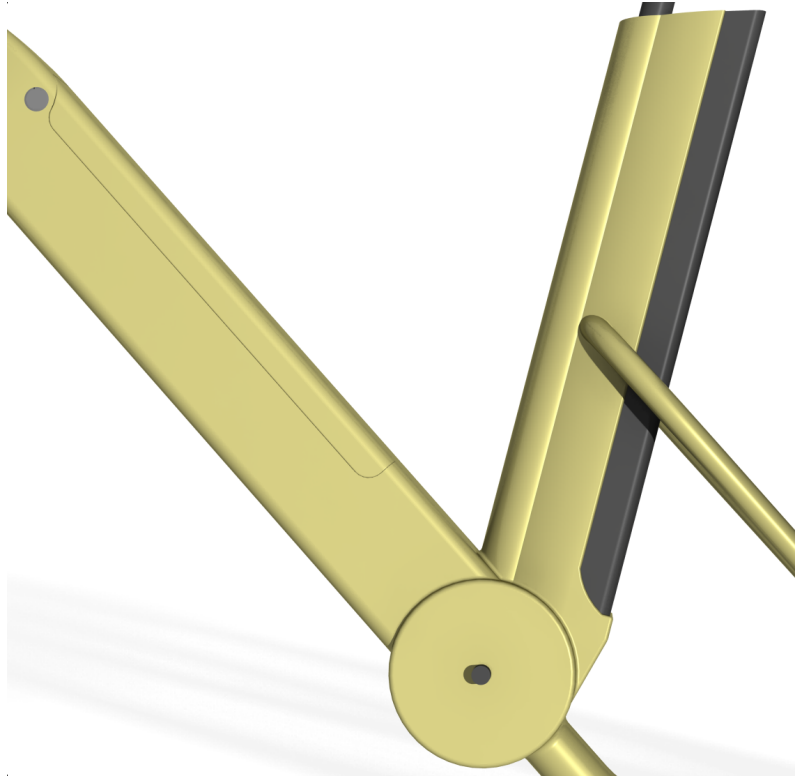
For case 2,

$$Time = 10/10 = 1hour \quad (5.19)$$

$$Batterycapacity = (1,6 * 224) + (1 * 1054) = 1412,2Wh \quad (5.20)$$

The calculations provided the approximate battery capacity needed for the vehicle to travel 50 km. Search for standard batteries with this capacity was done to choose them directly, but the needed capacity was a bit large to accommodate using just one battery. So, it was decided to use two batteries on the vehicle to compensate for the needed power. Two batteries having a capacity of 750 Wh each would be a great fit for this application. They both were placed on the front frame. One seamlessly

integrated with the down tube and one into the seat tube. Both batteries are also removable. Placing the batteries in the front frame will make a good weight distribution across the vehicle and a picture of the battery placement is shown in Figure 5.27.



**Figure 5.27:** The two batteries of the vehicle.

## 5.7 Brakes

The brakes are another important part of the vehicle and the needed brake torque for the vehicle had to be calculated (Patel, Raval, & Patel, 2016).

$$K_e = 1/2 * (m * v^2) = 0,5 * 60 * (6,95)^2 = 1449 \text{ Joules} \quad (5.21)$$

$$S_D = (V * RT) + V^2/2 * \mu * g \quad (5.22)$$

$$S_D = (6,95 * 0,1) + 6,95^2 / (2 * 0,37 * 9,81) \quad (5.23)$$

$$T_W = F_t * R \quad (5.24)$$

$$BF_t = K_e / S_D = 1449 / 13,6 = 106,54 \text{ N} \quad (5.25)$$

$$F_t = BF_t / 3 = 106,54 / 3 = 35,51 \text{ N} \quad (5.26)$$

$$T_W = 35,51 * 0,34 = 12 \text{ Nm} \quad (5.27)$$

The calculations show that the needed brake torque to be provided by the brake calipers is 12 Nm. Different brakes were taken into consideration while choosing the

brakes but it was clear that hydraulic disc brakes were the most effective. Also, as this application involves the transport of small cargo or children the use of hydraulic disc brakes seemed to be a good fit.

### 5.8 Other Parts

There is a list of other smaller subsystem parts existing in the concept. First is the display which is fixed to the handle in the front and is responsible for letting the user know various information about the ride such as the speed, battery capacity and headlight conditions, shown in Figure 5.28. The display stays permanently on the vehicle but is detachable if needed.



**Figure 5.28:** Display with information attached to the handlebars.

The design for seats was mainly based on the need for comfort. Two major options that existed for seat selection were that it was either looking sleek with less material on or it was a bit bulky with more material to provide more comfort and the latter was proceeded with in the project. The saddle height is also adjustable so that it can fit users of different heights.

The wheels were responsible for allowing the vehicle to move come next on the list. They are normal air-filled tires which were chosen for the purpose of improving the comfort for the user as there are no specific suspensions in the vehicle. The size of the front tire is 26" and the rear tires are 24". The size of rear tires is slightly bigger compared to the existing similar vehicles in the market once again to provide more comfort. As the angle of attack of bigger wheels is bigger compared to the smaller ones, it reduces the jerk when the wheel goes over a bump for example.

## 5.9 Weight Specification and Dimensions

Once the virtual CAD models of all the parts were created, masses of all of them were quantified using the CATIA software and they are listed in Table 5.1. The frames and the whole electric drive system contributed to most of the weight, and everything added up together to 53,34 kg. The material chosen for the frames was Aluminium 7005 and the main reason is that it is lightweight and comparatively strong compared to many other materials (Bikeradar, 2021).

**Table 5.1:** Weight specification list.

<b>Part</b>	<b>Weight (kg)</b>
Front frame	5,7
Cargo frame	5,47
Cargo basket	5
Cargo door	0,3
Seat	1,7
Rail	0,1
Hinge	0,05
Motors	10,2
Batteries	7
Controllers	4
Generator	3
Fork	0,6
Front wheel	1
Rear wheel	2
Disc and caliper	1,2
Seat and post	0,5
Pedal	0,48
Bearing	0,4
Tilt lock system	0,08
Wheel holder bracket	0,46
Neidhart spring	0,2
Cables	2
Handle	0,2
Mud guard	0,2
Seat cushion	1
Head rest	0,5
<b>Sum:</b>	<b>53,34</b>

The dimensions of the vehicle, including total length, wheelbase, and width are shown in Figure 5.29.

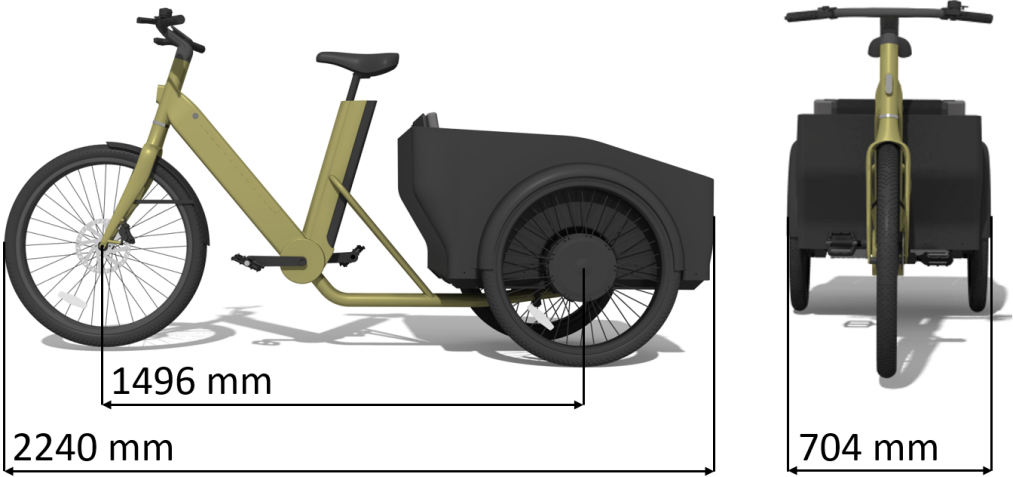


Figure 5.29: The dimensions of the vehicle.

# 6

## Discussion

Looking back to the beginning of the report, this project's goal could be summarized as developing a concept for lightweight urban mobility providing a safe and enjoyable ride for its user. This chapter will discuss the findings related to each research question, a discussion on the work process, and lastly bring up future recommendations.

### 6.1 Research Questions

The posed research questions from Section 1.1 will be addressed in the following sections, and discussed one by one.

- **How can the dynamical behaviour of the vehicle be verified?**

Figuring out which way to go about this problem was the most time-consuming out of all since the problem had to be researched and many different methods had to be explored to find a suitable option for the project. Creating physical prototypes similar to the method used in D'Hondt, Juwet, et al. (2022) would have been the optimal method to solve this problem as getting a true feel of the vehicle is only possible in this way. As this would have not been possible with the time constraints on the project other solutions were aimed for from the beginning. Another option could have been to perform simulations using multibody dynamics simulation software as mentioned in Section 3.3. From this type of software, the vehicle could have been simulated doing certain manoeuvres and then use different data such as lean angle rate, yaw angle rate, lateral acceleration etc., to compare to a normal bike's data while also performing these manoeuvres in a simulation. The data could also have been verified by doing measurements with an IMU (Inertial measurement unit) on a real-life bike. This was believed to have been a suitable way of testing different tilt mechanism configurations quickly and accurately. However, as mentioned, the simulations could not run properly without having to spend too much time on this part of the project. Otherwise, this would have been a good complement to the research articles found on tests of these types of vehicles. In the end, it is believed that simply getting an appreciation of the vehicle geometry using CAD to understand how the movements are affected by the tilt mechanism setup, in combination with the research already published on this, was a sufficient method of solving the problem.

- **How can a natural feel be established when tilting the front part of the vehicle?**

There were different options available for giving the vehicle the ability to tilt. The decision to go with the dual-bearing setup became fairly obvious as the final concept and its constraints became clearer. What was needed was a lightweight mechanism that would not consume a lot of free space in the vehicle which helped reduce the options available. Even though a rail mechanism could have given slightly better performance by allowing a tilt angle that coincides with the front contact patch while also being horizontal, it would have introduced a lot of weight and mechanical complexity to the vehicle. From the market research, a bearing setup seems to be the most common method for these systems, further strengthening the argument for going with this solution.

- **How can the inertia be centered to allow for self-balancing in a standstill position?**

The results from the Pugh matrix suggested that the optimal solution for this problem was the pin spring system. The other two solutions which were the sawtooth and tilt brake systems did not proceed from the elimination as they were seen as inferior. This was, as mentioned, due to the fact that they can be activated while the vehicle is not upright, which could lead to unforeseen effects. They would also likely require more space than the pin spring system as they consist of parts that need to be large, e.g. the brake "disc" for the tilt brake system, and the circular part which holds the teeth in the sawtooth system. Another system that was discussed in the process was to include an actively controlled balancing system using a controller with an actuator at the connection between the two frames which could keep the vehicle upright when needed. This system would probably have been comfortable from a user perspective as little effort would have to go into putting the vehicle in upright mode. The current system still needs the user to line the front frame up with the rear frame in order for the pin to enter the hole. However, a control system would introduce more weight and space requirements on the vehicle which at an early stage was decided non-fitting.

- **In what specific conditions should the self-balancing system be activated?**

This was decided to just be user controlled with a switch on the handlebars and is believed to be the best method of controlling this. If the pin spring system was controlled in a different way, such as activating at low speeds, there is a risk of the user not being aware that the system has been activated and the pin locking when not wished for. Such unexpected behaviour could be dangerous if the user is not anticipating a sudden stop in the tilting motion. Thus for this tilt lock system in particular this is what is believed to be the best activation condition, completely user controlled. If the self-balancing system instead was a controller with an actuator, it could be better to have the system activate by itself during slow speeds.

The reason is that the user would at an earlier stage feel a slight resistance from the system until it aligns completely. Thus there would be no risk of an unexpected activation.

- **How can the drive be transferred from the pedals to the rear axle?**

As mentioned in Section 4.5.2, the drivetrain system solution fell on the series hybrid drivetrain which included a generator combined with two separate hub motors in the rear. The main concern with this drivetrain is the lowered efficiency when compared to a chain or belt drive system. Using batteries would however to a big degree reduce this issue since the vehicle could be driven purely with the battery power. The generator would then charge the batteries continuously throughout the ride. However, the batteries could eventually run out of charged power completely, in which there is a risk of the power loss from the generator being too big causing the user to have to pedal excessively for only a small amount of power to the wheels. One solution to this problem could be how the software is programmed. If the user was warned of a low battery level before it actually becomes low, they could still have a chance of making it to a charging point before completely running out of power. When reaching this pseudo-low battery level, the power to the wheels could also be reduced to still allow for forwards propulsion but at a lower speed, to save some battery.

- **How can a modular cargo space be designed to allow for the transportation of both children and cargo?**

This problem had a lot of creative freedom and could be solved in a number of different ways, which is why it was chosen to select this concept individually. This was a good decision since there could have been a risk of a concept not being chosen if a completely unrelated sub-system would have scored poorly in the Pugh matrix.

- **How can adequate safety be achieved for a child riding in the cargo space?**

To achieve safety for children there were a number of considerations to handle during the development of the vehicle. How to attach the seat, where to attach it, and how to secure the children while riding are all examples of this. The reasoning behind having the seat rear-facing instead of forwards-facing is to handle frontal collisions better since it is better to be pushed into the seat rather than having the belts be the only thing holding the child. It was also important to have the seat firmly fixed to the rear frame which was incorporated in the rail mechanism. The seat frame uses both the rails and the edge of the rear frame to stay firmly fixed in place while also being easily removable to allow for bigger cargo space. In the event of a frontal collision, it was important to also give support to the heads of the children to avoid whiplash injury. From the data gathered on the height of children, it was clear that a headrest also had to be included in the design. To avoid the issue of having an unnecessary headrest in the case of no children being in the cargo box, it was

decided to make the headrest adjustable, and it can thus be made invisible if it is inserted all the way into the seat.

All these solutions are believed to allow for a good design and good usability while also not compromising on safety, which was one of the most important factors to consider for this vehicle.

- **How can the weight of the vehicle be minimized?**

This was more of a general requirement which had to be kept in mind throughout the project. The weight factor played a role in each and every part which were used in the vehicle. The weight of some of the components such as the brakes, bearings, motors, etc., are fixed if standard components from the market are chosen whereas the other components such as the front and rear frame were scrutinized a bit to reduce weight. The analysis of the frames using FEA as explained in Section 4.7, acted as the main source which provided information on the areas where weights could be reduced. Iterations had been performed in order to reduce the weight of the components in a step-by-step fashion. In addition, the material choice for the frames was made by providing the weight factor with a bigger importance to reduce the overall weight of the vehicle. Within the given time, the analysis was carried out to the maximum extent which led to almost reaching the required weight of 50 kg, but the result was slightly above the target which could have been solved with a few more iterations. Considering the use of a mid-drive system with a chain could have saved some weight as it would have led to the removal of a motor, generator and possibly a battery too. The use of this system would however require the addition of some mechanical parts which are not lightweight. These parts include e.g. a differential and a mechanism for allowing the chain to tilt. It is unclear how much the total weight would have changed with a system like this. An added benefit of the series hybrid drivetrain is also that the design freedom is larger for the rear, as the room does not have to be given to any mechanical parts. It is a trade-off problem where the prioritised functions had to be put first.

## 6.2 Societal and Sustainability Aspects

Considering the sustainability aspect, the importance of reducing the usage of fuel-powered vehicles has continuously started to grow fast. Keeping that in mind the developed concept is fully electrically driven which is a major factor in the vehicle contributing towards sustainability. Also, the fact that a generator is capable of producing electricity by pedalling adds up to a greener way of charging the vehicle. This not only minimizes the use of electricity produced but is also better from the physical health point of view.

With the vehicle's small size yet large carrying capacity, it should act as a good complement to the cities of the future, making short urban trips both quicker and more efficient. This should help with the transition to smarter cities where smaller vehicles will play a larger role. From a societal perspective this will be better since

big roads and cars will not, to the same extent, come in the way of the people, and can free up room for green space which will benefit society.

### 6.3 Limitations and Future Recommendations

The largest limitation of this study is that it was not possible to perform real-life tests with physical prototypes to get a true feel of the tilting mechanism. There seemed to be no use of small-scale prototypes because they could never be used to get the feel of the rider. So, building a simple full-scale prototype with different tilting mechanisms would be the first proceeding that could be done in the future.

Another recommendation is to develop a dynamic simulation model for the whole setup to try to compare the different types of forces and accelerations acting on the vehicle for different tilting systems. The development time for the simulation model was a lot which limited the use of it in this project. The findings suggest that the method used was the best for the situation.

Since the rear frame of the vehicle has a high FoS in most of the structure it is believed that some weight could be saved on this part to get closer to the goal weight of the vehicle. Running a more iterative design along with FEA of the strength could give a better frame than the current one. In addition, topology optimization of all the parts could be done in order to identify the load travelling paths for better weight reduction.

Also, the Neidhart springs used for providing the tilt resistance needs a bit of development compared to the current state. The four rubber pellets inside the spring are the major constituents which are responsible for the proper working of the spring. The stiffness of the rubber pellets directly affects the rate and maximum tilt angles of the vehicle. Currently, only the use of Neidhart springs has been suggested in this project and not a detailed design of it. So, research and calculation of the stiffness of the rubber pellets are to be looked into a bit more in detail.

A bigger simplification of neglecting the acceleration details when calculating the battery capacity needs was made to simplify the process. Deciding exactly how the vehicle will be ridden taking the details of slopes and acceleration into account could provide more credible data on the needed battery capacity. As the motors depend completely on the batteries it would be much better to have a good estimation.

Once all the improvements have been made a good estimation of the cost of the product could also be something useful to look at in the future. Since the project was just about the concept development, the cost factor was not taken much into factor but when the product is being manufactured in full scale, cost plays a major role. Even some of the designs or products could be changed and so it would also be one of the topics to be researched in the future.

Taking the requirement specification fulfilment into consideration, almost every re-

quirement was satisfied with the help of the solutions explained in the final concept chapter. There were just four requirements which did not fall into that. The first one is a characteristic requirement where the vehicle is supposed to provide adequate shelter for example, to the children sitting at the back. This requirement was partially satisfied because the cargo box at the back does provide shelter to some extent. Future development could be an extra fitting which the users can purchase in addition, that covers everything at the back and is capable of providing complete shelter. In addition, the weight requirement was not completely fulfilled, as it is currently 53,34 kg and the needed weight was 50 kg. It is not a huge increase though and could be achieved with the help of optimization of some of the parts and material. The third requirement is the durability requirement where the lifecycle of the vehicle should be at least 5 years. To partly verify this, fatigue analysis of the frames using FEM could have been done, but unfortunately had to be de-prioritized in favor of the other analyses. The last requirement that was not fulfilled is the dimensions of the vehicle. It is slightly too long and wide. The length could quite easily be adjusted in the future by dimensioning the cargo box differently and placing it further forwards, closer to the front frame. The width is slightly tougher since space is required for the wheels and also two children sitting in the cargo space. However, this increase is not a significant amount and should not lead to any big negative effects.

# 7

## Conclusion

The project was targeted towards the development of a concept design of an urban mobility vehicle in collaboration with Volvo Cars, taking the safety of the rider and the dynamic behaviour of the vehicle into consideration. Several steps of the product development process were incorporated into the development process leading to the step-by-step evolution of the vehicle to the final solution.

Extensive research has been carried out regarding the market requirements for the product over several years by Volvo Cars and a detailed requirement specification list was prepared at the start to decide upon the deliverable. In order to fulfill the customer requirements a function analysis was carried out to convert them into engineering requirements. Once the functions were mapped out, several ideas to solve all the function requirements were generated with the help of three different methods. The idea generation process was done within the team as well as with fellow thesis students in order to get a different perspective. Following that, the ideas were combined to generate a variety of concepts in an iterative manner and were evaluated to figure out the effective ones.

Consequently, the highlighting factors of different concepts were combined together to form a final single concept solution which was capable of fulfilling all the customer requirements. The major parts of the final concept were also verified virtually with the help of FEM simulations to make sure that the solution works. The design of certain components was optimized using the simulations too to improve the load-bearing capability and also to reduce the weight of the whole product.

In the end, the features of the final product were cross-checked with the requirement specification list to check the fulfillment of the needs. Most of the requirements were satisfied except a few which could not be measured or compared. In addition, there is always room for future development and the areas of the product where there is a need for more work were also identified. Overall, the result of the project is a complete concept solution for an urban mobility vehicle which is safe and comfortable for the consumers to use.



# References

- Adrian, W. (2022). *Vehicle*. (Patent No. EP4098531A1. <https://worldwide.espacenet.com/patent/search/family/076269685/publication/EP4098531A1?q=EP4098531A1>)
- Alpine Electric Bikes. (n.d.). *Alpine electric bikes - electric tilt trike - e tricycle*. Retrieved from <https://www.alpineelectricbikes.co.uk/products/alpine-electric-trike> (accessed: 2023-05-15)
- Anders, G. (2017). *Cargo space: The overview*. Retrieved from <https://cargobikemag.com/cargo-space-the-overview/> (accessed: 2023-05-11)
- Ansys. (n.d.). *Ansys mechanical*. Retrieved from <https://www.ansys.com/products/structures/ansys-mechanical> (accessed: 2023-05-23)
- Antoine, D. (2019). *Electric tricycle with roll*. (Patent No. WO2019025898A1. <https://worldwide.espacenet.com/patent/search/family/060020241/publication/WO2019025898A1?q=W02019025898A1>)
- Babboe. (n.d.). *Babboe carve-e*. Retrieved from <https://www.babboecargobike.com/babboe-carve-e> (accessed: 2023-05-15)
- Barbagallo, R., Sequenzia, G., Oliveri, S., & Cammarata, A. (2016). Dynamics of a high-performance motorcycle by an advanced multibody/control co-simulation. *Proceedings of the Institution of Mechanical Engineers, Part K: Journal of Multi-body Dynamics*, 230(2), 207 – 221. doi: 10.1177/1464419315602825
- Bikeradar. (2021). *Bike frame materials explained: carbon vs aluminium vs steel vs titanium*. Retrieved from <https://www.bikeradar.com/advice/buyers-guides/bike-frame-materials/> (accessed: 2023-06-01)
- Butchers & Bicycles. (n.d.). *The mk1-e gen. 3 is a fast, safe, and super easy to ride e-cargo bike with car-like comfort*. Retrieved from <https://www.butchersandbicycles.com/mk1-e> (accessed: 2023-05-15)
- Bäst i test. (n.d.). *Bicycle trailer: 9 models in test*. Retrieved from <https://www.xn--bst-i-test-q5a.se/cykelvagn> (accessed: 2023-03-06)
- C40. (2016). *Cities100: Barcelona - redefining city blocks to tackle traffic-related emissions*. Retrieved from <https://www.c40.org/case-studies/cities100-barcelona-redefining-city-blocks-to-tackle-traffic-related-emissions/> (accessed: 2023-05-15)
- C40. (2018). *The implementation of the superblocks programme in barcelona: Filling our streets with life*. Retrieved from <https://www.c40.org/case-studies/barcelona-superblocks/> (accessed: 2023-05-15)
- C40 Cities Climate Leadership Group. (2022). *Benchmark: 15-minute cities*. Retrieved from <https://www.c40knowledgehub.org/s/article/Benchmark>

- 15-minute-cities?language=en\_US (accessed: 2023-05-15)
- Castaing, P. (2010, 05). *Status report of informal group on crs*. 47th GRSP Session 17-21 May. Retrieved from <https://unece.org/DAM/trans/doc/2010/wp29grsp/GRSP-47-27e.pdf>
- Cavallari, D. (2022). *Do i need a hub drive or a mid-drive motor?* Retrieved from <https://www.cyclevolta.com/story/ebike-basics/hub-drive-vs-mid-drive-e-bike-motor-comparison-analysis/> (accessed: 2023-05-12)
- Christphe, L. (2022). *Tiltable mobility vehicle*. (Patent No. WO2022223562A1. <https://worldwide.espacenet.com/patent/search/family/081448270/publication/WO2022223562A1?q=W02022223562A1>)
- Chyuan-Yow, T. (2022). *Coupling mechanism for a vehicle body*. (Patent No. US11338879B2. <https://worldwide.espacenet.com/patent/search/family/068342721/publication/US11338879B2?q=US11338879B2>)
- Cossalter, V., Ruffo, N., & Agostinetti, P. (2005). Experimental analysis of handling of a three wheeled vehicle.. Retrieved from <https://www.pieroagostinetti.eu/wp-content/uploads/2023/03/Experimental-analysis-of-handling-of-a-three-wheeled-vehicle.pdf>
- CUBE. (n.d.). *Trike hybrid*. Retrieved from <https://www.cube.eu/uk-en/e-bikes/transport/trike-hybrid?p=1> (accessed: 2023-05-15)
- DHL. (n.d.). *Dhl express introduces new cargo bike: The chariot*. Retrieved from <https://www.dhl.com/nl-nl/home/pers/persarchief/2021/dhl-express-introduceert-nieuwe-cargofiets-de-chariot.html> (accessed: 2023-05-24)
- D'Hondt, J., Degryse, D., Demeester, E., Slaets, P., & Juwet, M. (2022). Handling qualities of a new last-mile vehicle. *Journal of Transportation Technologies*, 12(1), 137 – 158. doi: 10.4236/jtts.2022.121009
- D'Hondt, J., Juwet, M., Demeester, E., & Slaets, P. (2022). Development of an electric tricycle for service companies and last-mile parcel delivery. *TRANSPORT PROBLEMS*, 17(2), 175 – 187. doi: 10.20858/tp.2022.17.2.15
- Espacenet. (n.d.). *Espacenet*. Retrieved from <https://worldwide.espacenet.com/> (accessed: 2023-05-26)
- EUR-lex. (2020). *Regulation (eu) no 168/2013 of the european parliament and of the council of 15 january 2013 on the approval and market surveillance of two- or three-wheel vehicles and quadricycles text with eea relevance*. Retrieved from <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02013R0168-20201114> (accessed: 2023-06-05)
- European Commission. (2022). *Commission announces 100 cities participating in eu mission for climate-neutral and smart cities by 2030*. Retrieved from [https://ec.europa.eu/commission/presscorner/detail/en/IP\\_22\\_2591](https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2591) (accessed: 2023-05-15)
- Evans, J. (2022). *No chain, no belt – this could be the world’s first fly-by-wire ebike drive system*. Retrieved from <https://www.bikeradar.com/news/schaeffler-free-drive-chainless-drive-system/> (accessed: 2023-06-11)
- Fryar, C., Carroll, M., Gu, Q., Afful, J., & Ogden, C. (2021). Anthropometric

- reference data for children and adults: United states, 2015–2018. National Center for Health Statistics. *Vital Health Stat* 3(46).
- Fulpra. (n.d.). *The capacity of a van, simply by bike*. Retrieved from <https://fulpra.com/> (accessed: 2023-05-24)
- Gerard, D. (2011). *Tricycle*. (Patent No. WO2011121211A1. <https://worldwide.espacenet.com/patent/search/family/042831537/publication/WO2011121211A1?q=WO2011121211A1>)
- Glazener, A., & Khreis, H. (2019). Transforming our cities: Best practices towards clean air and active transportation. *Current Environmental Health Reports*, 6, 22 – 37. doi: 10.1007/s40572-019-0228-1
- Google. (n.d.). *Google patents*. Retrieved from <https://patents.google.com/advanced> (accessed: 2023-05-26)
- Halme, J. (n.d.). *What is brainstorming?* Retrieved from <https://info.orchidea.dev/innovation-blog/what-is-brainstorming> (accessed: 2023-06-11)
- Hamax. (n.d.-a). *Bike trailer for kids*. Retrieved from <https://www.hamax.com/product/outback/> (accessed: 2023-03-06)
- Hamax. (n.d.-b). *Bike trailer for kids*. Retrieved from <https://www.hamax.com/sv/produkt/traveller/> (accessed: 2023-03-06)
- Hamax. (n.d.-c). *Single and double kids bike trailer*. Retrieved from <https://www.hamax.com/product/avenida/> (accessed: 2023-03-06)
- Hanson, L., Sperling, L., Gard, G., Ipsen, S., & Olivares Vergara, C. (2009). Swedish anthropometrics for product and workplace design. *Applied ergonomics*, 40(4), 797–806. doi: 10.1016/j.apergo.2008.08.007
- Haraguchi, T. (2009). *Tricycle tilting device*. (Patent No. CN101559803A. <https://worldwide.espacenet.com/patent/search/family/041218822/publication/CN101559803A?q=CN101559803A>)
- Harald, K. J. T. (2022). *A utility vehicle*. (Patent No. EP4074586A1. <https://worldwide.espacenet.com/patent/search/family/075659762/publication/EP4074586A1?q=EP4074586A1>)
- Hexagon. (n.d.). *Adams*. Retrieved from <https://hexagon.com/products/product-groups/computer-aided-engineering-software/adams> (accessed: 2023-05-16)
- Hubertus, V. M. (2019). *Tricycle*. (Patent No. WO2019125138A1. <https://worldwide.espacenet.com/patent/search/family/066380105/publication/WO2019125138A1?q=WO2019125138A1>)
- Institute, T. B. (2021). *Asknature*. Retrieved from <https://asknature.org/>
- Lucidchart. (n.d.). *What is a flowchart*. Retrieved from <https://www.lucidchart.com/pages/what-is-a-flowchart-tutorial> (accessed: 2023-06-11)
- Maestrelli, L., & Falsini, A. (2008). *Bicycle frame optimization by means of an advanced gradient method algorithm*. 2nd European HTC Strasbourg September 30th–October 1st. Retrieved from <https://docplayer.net/47217959-Bicycle-frame-optimization-by-means-of-an-advanced-gradient-method-algorithm.html>
- Masaki, W. (1987). *Tiltable tricycle*. (Patent No. US4678053A. <https://worldwide.espacenet.com/patent/search/family/011504600/publication/US4678053A?q=US4678053A>)

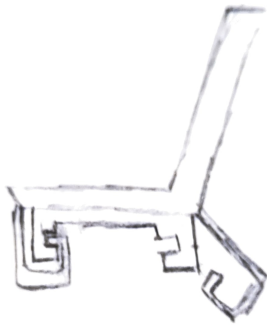
- MathWorks. (n.d.). *Simscape*. Retrieved from <https://www.mathworks.com/products/simscape.html> (accessed: 2023-05-16)
- Miri, I., Fotouhi, A., & Ewin, N. (2021). Electric vehicle energy consumption modelling and estimation—a case study. *International Journal of Energy Research*, 45(1), 501-520. doi: <https://doi.org/10.1002/er.5700>
- Parrot, L. (n.d.). *Function tree models – a tool for optimization*. Retrieved from <https://www.martin-parrot.com/en/function-tree-models-a-tool-for-optimization/> (accessed: 2023-06-11)
- Pashley. (n.d.). *Alecs*. Retrieved from <https://www.pashley.co.uk/products/alecs> (accessed: 2024-05-24)
- Patel, M., Raval, M., & Patel, J. (2016). Design of disc brake’s rotor. *International Journal of Engineering Development and Research*, 4, 919-926. Retrieved from <https://www.ijedr.org/papers/IJEDR1604140.pdf>
- Patsnap. (n.d.). *Patsnap*. Retrieved from <https://www.patsnap.com/> (accessed: 2023-05-26)
- Persson, N., Ekström, M. C., Ekström, M., & Papadopoulos, A. V. (2021). Trajectory tracking and stabilisation of a riderless bicycle. In *2021 IEEE International Intelligent Transportation Systems Conference (ITSC)* (p. 1859-1866). doi: 10.1109/ITSC48978.2021.9564958
- Peter, O. (1993). *Tricycle*. (Patent No. US5240267A. <https://worldwide.espacenet.com/patent/search/family/025067530/publication/US5240267A?q=US5240267A>)
- Rasch, A., Dozza, M., & Håland, Y. (2016). *Evaluation of a new narrow and tiltable electric tricycle (e-trike) concept*. (unpublished)
- Robert, E. (2012a). *Tricycle*. (Patent No. US20120175856A1. <https://worldwide.espacenet.com/patent/search/family/043126590/publication/US2012175856A1?q=US20120175856A1>)
- Robert, E. (2012b). *Tricycle*. (Patent No. JP1983067588A. <https://worldwide.espacenet.com/patent/search/family/043126590/publication/US2012175856A1?q=US20120175856A1>)
- Smb bearing. (n.d.). *Can a ball bearing take axial load?* Retrieved from <https://www.smbbearings.com/can-a-ball-bearing-take-axial-load> (accessed: 2023-05-05)
- Sutton, M. (2022). *Cargo bike use flourishes as eu cycling initiative spend accelerates*. Retrieved from <https://cyclingindustry.news/cargo-bike-sales-eu/> (accessed: 2023-05-15)
- Su-Yuen, H. (2017). *Vehicle tilting system and tricycle*. (Patent No. CN106809323A. <https://worldwide.espacenet.com/patent/search/family/057482250/publication/CN106809323A?q=CN106809323A>)
- Thule. (n.d.-a). *Thule chariot cab*. Retrieved from [https://www.thule.com/sv-se/bike-trailers/bike-trailers-for-kids/thule-chariot-cab-2\\_-10204021](https://www.thule.com/sv-se/bike-trailers/bike-trailers-for-kids/thule-chariot-cab-2_-10204021) (accessed: 2023-03-06)
- Thule. (n.d.-b). *Thule chariot cross*. Retrieved from [https://www.thule.com/sv-se/bike-trailers/bike-trailers-for-kids/thule-chariot-cross-2\\_-10202024](https://www.thule.com/sv-se/bike-trailers/bike-trailers-for-kids/thule-chariot-cross-2_-10202024) (accessed: 2023-03-06)
- Thule. (n.d.-c). *Thule chariot lite*. Retrieved from <https://www.thule.com/>

- sv-se/bike-trailers/bike-trailers-for-kids/thule-chariot-lite-2-  
\_10203022 (accessed: 2023-03-06)
- Toll, M. (2023). *Radical new ride-by-wire electric bike drivetrain with no chains or belts begins production*. Retrieved from <https://electrek.co/2023/02/22/radical-new-ride-by-wire-electric-bike-drivetrain-free-drive-schaeffler/> (accessed: 2023-05-12)
- Toyoyuki, Y. (2003). *Oscillation righting mechanism of tricycle*. (Patent No. JP3479946B2. <https://worldwide.espacenet.com/patent/search/family/018120777/publication/JP3479946B2?q=JP3479946B2>)
- Transportstyrelsen. (n.d.). *Cykel*. Retrieved from <https://www.transportstyrelsen.se/sv/vagtrafik/Fordon/Fordonsregler/Cykel/> (accessed: 2023-06-05)
- Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2020). *Product design and development*. New York, NY: McGraw-Hill Education.
- Universaldesignguide. (n.d.). *Negative brainstorming*. Retrieved from <https://universaldesignguide.com/method/negative-brainstorming/> (accessed: 2023-02-11)
- Volvo Cars. (n.d.). *This is volvo*. Retrieved from <https://www.media.volvocars.com/global/en-gb/corporate/this-is-volvo> (accessed: 2023-05-09)
- Where The Road Forks. (2023). *Mid drive vs hub motor e-bike: Pros and cons*. Retrieved from <https://wheretheroadforks.com/mid-drive-vs-hub-motor-e-bike-pros-and-cons/> (accessed: 2023-05-12)
- Yongbiao, L. (2017). *Tiltable electric tricycle*. (Patent No. US9731785B1. <https://worldwide.espacenet.com/patent/search/family/059561178/publication/US9731785B1?q=US9731785B1>)
- Zoltan, R. (2019). *Tricycle for passenger and cargo transport*. (Patent No. WO2019162714A1. <https://worldwide.espacenet.com/patent/search/family/065951805/publication/WO2019162714A1?q=WO2019162714A1>)



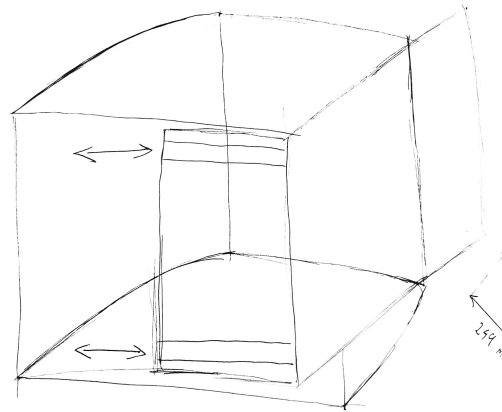
# A

## Appendix 1



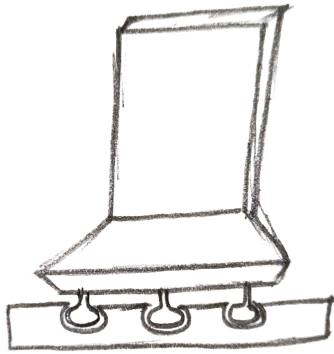
### Clasps.

The clasp concept locks the seat to the cargo frame by simply locking in place, similar to a plastic lunch box.



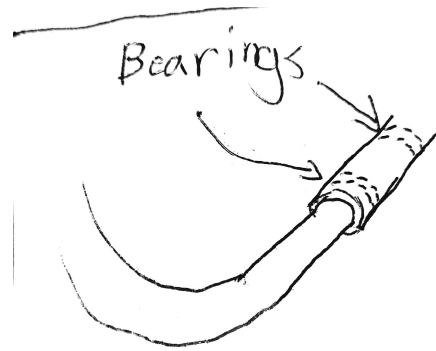
### Rail.

The rail concept for the seat consists of a rail attached to the cargo frame which fits with the frame of the seat, similar to a car seat. This allows for swift removal and attachment. It needs to be complemented with a lock pin to secure the seat in place.



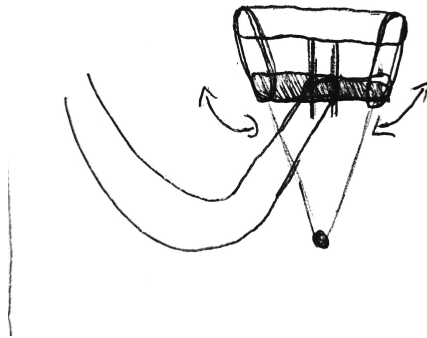
**Beetle fastener.**

The beetle fastener is a biomimicry approach and works by having a set of 'pins' underneath the seat. These pins have corresponding holes on the surface of the cargo frame where they lock in place when inserted.



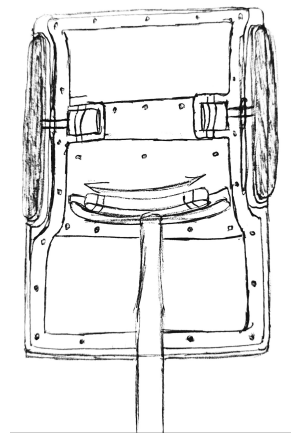
**Tubes attached with bearings.**

A simple solution where the front frame and cargo frame simply are connected using two bearings.



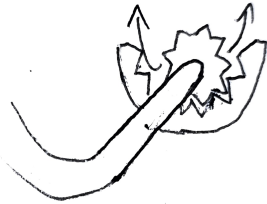
**Four bar linkage.**

The four bar linkage is inspired by Cossalter et al. (2005) and uses one horizontal bar attached to each frame, which are connected torque free by two angled bars. This allows for a virtual tilt axis, shown by the black dot, which could be placed on ground level for example. This could provide good vehicle dynamics since a normal bicycle also has its tilt axis on ground level.



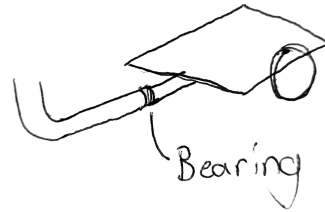
**Rail.**

The rail concept uses a rail-like solution, like Su-Yuen (2017), where one frame has an arch attached and the other frame has a connector which allows connector to move along the arch. Just like the four bar linkage, this also allows for placement of a virtual tilt axis on ground level.



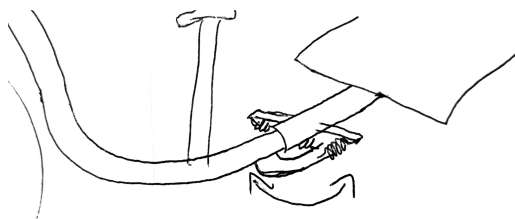
**Cup rack.**

The cup rack use a rack and pinion-like system where the front frame's end has a pinion and the cargo frame has a curved rack. By placing the pinion in this rack, the idea was that gravity would pull the pinion, and thus the front frame, down to the center of the rack. This would create a resisting mechanism which could help balance the vehicle.



**Flat bearings without tubes.**

This solution is simply a connection of the two frames using a single bearing.



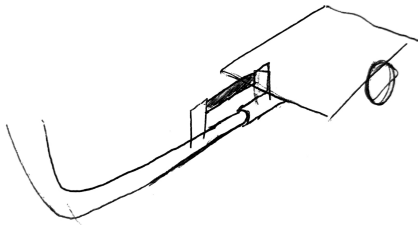
**Two springs on sides.**

This solution helps keep the vehicle upright using two springs. The springs connect the two frames to resist any tilting motion of the front frame.



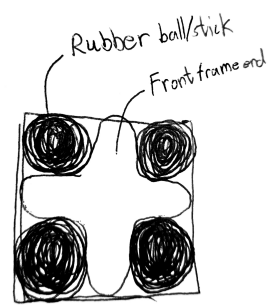
**Torsion spring around shaft.**

The torsion spring connects the two frames and resists tilting motion.



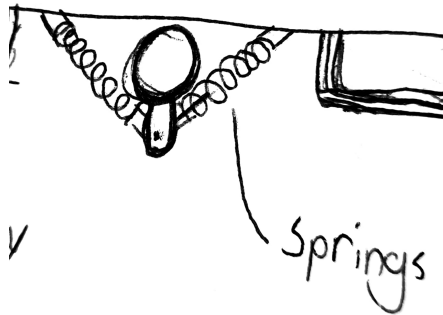
**Spring lever.**

The spring lever connects the two frames and resists tilting motion as seen in Haraguchi (2009).



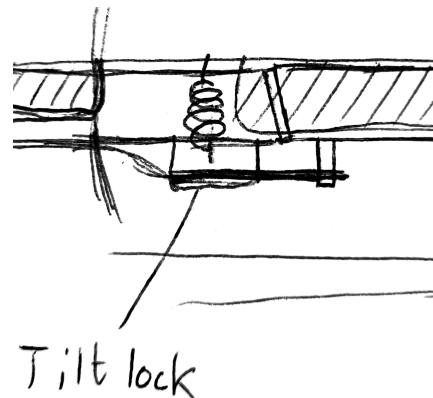
**Neidhart spring.**

The Neidhart spring uses a metal housing on the cargo frame with rubber pellets inside which resist any motion from the star shaped element which is attached to the end of the front frame, helping to keep the vehicle upright. Shown in Masaki (1987).



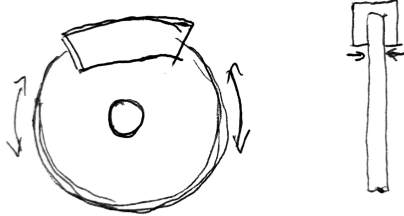
**V-spring.**

The V-spring is similar to the 'Two springs on sides' solution, but instead has the springs directly attached underneath the cargo frame.



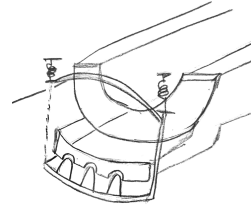
**Pin spring system.**

This solution uses a spring loaded pin attached to the front frame which is inserted into a hole on the cargo frame to completely stop the tilting motion, as in Haraguchi (2009). The pin is controlled by a switch on the handlebars.



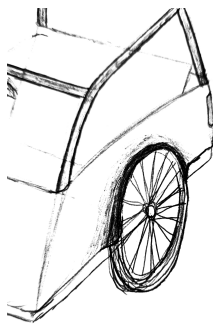
### **Tilt brake.**

The tilt brake consists of two parts, one circular element which is attached to one of the frames, and one 'brake caliper' which is attached to the other frame. When a switch is triggered by the user the 'brake caliper' will compress the circular element to stop its motion. Thus the front frame will be locked in place.



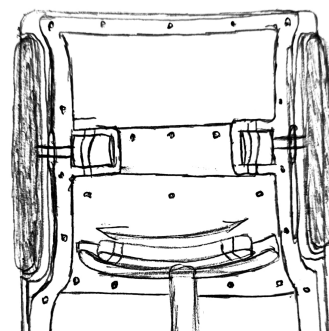
### **Sawtooth.**

The sawtooth mechanism uses a ribbed surface on one of the frames and a negatively ribbed surface on the other frame. When a switch is activated, the surfaces will be pressed together and thus lock in place, preventing any tilting motion.



### **Rear wheels 'built into' cargo box.**

This is a simple way to avoid splashes from the rear wheels. The cargo box will be built with room inside for the wheels so they are covered automatically.



### **Motors connected with individual drivetrain.**

This drivetrain uses individual electric motors for the two rear wheels which are connected using an axle.

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