Micromobility: Sustainability analysis, design and development of a personal mobility electric vehicle.

Daniel García Sánchez

Industrial Technologies Engineering

Master Thesis

Thesis supervisor:
Dr. Roberto Álvarez Fernández

Madrid
2021

ABSTRACT

This Master's Thesis develops itself around a thorough analysis of micromobility and future sustainable urban transportation modes. Micromobility being one of the emerging transport sectors in the late years as a way of achieving a more sustainable environment. Analysis is made not only as a environmental impact analysis, but also on other factors such as end user benefits, population health benefits, traffic congestion, etc. The development of a micromobility vehicle is then explained as a means of transportation for outside urban centers.

Keywords:

Micromobility, Sustainable transport, cities of the future, electric vehicles.

Content

List of Figures

List of Tables

List of Equations

1 INTRODUCTION

In recent years, there has been a clear trend towards what some consider the beginning of a transition to a more sustainable mobility [1]. This trend, which moves away from internal combustion vehicles and towards vehicles with more sustainable technologies and energy sources, is driven by several factors.

These factors include the population's growing environmental awareness, public incentives for the purchase of more sustainable vehicles, penalties on internal combustion vehicles, such as additional taxes and fees or a ban on circulation and parking in certain areas of cities; the rising cost of fossil fuels, the development of new technologies or other conveniences offered by electric vehicles [2].

While it is true that there is a considerable abundance of articles on climate change, studying its causes and its effects on our planet and population, what really portends an inevitable transition to a sustainable vehicle fleet is that fossil fuel reserves are becoming increasingly limited and difficult to extract. This, in turn, means that long before fossil fuel reserves run out their increasingly difficult extraction will lead to a considerable rise in the cost of use of an internal combustion vehicle, which will become financially unsustainable for many people [3].

Furthermore, it is also indisputable that air quality in large cities is greatly affected by the compounds and particles emitted by internal combustion engines. While it is true that there is great concern about the amount of CO_2 emitted by the world's vehicle fleet - due to climate change and all that this entails - it is other components, such as nitrogen oxides (NO_x) or volatile organic compounds (VOC), that directly cause health problems amongst the population, as well as environmental problems, such as acid rain, which affect the fauna and flora [4].

A clear example of this is the case of Madrid, Spain, the city from where this project is written, during the traffic ban of the CoVid-19 pandemic in the months of March and April 2021, the air quality of this city improved significantly compared to the same time in previous years [5].

All of the above are reasons why major mobility brands are increasingly tending towards launching more sustainability-oriented products, such as electric vehicles in the automotive industry.

However, the problem of sustainable mobility goes beyond pollution. The increasingly population agglomeration in large cities causes serious problems of traffic congestion, collapsing these cities during rush hour. Even public transport is also beginning to become overcrowded, where the service is not able to meet the demand. Not only is this a waste of time for many people on their daily commute, but also a slow in production during working hours due to mental fatigue and lack of personal time [6].

There are cities taking initiative to solve these problems beyond pollution. In Norway, a great part of the vehicle fleet is already electric, which means that cities such as Oslo, where petrol cars have been banned for years, are beginning to get crowded with cars. In response, Oslo has eliminated hundreds of parking spaces from the streets, converting them into bike lanes, green areas, parks, etc. Furthermore, it has banned car circulation in a large part of its central area. This does not only affect internal combustion cars, but electric cars also. Cities like Oslo are betting on pedestrianization, creating a more sustainable environment, not only in terms of pollution, but also in the capacity of the city in terms of internal mobility, increasing the city’s population life quality [2].

Therefore, in recent years, yet another revolution in sustainable mobility is being experienced with the popularization micromobility vehicles, such as electric bicycles, electric scooters, etc.

1.1 Objectives

This project’s objectives include the research and analysis of micromobility in big cities and elsewhere, as well as the prototyping and manufacturing of a micromobility vehicle and its real-world use cases.

2 BACKGROUND

It is important, to understand the motivations behind the development of new modes of transport such as micromobility vehicles, to first know the history and how these means of transport appeared and evolved over the years.

For this purpose, it’s necessary to take a closer look at the general evolution of transportation through recent history and what conditions caused micromobility to appear.

2.1 Socio-demographics

Transport is “the movement of people or goods from one place to another” [7]. The own definition of the word implies that properly understanding how transportation and mobility have changed and evolved in recent history, implies understanding, first, how socio-demographics work and what the world has done, and continues doing, to overcome the problems and make transportation more sustainable.

Going back to 1924, the first while line was painted in London, as seen in Figure 1. This while line was the first attempt to solve traffic congestion caused by the movement of people in horse carriages and combustion powered cars [1].

Figure 1: First white traffic line painted on the pavement of a London street.

This is the first time in history where the then biggest city of the world, soon to be overtaken by New York, with over 5 million people living there [8], was experiencing such an abundance of people that the need of transportation exceeded the infrastructure, causing major traffic congestion, enough to drive authorities to do something about it.

Cities have continued and continue growing, driven by factors such as lower times and costs in transportation, housing supply, amenities or agglomeration effects such as the availability of human capital and entrepreneurship movements [9]. This, in turn, causes major cities to have major traffic congestion. From the horse carriages and cars used in the London of 1924 to the modern cars of today.

And although, individually, people still perform roughly the same amount of travelling, take the UK example: 1091 trips per person per year in 1990 vs. 1019 trips per person per year in 2000; population growth and city population-agglomeration mean that much more distance is done globally and within a more constraint-area, again in the UK: 295 billion passenger-km per year in 1961 vs 731 billion passenger-km per year in 2001. And although public transportation has advanced, licensed cars in the UK have grown from 6.2 million in 1961 to 26.4 million in 2001, which represents a 425.8% increase in roughly 40 years [1].

More efforts to pursue a more sustainable traffic and traffic infrastructure have been made since then. Like the one made by the UK government in 1998, where some objectives for sustainable transport were made [1]:

- To protect and enhance the built and natural environment.
- To improve safety for all travelers.
- To contribute to an efficient economy, and to support sustainable economic growth in appropriate locations.
- To promote accessibility to everyday facilities for all, especially those without a car.
- To promote the integration of all forms of transport and land use planning, leading to a better, more efficient transport system.

These points are as relevant today as they were then. Although infrastructure is getting better, the population continues growing and moving to cities, which keep expanding, even upwards, constraining even more the transport infrastructure.

2.2 Sustainable transport

To understand why sustainability is growing in importance it is first necessary to know its meaning and its implications.

Sustainable development is defined as that of which meets the needs of the present without sacrificing the ability of future generations to meet theirs'. These needs often include developments such as economic development, social and human development or, most notoriously, environmental and ecological awareness. [10]

A lot has been said about limited resources such as carbon-based fuels. Sustainability in this regard would mean limiting the consumption and thus extending the life of these resources. It also implies its indirect effects which, by consuming these resources, cause damages to the environment that would affect future generations lives, needing to adapt to new conditions or losing resources by means of these effects.

In regard to mobility or transportation, which concerning resources when talking about "sustainable transport" are often questioned and this needs to be cleared depending on what it is that it's been talked about.

The transport sector consumes limited resources, first that will come to mind to many is oil. This is indeed one of the most talked about because of its concerning depletion and its effects on the environment. But transport also consumes other limited resources such as other types of energy, human resources, space resources, including ecological habitats or habitable space and time [10].

Although carbon-fuel depletion and carbon-fuel emissions are concerning, it is of importance to take into account all of the other limited resources when talking about sustainable transport as a whole.

Furthermore, transport related decisions are often made in favor of other matters such as economic growth and job creation, the use of certain space and socio-economic and socio-demographic matters like transfer of wealth [10].

As explained before, transport involves complex relation to socio-demographic habits and interests. This means that sustainable policies implementation is harder than a predictable, closed system would be. Trying to apply policies to solve one specific issue might be beneficial in the short term for that specific issue, but it might affect negatively other transportation matters. Thus, why transport sustainability is still a relevant problem after all these years since those first traffic congestions in London [10].

Taking traffic congestion as an example, bottlenecks might be easy to solve in some cases when looking at certain parts of the infrastructure. Fixing a crowded intersection by modifying traffic lights timing might solve congestion in that certain area, but it might cause other congestions elsewhere. The transportation system must be looked as a whole, applying too localized policies might just cause the bottlenecks to move around instead of improving the system as a whole [10].

Then there’s a fact often overlooked by policy-developers and analysts, which is that every action on the transportation system also induces changes in human behavior. An example of this might be opening a new highway or widening an existing one, while the analysis might have proven good results for the same traffic, people that used other paths for their transport needs will now move to use the new or modified path, increasing traffic or causing bottlenecks elsewhere [10].

Another example of human behavior affecting sustainability is in regards with safety, where some measures are put in place to increase traffic safety (i.e., road barrier), this might induce a riskier behavior on humans as the new, safer, environment elevates the risk tolerance of humans [10].

This is why some transportation “megaprojects” such as massive highways, enormous expansions on the railway system or other relevant high-cost projects’ outcomes are difficult to foresee and can sometimes have an overall negative impact on the system as a whole.

Some studies conclude that for transport to shift into a sustainable direction properly, the innovations, rather than being high-cost, massive projects; they need to be innovative, low cost, have a quick implementation and, most importantly, be scalable [10].

This is where micromobility enters the scene as a promising way of improving sustainability in the transport sector.

2.3 History of micromobility

The term “Micromobility” is increasingly used in transport literature in recent years, although sometimes not as well defined. Micromobility stands for those trips where a small, light vehicle is used as a personal mobility alternative for short distance-commutes or last-mile transport [11].

In recent years micromobility has made an entrance in major cities around the world in the form of shared micromobility. Although micromobility platforms have previously existed for a considerable amount of time, in the form of bicycles, skateboards or even electric longboards as far back as 2012 [12], it has become a commuting habit for many cities’ population thanks to the shared micromobility ecosystem.

Shared micromobility includes platforms like the notorious e-scooters, bicycles, e-bikes or electric bicycles. Although sharing transportation modes, like Copenhagen’s bike sharing one, date as far back as 1995, it wasn’t until recent history that the popularity has exponentially grown. In 2020 there were approximately 3000 bike-sharing transportation modes around the world, managed by both public entities, like city halls or universities, or private companies [13].

All of this goes hand in hand with the facts mentioned in the paragraphs above about cities growth, their transport challenges, and the need to find innovative, low cost and scalable solutions. Thus, why the adoption of micromobility as a flexible, sustainable means of transport has entered the scene globally in such a small period of time.

A consequence and proof of the rapidly growing popularity of these vehicles, is the number of successful start-ups which have become unicorns – a valuation of 1$ billion dollars - which operate different electric renting micromobility transportation modes around the world [14]. These start-ups have broken speed records of becoming unicorns, which comes to show how scalable micromobility is.

In summary, micromobility is a new form of transport derived from the necessities of highly populated cities to have a more sustainable form of transportation that benefits not only the users by providing flexibility, but to the cities as well, as the growing urban population makes it harder to use the limited public road space.

3 USE CASES

To understand the use case and why micromobility is becoming the choice for commuting or last-mile transportation for many people in the world, the use cases need to be analyzed.

Micromobility appeals to the end user as a way of transport which is flexible, sustainable, cost-effective and on-demand [15]. Made for short distances, micromobility reduces the risks and costs of using other private vehicles and it’s more flexible than public transport, although it can be used in a combination with these transport methods as well. Take the example of long-distance travel from outside or inside the city, because of its lightweight nature, micromobility platforms can easily be transported in a bigger private vehicle or in public transport and used for last mile transport, increasing flexibility and saving time.

Normally, micromobility vehicles are lightweight and don’t exceed 45 km/h [15], which makes them perfect for cities or urban centers. Although electric micromobility vehicles such as electric scooters, e-bikes or others, have gained popularity in the past years, they can also be human powered, which makes them even lighter and easier to carry, as well as provide more physical health benefits to the user.

Their popularity also comes from the fact that bigger private vehicles, such as cars, have an adverse impact on health and quality of life by terms of carbon emissions and other toxic emissions, as well as traffic congestion [15]. With micromobility vehicles, these issues are improved, or in some cases even solved, by means of flexibility and more sustainable energies like electric or human power.

There are mainly two types of micromobility users that can be derived from the type of ownership of these micromobility vehicles. These vehicles can be either bought from a tech manufacturer or on-demand-rented directly on the street, usually via a smartphone app. To rent these kinds of vehicles usually only a driving license and wearing a helmet is required, which makes the registration process easy and fast. Some of these services even include the helmets with the service [11].

3.1 Shared micromobility

Renting micromobility vehicles has become popular in many countries over the past few years. Multiple public and private entities over the world have been providing cities with shared micromobility transportation systems [14].

Shared micromobility enables users to be able to use on-demand transportation on an as-needed basis. These transportation modes were introduced manly to alleviate traffic congestion and provide low-emission public transportation options to the users [16].

3.1.1 Public bikesharing

Public bikesharing systems go as far back as 1965, when Amsterdam was the first to provide public bicycles which could be used by anyone in the city. These bicycles where painted white, thus the "white bicycles" name which they are referred as. This first generation of bikesharing failed due to the bikes being stolen as they were distributed all over the city [17].

The denominated "second generation" bike sharing systems tackled this problem by introducing dock stations on which bicycles were locked to. To be able to use one of the bicycles, a coin deposit needed to be made in order to unlock it from the station. Still, bicycles were often stolen as the deposits were a low price to pay compared to a bicycle and these were made in cash. These second generation bikesharing transportation modes were first introduced in the 1990s in Denmark [17].

Third generation bikesharing transportation modes were first opened in France in the late 1990s. New computing technology allowed for a safer, trackable system which meant that a bicycle use control could be implemented. Incrementally modern, these transportation modes allow the users to pay with electromagnetic badges, credit cards or even through smartphone apps, to unlock a bicycle from the docking station. New technologies also allow for the bicycles to be tracked live, which means that, although still happening, thefts are less frequent, and the bicycle fleet can be easily controlled and maintained. These bicycles have become electric in the past decade, allowing for assisted pedaling and a low effort transportation [17].

Although these transportation modes have become popular, they still have its limitations. Mainly, the docking station. Although these services are on-demand, docking stations are limited in number and also in bicycle docking spaces. This means that the origin or destination of the user can be far from the closest docking station, and it’s not guaranteed that the docking station will have any bicycles available.

3.1.2 Dockless micromobility sharing

To solve this last-mentioned issue, a denominated “fourth generation” sharing transportation mode has entered the scene in the past few years. These transportation modes involve the so called dockless sharing.

Technological improvements have made possible the implementation of free-floating ridesharing transportation modes. Where bicycles are parked anywhere around a city and can be unlocked using a smartphone application. These services have normally a limited use area, where the platforms cannot be parked outside a geofenced area, at the risk of receiving a fine by the entity operating them.

These systems where first started to be implemented around 2017, where companies such as Social Bicycles (now JUMP and owned by Uber), Motivate (currently acquired by Lyft) and LimeBike, with their recognizable lime-green bicycles, began operating these transportation modes in the United States with electric bicycles, also called e-bikes [16].

Later, around the beginning of 2018, companies like Lime announced the availability of electric scooters or e-scooters. These companies started leaving hundreds of scooters on the streets without any permission of the municipal authorities. The e-scooters were a success. Lime had presence in 120 cities across more than 30 countries [18].

The on-demand features, availability and flexibility of these platforms made it so that users rushed into these transportation methods quite quickly. The success and rapid scalability of these companies took many municipal governments by surprise, with thousands of e-scooters and e-bikes appearing parked overnight on the cities’ sidewalks [19]. Many of these companies have had to resign from certain locations, as well as pay fines due to the avoidance of permits in certain municipalities.

These transportation modes are much more flexible than docked systems. They are self-arranging, meaning that during peak hours the vehicle availability is where it's needed as users use them to commute to work and back. Furthermore, they are not used the same way as the docked systems. Studies have shown that while docked bikesharing systems are used almost exclusively for commuting to work and back, e-scooters are also used as a free time or leisure transportation system [19].

In terms of pricing, e-scooter sharing platforms often use an unlock fee plus a charge per distance or time unit. In the city of Madrid, Lime e-scooter, for example, cost 1 € to unlock plus 0.23 €/minute to use [20].

With these services being on demand, it makes it easy for people to choose them over public transportation if there are disruptions on the later, or the public transport system takes too long to arrive.

All the above proves that there is an appeal for the urban population to use these sharing platforms. On-demand and flexibility mean that people can use these platforms as they want without having to commit to buy and carry around a device of their own, making it more comfortable if the use of public transport or car is needed for the daily commute.

3.2 Owned vehicles

Owning a micromobility platform is affordable and hustle-free for the most part.

Their cheap entry price compared to other bigger means of transportation, like cars or motorcycles, make them affordable to own. For instance, a Xiaomi standard standing scooter costs around 350 € in Europe [21].

These scooters also have a long lifespan, around 3 years or more if it's correctly maintained. Some users have also reported to do more than 10 000 km on them which, for the short commutes they are meant for, it's a considerable distance [22].

The user's only task to often perform is to charge the vehicle at home or the destination. This is also the only cost that these vehicles usually have as they require close to zero maintenance. Depending on the country, electricity spent charging these vehicles is usually cheap compared to fossil fuels [23].

In Spain, as of the writing of this paper, an electric scooter with 275 Wh like the Xiaomi S1, and an approximate range of 30 km [24] and electricity price of between 0.20 €/kWh and 0.3 €/kWh (without taxes) [25], would cost approximately between 0.05 and 0.08 € to charge to its full capacity. This means that electric scooters are cheaper than 1 cent per km in Spain. In comparison, a car with an average consumption of 6 l/100 km and with gas prices averaging 1.30 €/l [26], this roughly puts an internal combustion engine car at 0.08 €/km to use. This just proves that overall, the cost of buying and operating an electric scooter is much cheaper in comparison to other common transportation modes.

Apart from electric motorbikes, usually micromobility vehicles are easy to service. The most common serviceable items are tires (flat tires) and brakes [23]. The end-users can get the parts online and change them themselves even with limited tooling, as electric scooters often include the tools with the box. The same applies to other platforms like e-bikes or normal bicycles or boards.

These platforms are lightweight, which means that the user can be able to carry it if public transport or another transport method is used for the trip. Although shared mobility allows the users to not have to carry anything in other transport methods, owning the platform ensures that the user will always have the method available when needed and isn't affected by rush hours vehicle shortage.

Overall, comparing to e-scooter sharing prices, if used daily or often, e-scooters seem better to be owned than shared with ride sharing platforms.

4 MICROMOBILITY SUSTAINABILITY

Micromobility helps the transport system by introducing environmental, economic and social benefits to both the users and the general population of the cities where micromobility is used [15].

As written previously, transport sustainability not only involves environmental concerns, but rather a complex agglomerate of benefits. The next are some of the benefits provided using micromobility.

4.1 Efficiency

There have been studies where the e-scooter sharing systems have been analyzed and compared to other modes of transport. A study made in 2018 explored these benefits by studying 30 000 random, hypothetical trips in Chicago with around 1 000 e-scooters scattered around the studied area [27].

This study showed that e-scooters are most efficient for distances of less than around 3 kilometers [27]. This comes from the fact that there are multiple scenarios where the limitation of existing transport infrastructure, private or public, leave only few choices to cover these distances. Micromobility vehicles are the faster and more efficient platform to perform these tasks.

There is also the so-called first-mile or last-mile transport, where the users need to go from their parking spot, if using a car, or final public transport station to their destination. Depending on the city, these distances can sometimes be time and energy consuming if performed by foot, especially in the outskirts of cities where public transport is further scattered [27].

Another study conducted in Germany, concluded that a light weight, foldable, micromobility vehicle could potentially shift close to 5 000 car-driven-km to public transport and save time on commutes [28]. Together with the fact that users could also save costs on parking, fuel, and maintenance, make micromobility platforms ideal to switch to from certain cases.

Not only is efficiency applicable to the general population, transportation or delivery companies could also benefit from micromobility transport. Studies conducted have concluded that, by using micromobility vehicles, delivery services could not only save time by avoiding congested traffic and finding easier parking spots, but also costs related to the use and maintenance of fossil fuel vehicles [15].

Overall, when talking about efficiency and cost saving, micromobility is a sound choice for short or last-mile trips.

4.2 Accessibility

In terms of accessibility, micromobility provides access to harder-to-reach destinations or origins. This provides both professional and personal opportunities to people that, otherwise, couldn't afford them or had harder access to them.

This comes from a point explained earlier, where public transport can't cover every small area and thus, the further away from the city, the more scattered public transport stations are, making it harder to reach some places.

There is also the fact that city centers are increasingly becoming harder to reach by means of private vehicles. This is a direct result of traffic congestion. Cities are becoming growingly concerned about the negative health and economy effects that both traffic congestion blocking city centers, and pollution emitted by carbon-based fuel vehicles, directly and indirectly cause. Some cities like Madrid have restricted traffic in certain areas of the city center. These measures have proven to reduce pollution as well as change transport habits in the population [4]. Public transport and micromobility are the go-to choices when needed to move around these areas.

Figure 2:People using shared e-scooters to move around a LEZ (Low Emission Zone) in Madrid, Spain.

Micromobility makes also transport readily accessible for the users. These vehicles are lightweight, in case of ownership, the devices can be carried to the user's home or place of work without much effort, thus reducing the need of walking to a parking spot in case of owning a car. Vehicles like e-scooters or e-bikes are also chargeable by means of a normal power outlet, making it always easy to charge and leave with the appropriate charge.

Shared micromobility vehicles are also readily available for use, mostly, in urban centers, as seen in Figure 2. A difference must be made here between docked and dockless or "free floating" vehicles. Docked vehicles use a docking station that charges them, as is the case of many public-funded micromobility transportation systems like BiciMAD in Madrid [29] or citibike in New York [30]. The introduction of dockless or "free floating" vehicles, which are normally parked on the sidewalks, was made by private shared mobility companies. Because of its scalability, thousands of micromobility vehicles can be found around many cities only a few meters away from the point of origin, as seen in Figure 3.

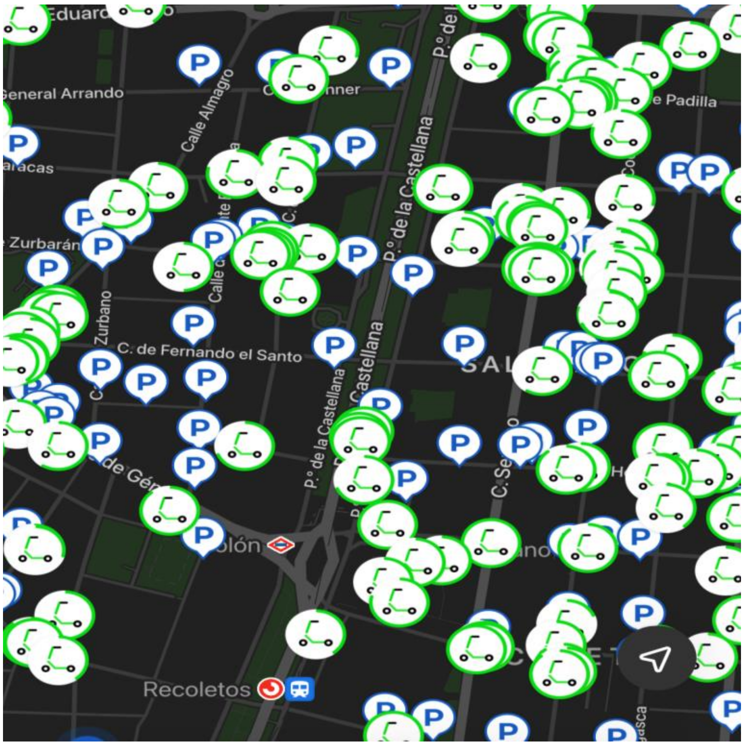

Figure 3: Map of Lime-branded e-scooters available for use in a part of Madrid, Spain.

Accessibility is native of micromobility vehicle design and scalability, and it is another big factor in favor of the sustainability of this method of transportation.

4.3 Environment

Although there are many factors when talking about a sustainable environment, the main factor that is talked about when speaking about environmental sustainability in electric vehicles are greenhouse gas and other gas emissions to the atmosphere.

4.3.1 Emissions

The transport sector is one of the most greenhouse-emitting ones, making up around 14.5% of global greenhouse emissions, as seen in Table 1 [31].

Sector	Percentage (%)	Sector	Percentage (%)
Industry	**29.1**	**Transport**	**14.5**
Non-ferrous materials	6.2	Road	10.6
Iron and steel	4.8	Air	1.5
Chemistry and petrochemistry	4.3	Rail	0.5
Non-ferrous metals	1.4	Other	1.9
Food and tobacco	1.0	**Energies (other)**	**14.5**
Paper, pulp and print	0.9	Energy utilized in the energy sector for its own needs	8.1
Other industries	10.5		
Agriculture and Forestry	**20.2**	Coal mining	2.7
Livestock and manure	6.5	Crude oil and natural gas production, refining and processing	3.7
Energy utilized in agriculture	0.8	**Waste dump areas and waste water**	**3.4**
		Waste dump	1.6
Combustion of agricultural waste	0.1	Waste water and other	1.8
Agricultural soil	5.2		
Forestry and other uses of soil	7.7		
Buildings	**18.3**		
Residential	11.2		
Commercial and public services	7.0		

Table 1: Greenhouse gas emissions by sector [31]

Although there are other sectors which make up the same or even more greenhouse emissions as the transport sector, other health-threatening gases need to be looked at to gather a better idea of just how harmful combustion engine exhaust gases are.

While these other exhaust gases are less mentioned compared to CO_2, CO_2 levels can be an indicator of the proportion of these other gases in the air.

4.3.1.1 Combustion engines

Combustion engine vehicles create exhaust gases product of the combustion of fuels inside their engines [32]:

- Nitrogen – N_2
- Oxygen – O_2
- Water, water vapor – H_2O
- Carbon monoxide – CO_2

- Sulphur dioxide – SO_2
- Hydrocarbons – HCs
- Nitrogen oxides – NO_X

Nitrogen and oxygen are found in clear air and are not harmful to humans or the environment [32].

Water vapor has been found to cause two thirds of natural greenhouse effects. Water molecules in the air are able to capture and retain heat. Having said this, water vapor is naturally present in the atmosphere and human activities barely add to this amount [32].

Carbon monoxide is produced when the oxidation of the carbon fuel in the combustion process is not fully completed. Carbon monoxide is highly toxic and harmful to life. Carbon monoxide molecules are able to bind to red cells in the blood, which displaces oxygen and reduces the system's ability to transport it. Low carbon monoxide inhalation already produces some symptoms of fatigue or even unconsciousness [32].

Carbon dioxide is the most talked about gas when talking about climate change and greenhouse gases. It is considered the most harmful human produced greenhouse gas because it makes up to 55% of total emissions. Carbon dioxide in the atmosphere is increasing at a rate of 0.20% every year. This gas is naturally cycled by means of the biosphere, where natural geological events or life itself produce carbon dioxide and plants and other organisms absorb it and convert it to carbon by means of photosynthesis [32].

Sulfur dioxide, although emitted in small amounts in a sulfur-containing-fuel combustion process, can cause respiratory problems.

Hydrocarbons, like carbon monoxide, are a result of incomplete combustion processes. These are cancerogenic particles of non-combusted fuel emitted to the atmosphere and can cause health issues from irritation of certain organs to more severe forms of cancer [32].

Nitrogen oxides are produced as a result of the combustion of hydrocarbon fuels at high temperature and pressure, such conditions are present in internal combustion engines. Diesel engines generate more NO_X , 10 to 20% of exhaust gases, compared to petrol engines, with around 2% of exhaust gases [32].

Nitrogen oxides are relevant in cities as their quantity and toxicity are most concerning compared to the rest of emissions [4]. These gases can modify hemoglobin, restricting O_2 transport and can also react with the moisture in the lungs to create nitric acid and nitrous acid. Nitrogen oxides can cause severe respiratory symptoms like pneumonia and can cause severe blood-related issues like heart diseases [32].

In particular, nitrous oxide acts as a narcotic and affects psychomotor performance and the ability to remember; nitric oxide creates nitric acid when combined with water, causes smog and reacts with metal and organic materials; nitrogen dioxide is more toxic than nitrous oxide and causes ground level ozone [32].

4.3.1.2 Electric vehicle emissions

Although, as is the case with any electric-powered vehicle, micromobility vehicles like e-scooters and e-bikes are considered environmentally friendly due to the nature of electricity and its renewable capabilities, in reality they often do cause indirect carbon emissions.

Although electric vehicles don’t cause any direct emissions by using them, depending on the country where the vehicle is used, electricity might be a product of fuel burning power plants. With great variations between countries, while a country might mostly use renewable or non-emitting power plants such as solar or nuclear, another country might mostly use carbon power plants. Charging an electric vehicle in the first country might barely cause any emissions while doing it in the second one might produce the same or more CO_2 emissions per km as a combustion engine vehicle [33].

A negative example of this is the case of Paris, France. In 2020 a study revealed that the introduction of dockless e-scooters in the city of Paris caused an indirect emission of around 12 000 tons of greenhouse gases, because of people switching from public transport to micromobility alternatives [34]. This is because, while Paris’ public transport vehicles use renewable energy, electricity in the city does not. France’s electric energy can produce up to 70g of CO2 eq. per kWh [33].

4.3.1.3 Comparison

While some studies compare indirect CO_2 emissions caused by charging an electric vehicle to direct CO_2 emissions by internal combustion engine vehicles, a more adequate comparison should be between electricity generation and distribution to fuel extraction and distribution. As combustion engine vehicles do emit harmful gases while being used, electric vehicles do not.

The transportation fuel supply chain is complicated, from finding oil resources, and extraction, to transportation of these raw resources, often by internal combustion vehicles such as boats or trucks as well, which accidents in themselves can cause devastating effects to local ecosystems [35]. Storage and refinement of the resources, to more transportation chains, again, often in fuel-burning vehicles, to the end distribution centers [36].

Every one of these steps, referenced in Figure 4, represents direct and indirect CO_2 and other toxic gases emissions.

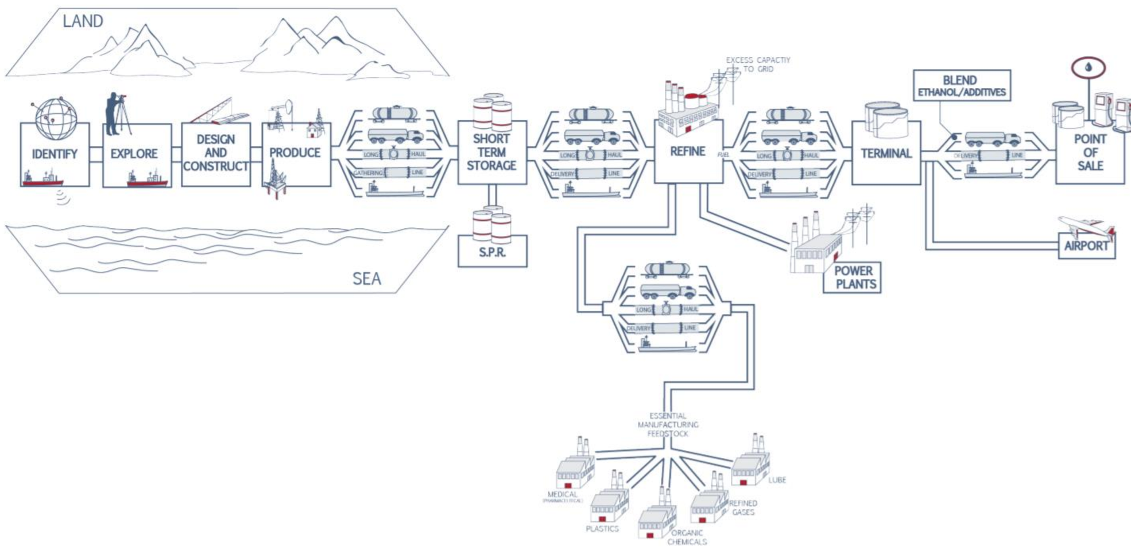

Figure 4: Oil supply chain [36]

In contrast, while building and maintaining the electric supply chain might indeed cause emissions, the nature of distribution of electric power, seen in Figure 5, makes it much cleaner to the environment than the oil supply chain [37] [38].

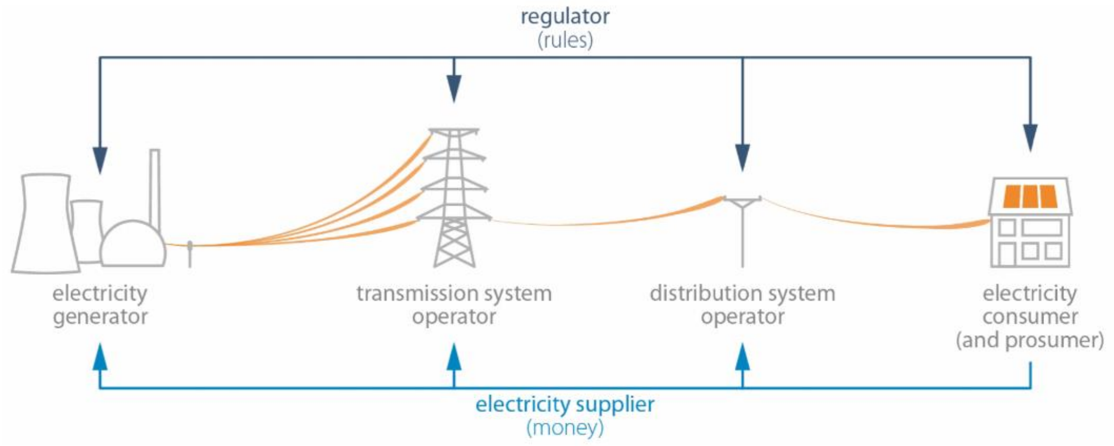

Figure 5: Schematic overview of the electricity system[38]

While countries like France still use greenhouse emitting power plants now, electricity generation is also transitioning to a more sustainable production by means of renewable energy. There are realizable ways to perform this, with some countries already planning to reach 0 emissions in the near future [39], [40]. This would mean that any electric means of transport would barely indirectly emit any toxic or greenhouse gases when used.

An often-overlooked factor, over CO_2 and greenhouse gas emissions, is that combustion engine vehicles emit far more toxic gasses, such as nitrogen oxides or NOx, which directly harm the population living in the same area where these vehicles are driven [4]. Even in the current day where great part of electricity is made by means of carbon-based fuels in many countries, these processes are cleaner and more efficient than the one from a car's internal combustion engine [41]. Together with the fact that this production plants are often far from urban areas, it limits the negative impact of these emissions on the population and other ecosystems.

The use of micromobility is positive at the moment in many cases where the main means of transport is the private, internal combustion engine vehicle. An example of this are the cities of Sydney and Melbourne, in Australia, where around 67% and 76% of short trips, respectively, involve the use of private vehicles [42].

Another example is the United States, where more than half of car trips are used to travel less than 8 km, a distance that can be done by most micromobility vehicles. Transitioning to these vehicles would signify a drastic reduction in greenhouse and toxic emissions [43].

Emissions and pollution due to vehicle production and battery manufacturing is another factor to consider. This factor is more difficult to account for as the whole manufacturing process needs to be traceable to be able to accurately calculate the effects of this on the environment. Having said this, bigger mobility products like cars, busses, trains, etc.; have many more manufacturing parts and processes to them, which in turn make them a more contaminating factor. It will depend on how these vehicles are used, how many people the often carry and how long their use life is.

Finally, transport should be also considered. These transportation vehicles need to be shipped and distributed from the manufacturing facility to the end users. Depending on the end user's location, this process often involves shipping by cargo vessel and then by train or truck to the dealership [44]. With ships, trucks and some trains still being carbon-fuel based, the emissions keep ever growing.

While micromobility vehicles often suffer the same shipping path, many more can be fitted into the same space that a car would occupy, considerably reducing their carbon footprint.

4.3.2 Other environmental factors

While emissions are often looked as the most relevant factor when studying transport environmental impact, other factors shouldn't be ignored when evaluating the impact transportation has on the environment.

One main factor to look at in this regard is service. Internal combustion engines require periodic servicing which often requires replacing oil, coolant, refrigerant gases, etc. The change of this liquids is hard to do in a clean manner, which can cause some of these fluids to escape into the environment. Furthermore, these fluids often need to be disposed of or recycled in some way, which pose another set of other concerns in these processes.

On the other hand, electric micromobility vehicles require none of this service factors. The only consumables, which are not necessary to replace that often as a cause of the nature of their use, are the tires, brakes or transmission pulleys (if applicable). Compared to their private car counterparts, these parts are much smaller and are compose of less parts. With the vehicle being so light, the degrading of these components is not expected to be as quick as a bigger vehicle. [23]

There is also the factor of pollution of end-of-life vehicles due to the contaminating nature of the batteries that often power micromobility vehicles. Although the fact is that this act depends on companies and end users, which might not go into the recycling process and, consequently, their vehicles ending up contaminating soil and water; studies support a future vision and options for vehicle's battery recycling [45].

Overall, looking at the life cycle of a private combustion engine vehicle, referenced in Figure 6, its manufacturing process, maintenance, use and end of life is often much more complicated, involving many more processes, than a micromobility vehicle.

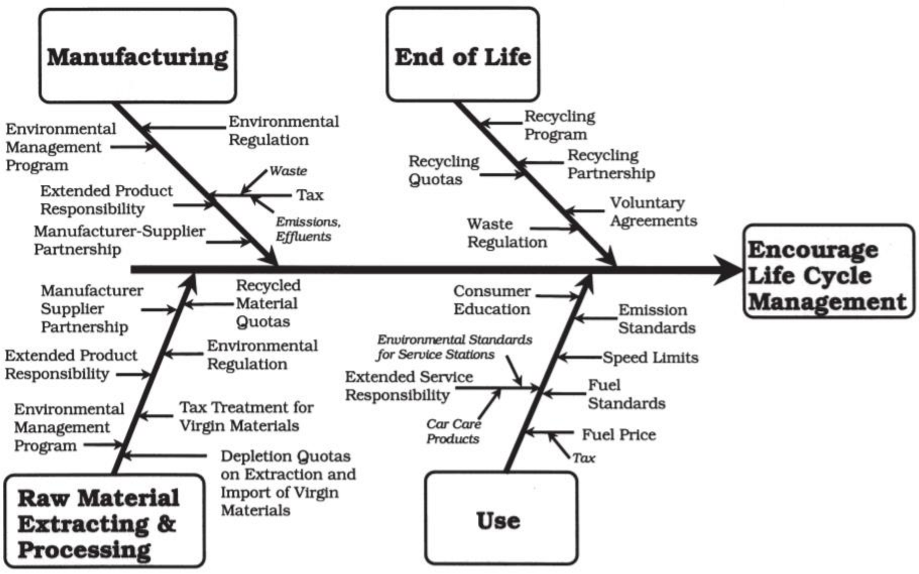

Figure 6: Life Cycle management of a combustion engine car [46]

Lastly, micromobility vehicles, either if electric or human powered, contrary to internal combustion engines, barely cause any noise. The European Union estimates that 40% of its population is exposed to concerning levels of traffic-relevant noise, which exceeds 55 decibels, exceeding the safe levels of long-term noise exposure. An infographic can be seen in Figure 7. This can cause negative effects in the well-being and can be linked to anxiety, depression and limiting learning capabilities [47] [48].

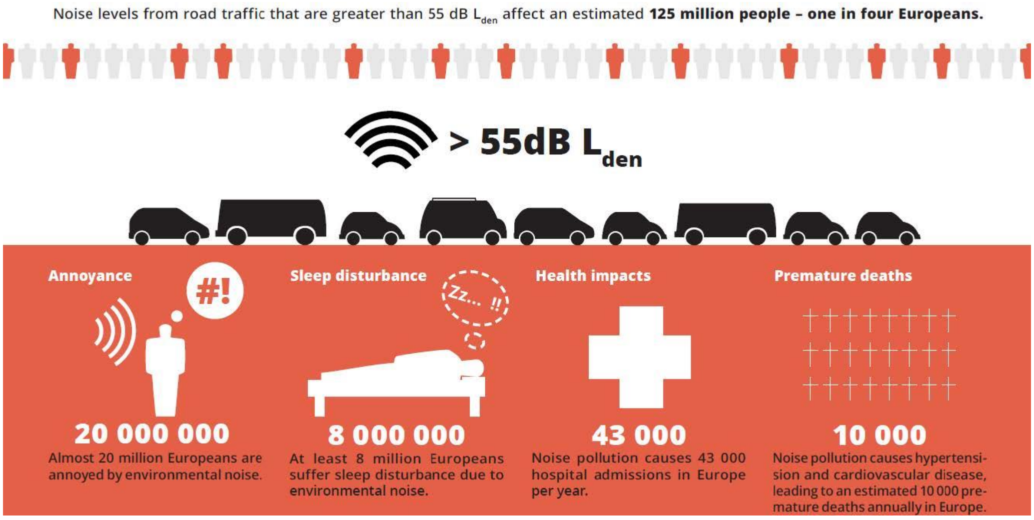

Figure 7: Noise pollution health risks [48]

4.4 Traffic congestion

Another important factor when looking at micromobility sustainability is traffic congestion.

There is only so much public road space out there. With the cities becoming more and more populated, incrementing this space is becoming difficult and the road space per capita is, in turn, shrinking with time. Because of the nature of micromobility vehicles, they don't occupy as much space as a car, which means that there would be more road space per capita with the use of micromobility.

This will also help with congestion as micromobility vehicles can take advantage of their small size to use the road space more efficiently.

Parking space is also becoming a concerning factor in bigger cities, where limited parking space is becoming more common and costly. Micromobility vehicles occupy a fraction of the space that a car does. Studies have shown that as many as 20 e-scooters can be parked in the same space that a private car would occupy [47].

Having said this, recent e-mobility sharing transportation modes have caused polemic in certain cities as their dock-less system, which allow users to park the scooters directly on the sidewalks, often blocked sidewalks and caused disruptions to pedestrian paths. The parking of the e-scooters are responsibility of the users, which often do not abide by the rules and park the scooters in the middle of the sidewalk or blocking crosswalks [49].

Users of shared and owned micromobility vehicles also cause major disruptions to pedestrians by using the vehicles on sidewalks, going at high speeds compared to pedestrians [50].

Cities like Madrid have implemented measures to try and solve this issue by ticketing the users of these services if they park the vehicle incorrectly or riding on the sidewalk, as well as creating designated parking areas for these vehicles [51]. Sharing company apps are also trying to suppress this issue by implementing internal fines to those who park incorrectly, displaying warnings on their apps like the one seen in Figure 8.

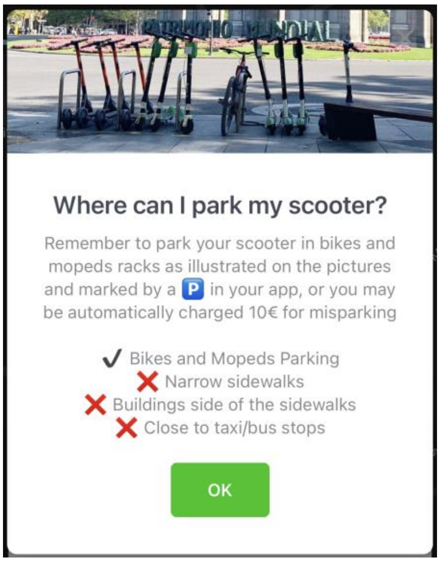

Figure 8: Screenshot of Lime's mobile App notice, which warns users to park the rented scooters correctly under the risk of a fine.

4.5 Wellbeing

Regarding wellbeing, human-powered micromobility vehicles such as non-electric scooters, roller-boards or bicycles, promote physical movement and can, in turn, improve mental health [52]. Some studies have shown that, after introducing micromobility alternatives in certain cities, physical activity increased, consequently improving health at population level [53].

Improving health at population level is not only important for each individual, but also helps ease the sanitary system and reduce costs in public health, which in turn can be invested in investigation or improving the current health infrastructure.

While human powered vehicles offer more physical activity, electric micromobility alternatives also have their advantages. An example are electric bicycles which, by making it easier for a person to pedal, individuals might choose it to perform more challenging journeys rather than taking a private or public vehicle and consequently not performing any physical activity. It makes physical activity accessible for those who might not be fit enough to endure commuting in a normal, human powered, bicycle. There is a risk, however, and it's that those individuals might have walked or performed a tougher physical activity overall [52], [54].

Furthermore, not only do micromobility end users take advantage of this wellbeing benefits. By implementing micromobility in a city, there is a potential to improve the wellbeing of the population in general.

As talked in previous points, the positive access and environmental benefits that micromobility introduces, would have a positive impact in the population:

- By easing traffic congestion, people that have to use private vehicles to perform their commute would see a reduction in their travel time and thus an improvement in wellbeing by having more time to perform other activities.
- By lowering emissions, air quality in the city would improve, reducing health risks, like stress or depression, in the population that lives there, while also improving cognitive capabilities and improving performance in professional and personal activities.
- By reducing noise pollution, health risks associated to long term exposure to levels of more than 55 decibels, which in turn can improve anxiety, sleep and other health impacts.

On the other hand, by nature of their use, micromobility vehicles are more prone to more dangerous accidents. While in car driving individuals are protected by all the security systems the vehicle has as per homologation rules and are protected by a enclosure, micromobility users only protection is the one they choose to take. While helmet is mandatory, some users choose to not wear one, worsening the risks associated with a micromobility vehicle's accident [55]. Pads are also recommended but most users don't wear them.

Some studies have seen a sudden and concerning increase in emergency room visits related to e-scooter accidents after a micromobility sharing transportation mode had been introduced to the city in question [55].

Overall, wellbeing benefits are relevant both to micromobility users as well as the general population. As micromobility services have scaled so quickly, many cities have not been quick enough to react to the disruptions caused and use of these vehicles. Policies need to be better implemented [56].

4.6 Legality

Because of their quick adoption, governments had little time to regulate the use of these electric personal mobility vehicles. It wasn't until, like mentioned previously, accident's started happening and people started complaining of the dangers that these devices could raise both while parked on the sidewalk and driven on the streets and sidewalks, that the governments started to react, making regulations accordingly [49].

Both national and local regulatory entities have worked in the past years to implement different normative that affect the use of these vehicles.

An example of the strict regulations that have been implemented to the use of these vehicles since their appearance is the case of Germany, where the following is mandatory for the vehicle to ride on public roads [57]:

- Maximum speed must not exceed 20 km/h *(the low-cost scooters can achieve speeds of 25 km/h [58]).*
- It's mandatory for e-scooters to have both front and back reflectors.
- It's mandatory for e-scooters to have two brakes that work independently of each other.
- A bell or signal that can clearly warn other public road users is also needed.

Furthermore, e-scooters in Germany must also have an insurance badge and a registered number plate. This last one needs to be issued by the registration authorities in Germany. These vehicles are also only rideable by people who are 14 years old or older.

On the other hand, in Madrid, Spain, a license plate or insurance number is not mandatory, but the law is stricter in other areas [59]:

- E-scooters are only rideable by people older than 15 years old.
- As is the case with bigger vehicles, no phone or headphones are allowed while riding these vehicles.
- Riders can be stopped and submitted to alcohol or drug tests and be fined accordingly.
- A helmet is always mandatory under economic sanctions of 200 €.
- They cannot be ridden on the sidewalks and cannot exceed 25 km/h.
- They cannot longer be parked on the sidewalks and have to be parked on dedicated spaces.

There are also plans to implement regulations like Germany, where these vehicles will need a circulation permit and insurance papers.

Some micromobility sharing companies have already caught up with these new regulations and updated their phone apps accordingly, indicating where the these vehicles can be parked and fining the user if they don't comply.

Some of them have even included an alcoholmeter in the scooters, which won't "unlock" if the rider has been drinking [60].

All in all, regulations are slowly but surely catching up to the adoption of these vehicles in cities. While they will bring controversy, these regulations are applied to any other bigger vehicle on the road, these vehicles were new enough to not be considered on any points in the then-current regulations.

5 THE CITY MOBILITY ECOSYSTEM

To gain a proper view of the advantages and disadvantages of micromobility, a comparison is made between micromobility platforms and other transportation methods.

For this, the most common transport methods for the city are taken into account:

- Cars – combustion and electric
- Motorbikes – combustion and electric
- Shared mobility
  - Motorbike and car-sharing
  - Public transport
  - Private ride sourcing
- Intermodalism

Finally, an analysis on how micromobility fits into the transport ecosystem for sustainable cities.

For simplicity's sake, in terms of price calculation, availability, road infrastructure, and other more specific factors; the city of Madrid is going to be taken as the baseline for this analysis.

The factors to be analyzed for all these methods will be in relation to transport sustainability, in the context of city transport, the same which were analyzed for micromobility previously, following these criteria:

- Transport efficiency
  - Journey time
- Accessibility
  - Entry cost
  - Use cost
  - Space needed
  - Availability

    - Travel reach
- Environment
    - Emissions
    - Noise
    - Other contaminating factors
- Traffic congestion
- Wellbeing
    - Physical effects
    - Psychological effects
    - Travel comfort
    - Accidents
    - “Dead time”

5.1 Cars

Although private cars make the same function no matter what type of engine they have, a difference must be made between electric cars, hybrid cars and internal combustion engine cars for emissions analysis.

The private car is one of the most popular transport methods in many countries as of now. This is a result of their practicability and convenience. Having a vehicle with great range and comfort, with great service and fueling infrastructure, that can take the user wherever he may want is a great advantage over other transport methods and part of why it’s so popular.

A study has shown five main motives for car use among the population [61]:

Minimizing journey time. Journey or travel time are often regarded as “dead” time, reducing other time available to pursue other activities. Road infrastructure in and around developed cities is often well connected and efficient in terms of reaching the final destination from the point of origin. Together with the fact that the further away from the city center the less connected the areas are to the public transport infrastructure, public transportation travel is sometimes unbearably long. Even sometimes, cars the only viable option to perform the trip to the city center. This, in turn, can achieve a positive or avoid a negative journey-based effect.

Minimizing physical and psychological effort. By driving a car, physical effort is almost null as the trip is performed while seating down. On the other hand, driving a car is psychologically less demanding than having to maneuver another transport method or have to plan and navigate the public transportation system.

Creating personal space. By traveling by car, a personal bubble is created, the user can talk with the passenger or on the phone, listen to music on the speakers or just have privacy. With other transport methods this is just not possible.

Minimizing financial expenditure. While this might not be objectively true, people often don't consider the upfront cost of the car, service, taxes, etc., and might think that other means of transport like public transport are more expensive to use.

Desire for control. This was found to be the main motive for most users and it's the underlying desire behind all other reasons. Drivers see themselves as self-sufficient and able to initiate journeys on-demand instead of waiting for a scheduled service like public transport.

While some of these reasons might be argued with, the fact is that most drivers value them and, be it because of marketing or social standards, think that owning a car is better in most terms [61].

5.1.1 Internal Combustion Engine cars

Internal combustion engine cars are the most common nowadays in most countries. This is a result of the evolution of automotive industry since what is considered the first affordable car produced by Ford Motor Company, the Ford Model T [62].

These cars were the first to be mass-produced and the ones that have evolved and cheapened the most because they had longer time on market.

Regarding efficiency, combustion engine cars, as with any car, usually provide extremely journey times outside city centers. The issue is that city centers and highway that serve as entryways into cities are becoming increasingly congested, which can exponentially increase journey time [63].

These cars, out of the three main car drivetrains (combustion, hybrid and electric) are the most accessible in terms of entry price. Because the technology has been around for such a long time, the manufacturing costs have decreased overtime. Because they are the most common, the secondhand market is also full of cheap options, as their price depreciate significantly once used [64].

Regarding use cost, however, accessibility is not that good. To be able to own an internal combustion engine car the user needs to periodically maintain it. The quantity of mechanical and electric parts in an ICE car means that service isn't as cheap as other platforms, which can significantly increase total cost over time.

Owning a car also means needing a parking space, be it on the street or privately owned. In city centers street parking is limited and, depending on the city, conditions might not be ideal for long-term maintenance. Furthermore, with real estate prices increasing in city centers, owning a private parking spot can often cost more than the vehicle [65].

However, a car is always available, albeit needing to refuel often depending on the car's characteristics.

Combustion engine cars have a great refueling infrastructure, which mean that they can virtually reach any place without major issues.

When talking about environmental impact, combustion engine cars are the more contaminant out of all the platforms. Not only do they emit a great amount of CO2, but also pollute cities' air with toxic gases that have negative impacts on the wellbeing of the population [4], [32].

Noise is also a big factor, long term traffic noise exposure has been proven to negatively affect people's mental health [47], [48].

Cars also have an environmental impact by polluting soil and water sources with fluids that the drivetrain needs to operate correctly. All the service, refueling and road infrastructure are full of processes which have negative effects for the environment, both in terms of pollution and in terms of ecosystem degradation.

Cars are also the main cause of traffic congestion in cities, occupying significant space of road infrastructure and being driven, often, only by one person [66].

Regarding wellbeing several factors need to be considered.

Physical activity is almost nonexistent while driving a car as the user is sitting down during the journey. Psychological effects can include anxiety produced by traffic congestion is also relevant [67]. While traveling in a car can be seen as comfortable, as the user has privacy, drivers see journey time as “dead time” because all the attention needs to be on the road [61].

5.1.2 Hybrid cars

Hybrid vehicles combine the efficiency of electric drivetrains at low speeds and the performance of internal combustion engines at high speeds.

While they follow mostly the same characteristics as internal combustion engine cars, there are relevant differences between these platforms.

Entry cost and use cost are usually more expensive than cars as the platform has more manufacturing parts and two drivetrains with two types of motors. This also means that service is often more expensive as the maintenance is more complicated than internal combustion engine cars [68].

However, when using electric drivetrain, there are no emissions and lower noise. These types of cars can be used in combustion mode on the highway and switched to electric mode when entering the city, which improves the environmental situation. On the other hand, the electric powertrain on these cars is often small with not a lot of range available and often not enough for some trips. Furthermore, unless the car is a plug-in hybrid, the battery would be recharged partially with regenerative braking and partly with the combustion engine’s power, which defeats the purpose of a not emitting powertrain [69].

5.1.3 Electric cars

The same applies to electric cars. While they are mostly the same, they have important difference with the other two platforms mentioned above.

One of the main differences lay in the entry cost, where batteries and other components make electric cars significantly more expensive to buy than other platforms. Use cost, however, is cheaper as they require little maintenance and can be recharged for a fraction of the cost of what an ICE or hybrid is refueled.

However, they significantly improve environmental impact as they don't emit any toxic gases and, if charged with renewable energies, they don't emit any indirect gases at all. Noise levels on these cars are also reduced considerable as there is not combustion or exhaust system. However, when their life cycle ends, batteries need to be properly handled to avoid pollution of the soil or other environments.

Regarding traffic congestion and wellbeing, electric cars are easier to control, which means that some companies have introduced ADAS or "Advanced Driver Assistance System" capabilities on these cars, which, depending on the countries' regulations, can alleviate traffic congestion-related anxiety and eliminate dead time as the car would drive by itself.

Furthermore, because electric cars are particularly efficient at low speeds [70], some manufacturers have launched specific products for city commuting, with small, lightweight and cheaper alternatives such as the Citroen AMI [71]. These cars don't have top speeds above 50 km/h, which is usually the top speed limit in urban centers in many European countries.

5.2 Motorbikes

Motorbikes are different in many ways with respect to cars when it comes to sustainable transport.

It's undeniable that more people are choosing motorcycles as their main mode of transport in cities. In some cities like Paris, motorcycles made up to 17% of all the traffic in 2011 [72]. Being two-wheeled, relatively small, motor vehicles, many people chose motorcycles as their main method of transportation and commuting due to their maneuverability compared to cars and being able to park directly on the sidewalks in some cities like Madrid.

Their thin profile and maneuverability also means that they can be used to easily cut through traffic congestion, saving much more time than if the journey was made with a car [72]. Cities like Madrid also have advantages for motorbikes users when it comes to time savings, as motorcycles in Madrid can drive on taxi/bus lanes, not accessible to cars, they can drive on carpool lanes on the entryways to the city [73] and have also dedicated spaces in front of traffic lights so they can be the first to start once the traffic light turns green [74]. All of this makes motorbikes extremely efficient when it comes to journey time.

People also chose them because they are much cheaper than cars [72]. Motorbikes can cost between three and four times less than a compact utility car. They can also cost only a fraction to maintain compared to a car [75].

Motorbikes are two-wheeled, thin, vehicles, which makes them perfect to park in tight spaces. Still, dedicated parking space is needed, they can be easily parked for free on the street in many cities though. If a private parking spot is desired, normally paid parking can have motorbike-dedicated space, otherwise, a car spot would be needed with its cost implications.

They are extremely good when it comes to availability as owning a motorbike would mean on-demand transport.

They are harder to pilot than driving a car due to their dynamic nature. Balance is needed at all times and, depending on the motorcycle, the driving position can sometimes be cumbersome to the body [72]. Driving a motorcycle requires also more attention than a car, not just because of the driving capabilities, but also due to the fact that motorcyclists often do cut through congested traffic, often through narrow passageways between cars.

This also means that, although journey time is also “dead time”, it can be reduced considerably compared to other vehicles.

Motorcyclists are also more prone to worse accidents. Without an enclosure or restraints as cars, having an accident with a motorbike will often imply that the user’s body will impact the road or another vehicle [72], [76].

5.2.1 Internal Combustion Engine Motorbikes

Internal combustion engine motorbikes are the most common in cities. As is the case with bigger vehicles, they are cheaper than their electric counterparts. Although maintenance is much cheaper than cars, they are more expensive than electric motorbikes to maintain due to the same reasons as cars and the nature of internal combustion engines.

They can go far, again, as the fuel infrastructure is widely available and common in many places.

When talking about emissions though, ICE motorbikes are worse than other transport method. They emit the same contaminants as ICE cars to the atmosphere, often being worsen by the fact that their constricted space doesn't allow to fit the same filters and catalysts as ICE cars, which means that pollution can be worse with motorcycles [77].

Although not true for all motorbikes, they have also been found to be more "annoying" than cars when talking about noise pollution in urban areas [78]. Again, because their constricted space, the exhaust point is often closer to the motor, and thus have lower noise isolation than cars exhaust systems.

5.2.2 Electric motorbikes

Similarly, to electric cars, electric motorbikes are more expensive and have less range than combustion engine motorbikes. This is accentuated by the fact that the limited space inside a motorbike's chassis leaves little room for big batteries, which limits even more the range these vehicles have.

However, again, similarly to electric cars, their use cost and maintenance is significantly lower than their combustion engine counterparts. However, in this case, motorbikes don't really benefit from being electric when it comes to parking space, as either of the types can be parked on the sidewalks most of the time free of cost in many cities.

When it comes to emissions these motorbikes don't have any direct emissions and their lightweight compared to cars make them more efficient in terms of energy use, thus energy required per km of travel can be less than electric cars. With smaller batteries, and overall, less parts, they are easier and less polluting to manufacture, which also reduces the waste at the end of their use life.

They are also much less noisy, similarly to electric cars, but even more noticeable by the fact that, as seen earlier, combustion engine motorbikes can often be more annoying to the population than combustion engine cars.

Regarding wellbeing, the only major difference is that the user will notice much less vibration transfer from the motor being anchored on the chassis of the motorbike, as an electric motor's operation is much smoother than a combustion engine.

Overall, for transport exclusively inside cities, electric motorbikes are a better alternative than electric cars because of the space and maneuverability benefits they provide.

5.3 Shared mobility

Because of the nature of shared micromobility, it's necessary to analyze the rest of the platforms in the ride sharing ecosystem.

These platforms characterize themselves in that they are either public or private entities providing services that citizens can use to share a vehicle.

5.3.1 Motorbike and car-sharing

Car-sharing and motorbike-sharing has been a trend in recent years. It's a service that provides people with access to a private fleet of, usually, electric vehicles. Similar to shared micromobility, users usually need to download an application in their phones, create an account and can then unlock cars or motorbikes parked either on the street or on determined private spaces with the phone's app [79].

Users will then be charged, again, similar to shared micromobility, a fee to unlock the vehicle and a time or distance-based fares after that. In Madrid, these services charge around

0.30€ and 0.40€ per minute of use [80]. These services also have geofences, meaning the users can only park the vehicles inside a determined area, which usually covers the whole city center but limits the reach of these transport modes.

While this method of shared mobility eliminates the need of the significant entry price of buying a vehicle of similar specifications, it has the drawback of lacking availability or having to walk great distances to get to an available car or motorbike.

Apart from motorcycles in cities like Madrid where they can be parked on the sidewalks, car-sharing requires the user to spend time and money in finding a suitable space to park it. With cities becoming more and more crowded with vehicles, this can be a cumbersome task in some cases.

5.3.2 Public transportation

Taking Madrid as a baseline, public transport includes buses, Metro (subway) and regional trains, longer distance trains connecting the center to the outskirts.

Urban metro or subway it's a popular transport method these days. Its network allows commuters to easily transfer between lines and reach their destinations. It's usually the fastest way to travel between two points in the city center as it avoids the traffic on the surface. This doesn't mean that it cannot be disturbed by service delays.

Buses and regional trains that connect people living in the outskirts to the city center are also well connected in many cities, providing affordable access to transport. One caveat is that, usually, the further away from the city center, the less common public transport stops are. This means that either users need to walk more to reach the stop or the public transport platform in question might take more detours to reach as many towns as possible instead of going directly to the city center.

In the case of Madrid, there are different passes that all public transport means can accept. From single tickets, which prices differ depending on the travel distance, to multiple use tickets to seasonal or annual passes.

Usually, if public transport is always used for daily commute, the annual pass is the cheapest way of traveling. As is the case with many metropolitan areas in Europe, there are different Zones that divide the city, labelled with letters and numbers, they identify distance to the city center. In Madrid's case, the center is regarded as Zone A, with consequent letters describing ring zones towards the outskirts, as seen in Figure 9.

Figure 9: Madrid Metropolitan Area by transport Zones

The cheapest 2021 annual pass price that includes Zone A, or the areas closest to the city center, is 479,00€. This pass will let the user take any means of public transport desired to reach the destination. The more zones included in the pass, the more expensive it will get.

5.3.3 Ride-sourcing

Ride sourcing includes services that will transport users in a private vehicle which includes a designated driver.

Ride sourcing includes taxi services, ride-sharing platforms like Uber or Lyft or private users' cars which can pick up people that want to travel in the same direction, like Blablacar.

These services are usually less journey time efficient, as they can't avoid traffic congestion and, in the case of private drivers, it's schedule cannot be determined as accurately as public transportation or have the availability of car-sharing.

They will only benefit the environmental concerns if the vehicle in question uses a more sustainable energy like electric vehicles, although this is not the most common vehicle platform on private fleets for ride-sourcing because of range concerns. The current share of low emissions vehicle in the taxi fleet of Madrid is around 30% [81].

Regarding wellbeing, these transport methods have the user as a passenger, which means that the user can multitask and do other things while being transported to the destination.

5.4 Intermodal transportation

Intermodal transportation has been gaining popularity in recent times. It is the transport method by which the user makes use of two or more transport platforms [82]. This definition can be broad and thus can be interpreted slightly different depending on the specific context.

For sustainable transport in the cities this means that people can use different transport methods for different tasks, optimizing each transport method for a determined use.

An example of Intermodalism is using a transport method suitable for long distances outside the city if traveling from the outskirts to the center, like regional trains or private vehicles, and then using a better fitted transport method for the city center like public transport or micromobility.

This transport mode can optimize journey time by using the most journey time-efficient vehicle for each leg of the trip. It can also improve availability and travel reach, as there are areas in the outskirts that can not be reached by public transport or micromobility, as well as areas in the city center that prohibit private vehicle access.

It helps reduce emissions and traffic congestion in the city center, by using more sustainable transport modes in this area.

It can also improve wellbeing in some areas like physical and psychological effects of using other transport methods which require more activity to use, while reducing others like travel comfort or travel “dead time” depending on the transport method used.

This method also implicates having to interchange from one transport mode to another in a station or similar, which can be cumbersome depending on the situation.

However, depending on the transport platform combination, it can reduce costs by avoiding paid parking or use fees of other transportation modes.

5.5 Micromobility

Micromobility fits in this transport ecosystem as a short distance-urban transportation method as well as a last mile transport mode.

The benefits of using micromobility in these scenarios outnumber the drawbacks. As exposed in chapter 4, micromobility is most efficient in shorter trips, where it’s availability, cost, efficiency, capacity to avoid traffic congestion and its environmental sustainability outweigh the comfort other transport methods might offer.

Micromobility also fits perfectly as part of intermodal transportation. In the cases where longer distances need to be traveled, micromobility performs exceptionally well as a last mile transport solution instead of walking or other transport methods.

An example of this can be taking regional trains from the outskirts into the city center and performing the last few kilometers in a micromobility vehicle rather than taking a bus or the subway, having to transfer and wait. Another instance is traveling by car to a private parking or free street parking just outside the city and moving around the city center by means of a micromobility vehicle, saving costs and avoiding traffic congestion.

It also acts as a sustainable means of transport for last mile transport outside city centers, where public transport is scarce and there are no other feasible means of transport to reach the destination from the closest public transport stop other than walking. This is especially important as it can provide professional and personal opportunities to people that otherwise would find hard to reach these places.

Micromobility is also a sustainable way of transporting goods, such as mail, around city and urban centers, making the job more efficient by means of faster travel time than walking or private vehicles like vans, cars or motorcycles.

Overall, micromobility isn't a substitute for all city transportation, but rather a tool to make shorter trips and last mile trips more efficient and sustainable.

6 MICROMOBILITY E-VEHICLE ARCHITECTURE

Micromobility stands for small, lightweight vehicles that can be used to perform short trips and last mile transport. The most common micromobility vehicles are small, two-wheeled vehicles, including small electric scooters, commonly known as e-scooters, bicycles and electric bicycles (e-bikes).

These vehicles are easy to maintain and require little to no service as opposed to internal combustion engines. Batteries can in some cases be easily swapped for seamless range extension.

In this chapter, an analysis is performed on the engineering side of micromobility vehicles, what parts are used in them, their architecture and use.

6.1 Electrified platforms

The most famous micromobility platform is the electric scooter. Their popularity might come from the fact that they are easier to ride than other electric micromobility vehicles. Their stability comes from the fact that their center of mass lays low and their long handle provides easy maneuverability and stability.

However, because of its broad definition, there are many vehicles that can fit the micromobility category. In this section more details are going to be provided for the most common micromobility vehicles, their advantages and their disadvantages.

6.1.1 e-bikes

E-bikes stand for electric bicycles. These vehicles use the normal vehicle frame with an added electric drivetrain.

The electric drivetrain, depending on the model, usually is lightweight with not much battery capacity, as most of the e-bikes' drivetrain are meant to assist pedaling and not as a standalone drive system.

Most recent models are trying to seamlessly implement the electric drivetrain, by means of storing the batteries inside the tubular frame of the bicycle and powering it with a hub motor installed directly on the back, front or both wheels [83].

The advantage of this platform is that running out of battery does not cause the user to get stranded as the bicycle can continue to be pedaled after the battery has died, although it requires a harder effort as it weighs more than a conventional bicycle.

Some of these bicycles have also a foldable frame so they can be easily stored away or transported in other means of transport for last mile trips.

E-bikes are pricier than other transport platforms, conventional bicycles are already expensive because of their complex manufacturing process, e-bikes have also the added cost of the battery and motor, which can put them easily at price tag of 1 000€, with some even reaching 8 000€ a piece [84]. A comparison of e-bike prices can be seen in Figure 10.

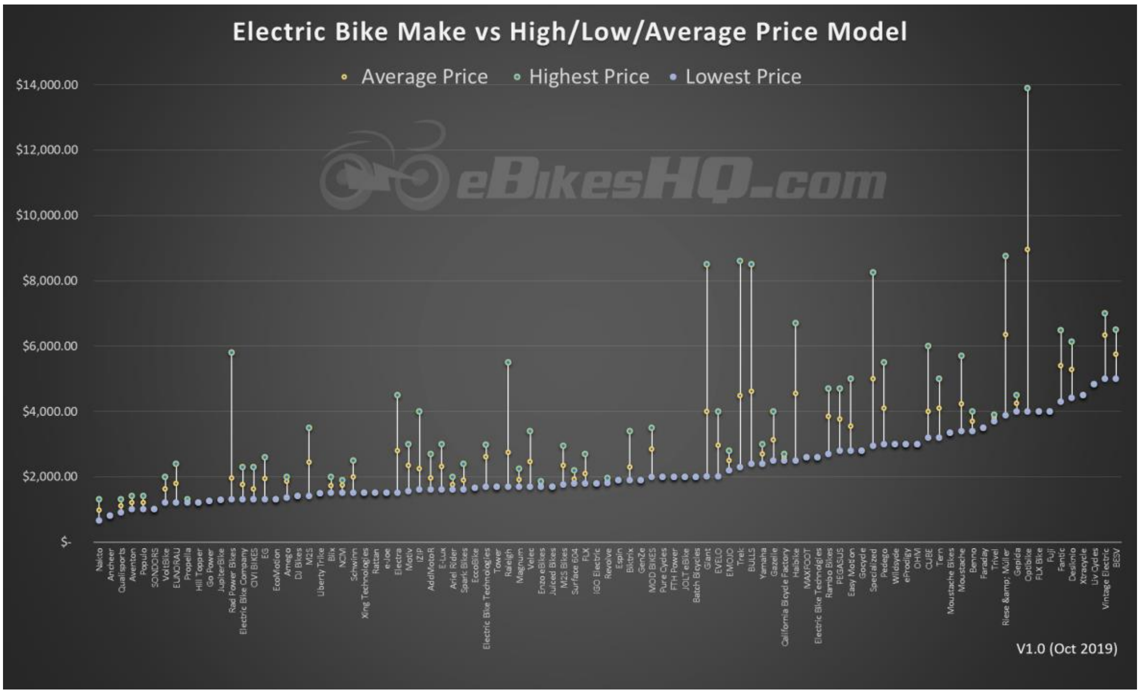

Figure 10: Comparison graph of 2019 e-bike prices [84].

Affordable e-bikes usually have between around 500 Wh and 700 Wh of battery energy. Standalone drivetrains consume about 15 kWh/km to 16 kWh/km, which gives them an estimated range of around 30 kilometers. Pedal assist e-bikes can go down to about 9 Wh/km, which improves the range drastically, reaching around 50 km of range for some affordable e-bikes [85].

They also have the advantage that most people have learned how to drive a bicycle, which eliminates a need of learning how to drive these vehicles, something that can be a great incentive for people who do not want to embark into a learning curve.

While e-bikes are heavier and bigger than other micromobility e-vehicles, being able to be pedaled around eliminates range anxiety and promotes exercise.

6.1.2 e-scooters

Scooters have become popular in recent years. This is mostly driven by their relatively low cost, ease of use, light weight, their flat learning curve and their range.

The learning curve is quite flat and is almost non-existent when learning how to ride these scooters [86]. This is due to their low center of mass and long handle, which improves maneuverability and makes it difficult to fall while riding.

E-scooters are also much cheaper than e-bikes. Their price range starts at the low price tag of 200€, mid-range ones will linger around the 400€-500€ mark, and most of them are below the 1 000€ mark [87].

They are also lighter than bicycles and they can be foldable, which, together with their small wheels and slim profile, make them occupy almost no space and be easily transported indoors or around in other means of transportation.

Their battery usually lives under the standing platform, with controls, accelerator, and brake, built into the handle.

These e-scooters usually have no suspension and have a hub motor built into the rear wheel, which considerably reduces price, making them cheaper, although harder to ride. The different components can be seen in Figure 11.

Figure 11: Ninebot's e-scooter anatomy

6.1.3 e-longboards

Longboards are similar to skateboards but have some key differences. Their decks are usually longer and wider, which makes them more stable, their wheels are usually bigger and are built with grippier materials, which help with traction when going at high speeds [88].

While skateboards are mainly used for tricks and other skateboarding activities, longboards are used for cruising and racing downhill. Depending on their "trucks", which are the parts of a longboard that house the axles, longboards can be maneuverable. Harder trucks are meant for riding at speed, while softer trucks are meant for lower speeds but increased maneuverability.

E-longboards are electrified longboards, usually with a belt drivetrain on the rear wheels that propel the board forwards by means of one or several motors. Some longboards have hub motors, which are built into the wheels, they provide less power but reduce costs and parts.

Their battery and other powertrain electronics are usually stored underneath the board, as seen in Figure 12.

Figure 12: Boosteadboard's dual motor e-longboard

Because they have no handle, they are usually controlled via a wireless remote, like radio-controlled toys. A user can be seen making use of one of said remotes in Figure 13.

Figure 13:e-longboard user powering the board via a hand-held remote

Because of their riding nature, e-longboards have a steeper learning curve than e-bikes or e-scooters. However, their architecture provides more stability and usually allows them to reach much higher top speeds. E-longboards are also more efficient than e-scooters or e-bikes, this means that they can reach the same range with less battery energy, which, in turn, also makes them lighter and easier to carry around.

While e-scooters usually reach around 20-30 km/h, mid-range e-longboards usually reach around 40-50 km/h, with some e-longboards even reaching top speeds of 70 km/h [89].

E-longboards usually don’t have mechanical brakes and use the regenerative function of electric powertrains to be able to slow down to a stop.

However, they are usually more expensive than e-scooter, as they have a more cumbersome and expensive manufacturing process.

6.1.4 e-mountainboards

Mountainboards are a type of longboard but with bigger wheels and, often, better suspension trucks. An example of these can be seen in Figure 14.

While longboards can go fast, their small wheel size makes them unsuitable for any terrain other than well-kept tarmac. Any stone on the pavement could cause a longboard to stop suddenly and cause an accident [90].

Mountainboards not only can go on unwell-maintained tarmacs but can also travel across rough or off-road terrain.

They also often have bindings, which are harnesses that tie the user to the board as rough terrains can make the user fly away from the board.

Figure 14: Trampaboard's electric mountainboard

Their controls and powertrain are similar to longboards, with the main difference being more powerful motors and the battery and electronics being on the top to avoid damage by contact with debris on the ground.

However, these boards aren't as efficient as their longboard counterparts due to their wheel size, weight and the nature of riding over rougher terrain.

6.1.5 Other platforms

Although not as common as all the vehicles mentioned above, there are other innovative electric micromobility platforms. Most notable brands inside this category are the Segway and the OneWheel.

Segways are self-balancing, 2-parallel-wheel vehicles with a handle. These are referenced in Figure 15. These vehicles require almost no learning curve. However, they go at low speeds, are big and much more expensive than other alternatives.

Figure 15: Segway use visual

OneWheels are smaller and lighter than other alternatives, they can also go fast. However, they have one of the steepest learning curves of the micromobility electric platforms, making them more of a leisure device than a commuting one. One example can be seen in Figure 16.

Figure 16: OneWheel riding visual

6.2 Batteries for electric vehicles

As technology advances, energy sources for electric vehicles are one of the most studied fields. This is a direct cause of desire of optimization, currently the most expensive part of an electric vehicle's powertrain is the battery. It's also one of the heaviest components of electric vehicles [91].

Energy sources are also the main concern as most of the electric-vehicle's components is already efficient, while energy sources are yet to be improved in terms of energy density, lifespan, power output and input, and cost. These in turn will improve range, charge time, use life of the vehicle and price.

Thus, it's important to know the fundaments of these batteries, their basic architecture and their behavior.

Batteries are usually made up of cells, which grouped in parallel and series, can provide the right voltage and power to the vehicle [92].

Furthermore, there are several energy source's types when talking about electric vehicles, it's necessary to know the advantages and limitations each battery type has in order to choose the adequate energy source for each specific vehicle application.

6.2.1 Battery fundaments

First, to be able to analyze the different battery types that electric vehicles can use, it's necessary to understand the batteries' components and how they work together to store and provide electrical energy to the different applications.

6.2.1.1 Electrochemical cells

Batteries are usually made of a number of electrochemical cells, connected in parallel and in series. These cells are mainly built upon two electrodes, negative and positive, submerged into an electrolyte and separated by a membrane [93].

The chemical reactions known as Redox or oxidation and reduction reactions, happen at the electrodes, where electrons are then transferred via an external circuit from one electrode to another. Ions are transferred inside the cell through the electrolyte. A common battery Redox reaction can be seen in Figure 17. The oxidation reaction happens at the anode, which is the negative electrode, while the reduction reaction happens at the cathode, which is the positive electrode. The voltage produced by a cell will directly depend on the characteristics of the chemical and physical properties of its materials [93].

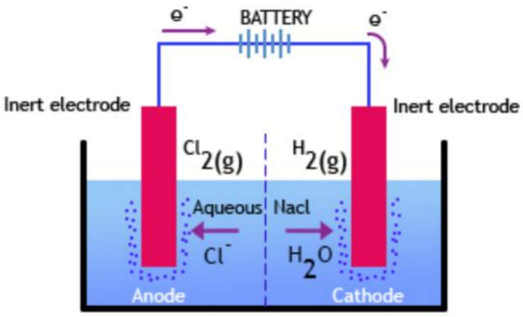

Figure 17: Electrolytic cell diagram.

Furthermore, there are two types of cells depending on their charge characteristics, as seen on Figure 18. Primary cells are only of galvanic nature, which means that they can only convert chemical energy to electrical energy, secondary cells can act as a galvanic or electrolytic cells, which means that they can convert chemical energy into electrical energy and vice versa, in other words, secondary cells are rechargeable and are the ones of interest for electric vehicles [93].

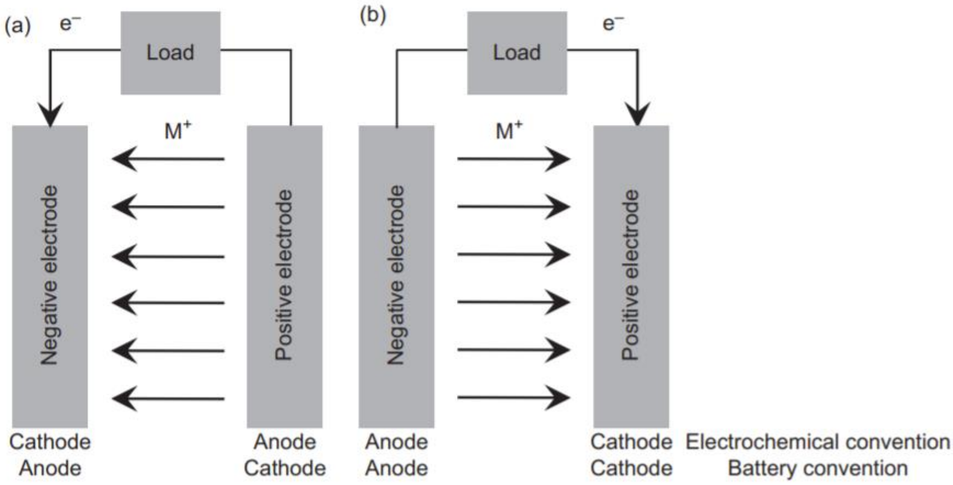

Figure 18: (a) Electrolytic cell and (b) galvanic cell [93].

6.2.1.2 Nominal voltage

The nominal voltage of a cell is a fundamental characteristic of a battery. The voltage value of a cell is a function of the chemical reactions and materials that make it up [94].

The nominal voltage of a battery is important as it will be determined by the load connected to it. Normally cell's voltage varies between 1.5 V and 3.7 V depending on the cell's chemistry and the electrodes' materials [94].

In reality, the voltage of a cell is not constant, as seen in Figure 19, and it will be a function of the state of charge and the discharge rate of the cell. The more the cell is discharged the less voltage it will provide. This curve is usually flatter in the mid-range capacity values.

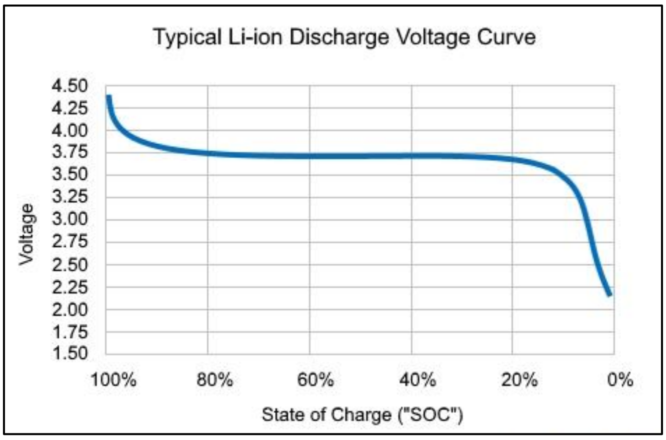

Figure 19: Typical voltage characteristic curve of a Li-ion cell.

6.2.1.3 Capacity

The capacity of a cell or battery relates directly to the amount of energy that a cell or battery can store as the chemical energy that can be transformed into electrical energy.

Capacity of a cell is usually measured in ampere-hours (Ah), which indicates the amount of energy as a measure of provided current during a certain amount of time. This is an ideal measure of energy under certain circumstances and it will also depend on several factors like temperature, discharge rate or age of the cell [95].

Capacity can be also measured in watts-hour (Wh) or kilowatts-hour (kWh), which is the result of multiplying the capacity in Ah and the nominal voltage of the cell or battery [95]. This units are more common in the automotive industry.

6.2.1.4 Specific energy or specific capacity

Specific capacity is the capacity by unit of weight of the cell or battery [93]. This is important when talking about electric vehicles as it affects directly the dynamic of the vehicle and, in case of micromobility, its transportability through interiors or other transport methods.

Specific energy or specific capacity can be measured in mAh/g, Ah/kg, kWh/kg, etc.

6.2.1.5 State of Charge (SOC)

State of charge or SOC is the parameter that indicates, from 0% to 100%, the capacity remaining in a cell or battery, where 100% would be the nominal capacity of the battery [96].

State of charge is important as it lets the user know the remaining amount of energy in the vehicle at a glance. However, usually the SOC shown to the user isn't the nominal SOC of the battery, as batteries discharged bellow a certain amount will die and won't be able to recharge again, thus the usable capacity of a cell or battery is lower than its nominal capacity.

In vehicles, SOC is usually calculated by OCV (open circuit voltage) look-up tables. Cells have a characteristic curve of SOC by OCV, which is also dependent on temperature, thus, manufacturers implement algorithms with look-up tables that can determine the SOC of the battery at a certain OCV and temperature [93].

Furthermore, depending if a cell or battery is being charged or discharged, the OCV measured will vary not only by the temperature factor, but also by the side reactions and other factors the cell experiences depending on the current direction, thus why there's an hysteresis effect on the cell SOC by OCV curve, as seen in Figure 20 [93].

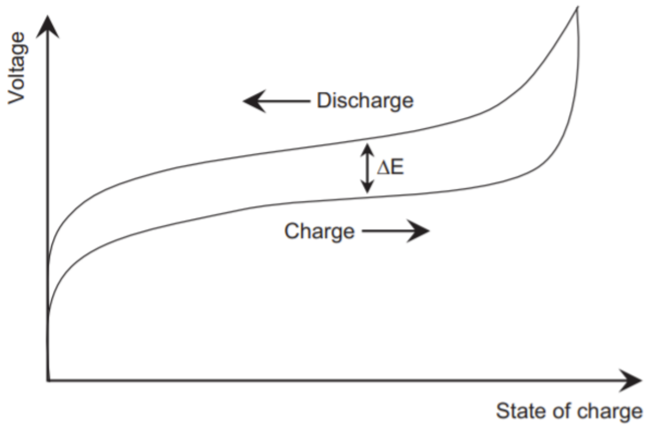

Figure 20: SOC by OCV [93]

6.2.1.6 State of Health (SOH)

The state of health or SOH of a battery is a measure that indicates the available capacity the battery has compared to the nominal capacity the battery had when new [97].

As batteries are used, degradation is caused in their materials, with the formation of dendrites and deterioration of the electrodes and electrolytes. This means that, as a battery ages, it will have less and less capacity with time. SOH is measured as the percentage of the current battery capacity compared to the capacity it had when fresh.

6.2.2 Lithium Batteries

Although there are many kinds of battery chemistries and because of their wide use and application on electric vehicles, for the sake of simplicity, only lithium batteries are going to be analyzed in this section.

Lithium is one of the best materials for anodes. It’s light and has a great specific energy, which is the energy amount that a material can store per unit of weight. In the case of lithium this value is around 3.862 Ah/kg [98].

There are several lithium battery technologies available, although the two most common ones for powering small vehicles are either lithium-ion or LIPO batteries.

6.2.2.1 Lithium-ion batteries

Lithium-ion or Li-ion batteries appeared as a solution to the drawbacks and dangers of Lithium-metal batteries, where Lithium metal dendrites will form at the anode during charging, which would grow and contact the cathode across the electrolyte, causing a short circuit and the cells to possibly burn [92], [98].

Li-ion batteries would use different anode materials and use lithium as a solution in the electrolyte where lithium ions would travel from one electrode to another. In these cells, the anode is usually carbon based (i.e., graphite) and the cathode is made of a lithium absorbing metal such as Co Ni, Fe, Mn or a combination of these. Subsequently, lithium ions will travel from the anode to the cathode when the cell is discharged and vice versa when the cell is charged [92].

6.2.2.2 LIPO batteries

LIPO batteries stand for Lithium Polymer batteries. They function in the same way as Li-ion batteries, but their electrolyte is a polymer matrix, which is plasticized. The electrolyte is perceived as a solid, thus the absence of liquid makes these batteries more stable and less dangerous to overcharges [92]. A comparison can be seen in Table 2.

However, the nature of a solid electrolyte, which also acts as a separator, prevents the cell from having as much of an effective electrolyte surface area as the Li-ion cells. Which means that they cannot be discharged as fast as the Li-ion cells [92].

6.2.2.3 Comparison table

Parameters	Li-ion battery	Li-polymer battery
Usable voltage range	From 3V to 4.2V	From 3V to 4.2V
Energy density	High energy density	Low and decreased cycle count compared to Li-ion
Flexibility	Low	High
Weight	Relatively heavier	Light weight
Safety/Explosive risk	More volatile as compared to Li-Po	More safety. Less chances to explosion
Charging duration	Relatively longer charge	Shorter charge
Cost	Cheaper	Slightly expensive
Capacity	Relatively lower	Same volume Li-Po batteries, capacity is around 2 times of Li-ion battery
Life span	Long	Long
Aging	Loses actual charging capacity over time	Retains charging capacity better than Li-ion
Temperature range usage	-20 to 60º C	-20 to 70º C
Impedance	<100 mΩ	<50 mΩ
Charge temperature	0 to 40º C	0 to 40º C
Storage temperature	-20 to 35º C	-20 to 35º C
Applications	Used in power backups/UPS, Mobile, Laptops, and other commonly used consumer electronic goods. Also used in Electric mobility and Energy Storage Systems	Mostly used in radio-controlled equipment. Mobile phones, laptops and other commonly used electronic products. Also, used in Electrical vehicles.

Table 2: Differences between Li-ion and LIPO batteries [99]

6.2.3 Supercapacitors

Supercapacitors, also known as EDLC (Electrochemical double-layer capacitors), are high-energy density capacitors that work similarly to common battery cells. They are suitable for high power applications like acceleration and regenerative cycles in electric vehicles due to their high-power rate [92].

A capacitor works by storing energy as a charge separation in an electric field between two electrodes, as seen in Figure 21. The ions in the electrolyte travel towards the electrodes of opposite polarity. They have no chemical reactions as the energy is stored in an electrostatic field, which means that the transfer of energy can happen much faster than electrochemical cells [92].

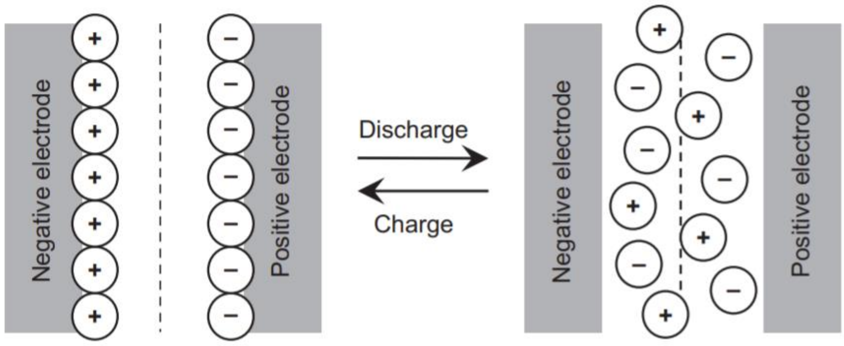

Figure 21: Illustration of a supercapacitor charged and discharged states [92]

Contrary to electrochemical cells, capacitor voltage drops significantly during discharge, which makes their use in vehicles more complicated by requiring complex electrical circuits that can manage these voltage drops [92].

Supercapacitors, while being able to provide more power, are not as well fitted to store energy as their electrochemical counterparts. This means that they are complicated to use as a standalone energy source to the vehicle but can be used together with a battery to provide more power in high-power demanding cycles like hard accelerations or breaking, which will help the degradation of the batteries by not pulling or imputing as much current from or to them.

6.2.4 Fuel cells

Fuel cells are galvanic electrochemical cells that convert chemical energy of a fuel into electricity as a result of the reaction with an oxidant [92]. A schematic can be seen in Figure 22. Clarification must be made as a fuel cell cannot store energy, energy in this case is stored as chemical energy in the fuel. The fuel cell just converts that chemical energy into electrical energy.

Fuel cells also have positive and negative electrodes separated by an electrolyte. The electrodes in this case are inert, which means that they don't react directly. Instead, they act as catalytic components, improving the reaction efficiency [92].

Fuel cells are often known as Hydrogen Fuel Cells, which just means that they convert hydrogen gas into water, creating electricity in the process.

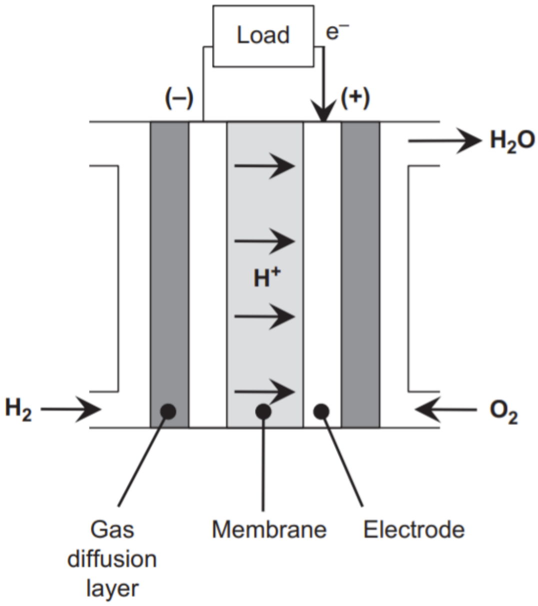

Figure 22: Schematic of a Fuel Cell [92]

But fuel cells can operate on several fuels and have different materials, described on Table 3, each one with different electrical properties which make them suitable for different applications.

	Polymer electrolyte membrane (PEMFC)	**Direct methanol (DMFC)**	**Phosphoric acid (PAFC)**	**Alkaline (AFC)**	**Molten carbonate (MCFC)**	**Solid-oxide (SOFC)**
Electrolyte	Fluorinated organic polymer	Fluorinated organic polymer	Phosphoric acid	Alkali hydroxide (KOH, aq)	Molten carbonate	Yttria-Zirconia
Temp. range (° C)	70–200	60–90	*Ca.* 200	25–220	*Ca.* 550	600–1000
Fuel	H_2	Methanol	H_2	H_2	H_2 or CH_4	H_2 or CH_4 or other hydrocarbons
Charge carrier	H^+	H^+	H^+	OH^-	CO_3^{2-}	O^{2-}
Advantages	High-power density, fast start-up, suitable for vehicle applications	Simple fuel storage	High fuel efficiency, low sensitivity to impurities, suitable for stationary applications	High fuel efficiency	High fuel efficiency, low sensitivity to impurities, suitable for continuous power needs	High fuel efficiency, low sensitivity to impurities
Disadvantages	Sensitive to CO, fuel storage	Toxic fuel, low power density	Slow start-up, low power density	Sensitive to impurities (e.g. CO_2)	Poor durability, high-temperature degradation	Slow start-up, high-temperature degradation

Table 3: Comparison of different Fuel Cell technologies [92]

However, fuel cells are not suitable as a standalone energy source for vehicles, this is due to their slow adaptability to changes in discharge rates, furthermore, because of their galvanic nature, they don't have recharge capabilities and will need another kind of energy storage to be able to have regenerative braking [92].

Furthermore, fuel cell systems require complex, heavy components to be able to manage the water and heat caused by the reactions, which will negatively affect a vehicle's performance.

6.3 Powertrain

The powertrain of an electric vehicle refers to the conglomerate of components needed to provide power and propel the vehicle forward by converting electrical energy to mechanical energy [100].

The components of an electric vehicle's powertrain often include:

- Battery
- Battery Management System (BMS)
- DC-AC inverter
- Motor controller
- Motors

6.3.1 Battery

The battery of the vehicle is what stores the energy in form of chemical energy to later be transformed into electrical energy while driving.

In electric vehicles the battery can be discharged, by using the vehicle, and charge, by means of an electrical source. For micromobility vehicles usually a charger is provided, which plugs directly into a wall outlet.

Depending on the vehicle, usually chargers don't have much power as micromobility vehicles have small battery packs.

E-scooter, for instance, usually have around 500 Wh of battery capacity, although more expensive models can even reach 2 kWh battery packs [58].

On the other hand, electric longboards follow more or less the same numbers, although some of them have less capacity battery packs but achieve the same range and more speed because of their efficiency [89].

Electric scooters have a median nominal efficiency of around 14 Wh/km [58] while electric longboards' median efficiency is around 10 Wh/km [89].

6.3.2 Battery Management System

As stated before, battery packs are made up of individual cells, which are grouped in parallel and series to achieve the desired voltage and power needed by the powertrain of the vehicle.

With high quantity of cells, it means that over time, with charge and discharge cycles, cells voltages can drift from each other, which can cause major failures when at low or high SOCs.

When discharging the pack, if a cell drops below its minimum voltage, it can die, causing further imbalance in the pack. On the other hand, if a cell has more voltage than the rest, when the pack is charged, it can go above its maximum voltage and be overcharged, which, depending on the cell technology, can cause fires and short circuits.

For this reason, a BMS or Battery Management System is needed. BMSs can actively or passively balance battery cells' voltages while charging or discharging. More advanced BMSs can monitor other factors like temperature or current drawn to detect early failures and mitigate risks like overcurrent, overcharge, undercharge, short circuit or critical temperatures. They can also be used to estimate the SOC of the vehicle and monitor the SOC of individual parallel-cell groups [101].

However, the more functionalities a BMS has, the more expensive it gets.

Because of the small battery packs of micromobility vehicles, BMSs can be simple. Because these vehicles don't have that much range or energy, usually the budget products have a passive BMS that only acts while charging. This brings the cost down and saves space and energy.

6.3.3 Motors

While there are a wide range of electric motor types, like AC induction or synchronous motors, or DC brushed or stepper motors, micromobility vehicles usually have brushless DC or BLDC motors because of their power/size ration or efficiency.

Contrary to Brushed DC motors, where fixed brushes provide electrical power to the coils on the rotor, while the stator is a permanent magnet, Brushless DC motors have a permanent magnet rotor with fixed coils in the stator [102].

The fixed coils in the stator generate magnetic fields by means of generated electrical pulses, which pull the magnet's orientation towards the stator-generated magnetic field [102].

The obvious advantage of this method is that there is no brush wear, as no parts are being touched apart from the rotor bearings.

They are extremely efficient, as these motors can be controlled at maximum torque at all speeds. They can also have hall sensors or encoders which can provide information on their exact position so they can be moved more accurately and thus have a better control of the vehicle [102].

Because they barely have any friction parts, they are more durable and cause less noise.

The motors nominal voltage needs to be considered as the battery needs to be dimensioned so it can provide the correct voltage value to the motors.

Micromobility motors are also divided in two types depending on the rotor placement, as seen in Figure 23. An inrunner BLDC's rotor lives inside and concentric to the stator, outrunner BLDC motors have the rotor on the outside of the stator [103]. This last kind of motors are often referred to as hub motors, as they can be implemented directly inside the wheels' hubs, with the stator anchored to the axle and the wheel on the outside rotor.

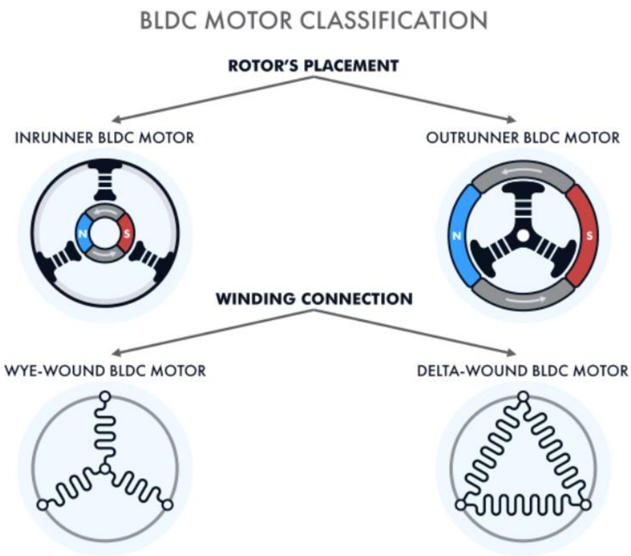

Figure 23: BLDC motor classification [103]

In some micromobility vehicles such as electric longboards, where space is limited, the motors also serve as the breaking mechanism, taking advantage of the regenerative breaking function natural to electric powertrains.

Depending on the micromobility vehicle, different motor distributions can be installed. For two-wheel vehicles such as e-bikes or e-scooters, the motors con either be placed in the front, back or both. For four-wheel vehicles they usually have one or two motors, with the rare cases of 4WD vehicles.

It's also important to mention that bigger AC motors require an inverter to convert the DC power from the battery into AC power for the motor. AC motors are controlled differently than DC motors and require a completely different controller. The advantage of micromobility vehicles is that the motors are DC, which saves costs and space as an inverter is not needed.

6.3.3.1 Brushless motors characteristics

Brushless motors can be defined by the following values:

- KV: Motor speed (rpm) when an input of 1V is applied with no load attached to the motor. This value multiplied by applied voltage, will give output speed.
- Max. power (W or kW)
- Torque (Nm)
- Max. current (A)
- Max Voltage (V)

6.3.4 Motor controller

To provide the necessary pulses to the motors, usually a motor controller is needed, like the one referenced in Figure 24. This controller takes the power of the battery and converts it into DC pulses required by the motors to function.

The motor controller also takes the input of the user, normally a handheld remote or a wired actuator, depending on the vehicle, and translates the input into power to the motors.

Depending on the motor controller, it can have more sophisticated features. If the motor is sensored, either by encoders or hall sensors, this information can be sent to the motor controller to provide the exact position of the rotor and provide a smoother drive, acceleration and breaking.

It can also receive information from the BMS or directly measure the battery's vitals to manage power appropriately. It can receive information from the motors to calculate speed, power and torque.

Furthermore, it can also provide information to the user via CAN or UART protocols, which can be processed and transmitted wired or wirelessly to a screen where the user can see the vehicle's components' vitals such as battery voltage and SOC, speed, current drawn, temperatures, etc.

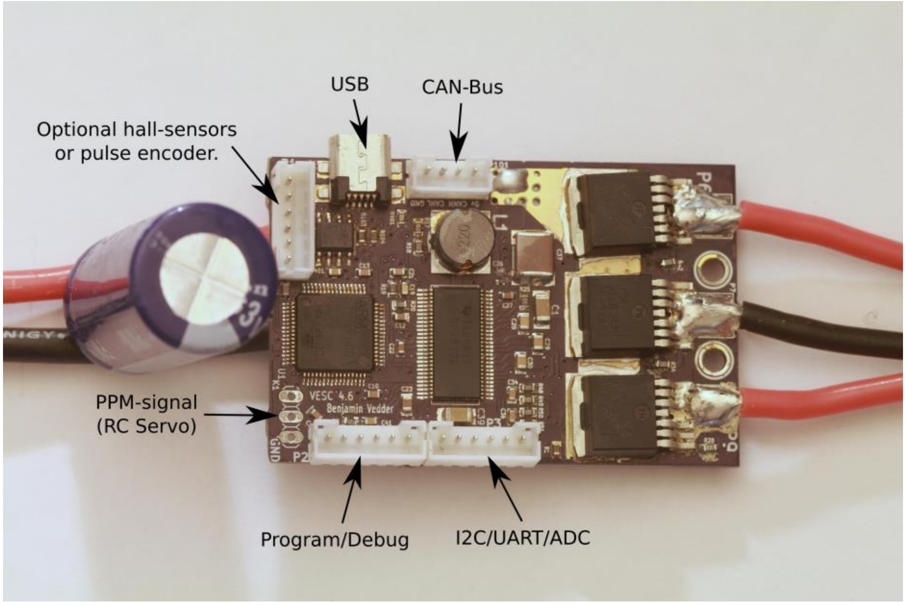

Figure 24: BLDC Motor controller diagram

The motor controller is the brain of the vehicle, processing all the information from most components to provide the correct power to the drivetrain at all moments.

6.4 Drivetrain

While powertrain and drivetrain are often confused and used interchangeably, the drivetrain of a vehicle is the group of parts that transmit power from the motor to the wheels. This includes transmission, differential (if one), driveshaft, axles or wheels [104].

The drivetrains of micromobility vehicles are often simple. They are usually composed of a chain, belt or direct drive transmission, axles and wheels.

Depending on the vehicle, the axles will have different characteristics, for the most part, micromobility vehicles don't have suspension elements apart from the rubber of the wheels or the radius of the hubs like in the case of e-bikes. More expensive platforms have incorporated dampers, although this is rare.

For this matter, in this section, the focus is going to be on the transmission systems, as gear ratios and efficiency of these systems affect directly to the efficiency, speed and maneuverability of the vehicle.

6.4.1 Gear ratio

Gear ratio is important when it comes to micromobility vehicles. Gear ratio will depend on the choice of motor and will impact efficiency, speed and torque.

Micromobility vehicles, apart from the ones that have hub motors as they don’t require a transmission system, often make use of a ger ratio reduction. This assembly is composed of two gears or pulleys, one smaller one, the driver gear, with less teeth, placed on the motor’s axle; and a bigger one, the driven gear, with more teeth, placed on the wheel or wheels. The gear ratio formula can be seen in Equation 1 [105]:

$$GR = \frac{Number\ of\ teeth\ driven\ (output)\ gear}{Number\ of\ teeth\ driver\ (input)\ gear}$$

Equation 1

Speed and torque are proportional and follow the rule seen in Equation 2 [106].

$$S_1 * T_1 = S_2 * T_2$$

Equation 2

Where S_1 and S_2 are the speeds of gear 1 and gear 2 respectively, and T_1 and T_2 are the torque of gear 1 and gear 2 respectively. These values are proportional to the gear ratio.

To calculate output speed, the motor speed is divided by the gear ratio. To calculate output torque, the motor torque is multiplied by the gear ratio [106].

Gear ratio in micromobility is often a reduction gear ratio. With a smaller gear on the motor(s) and a bigger one on the wheel(s). This will increase torque while reducing speed.

6.4.2 Chain drive

The most common chain driven micromobility vehicle is often the bicycle [107].

Chain drives require sprockets instead of geared pulleys, as seen in Figure 25, they interact with the chain, which are made of individual pivoting links [107].

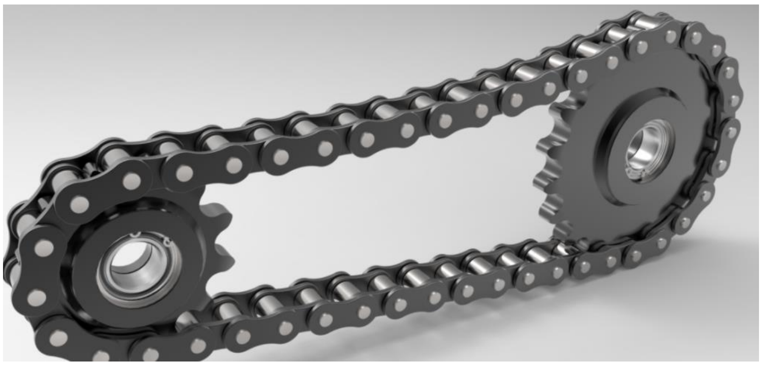

Figure 25: Visual of a chain drive system

Chain drive systems have a wide range of speed and torque specifications. Chain drives can be enclosed or opened, the difference being noise, where an open chain system is noisier than an enclosed system; and maintenance, where an open chain drive system is open to the elements and can be damage or deteriorated by contaminants [108].

There are several types of chain drive transmissions, with the most common one being the roller chain, as it is the simplest one to efficiently transmit power. Chain drives can transmit power with around a 96% efficiency [107].

One of the main advantages of using chain drive is its low cost, wide range of speed and torque specifications, their efficiency. They also avoid slipping by using sprockets. They are easily installed and, because of their material properties, they can withstand rough conditions [107].

However, some disadvantages of chain drives are that they are required to be maintained periodically, as frequent lubrication is needed for their correct functionality. Their installation is also more cumbersome, as their alignment is more complicated. They are not precise and cause noise and vibrations [107].

6.4.3 Belt drive

Belt drive transmissions are mechanisms where the power is transmitted via a flexible belt, as seen in Figure 26. Belt drives are commonly found in modern vehicle engines [109].

Figure 26: Belt drive mechanism illustration

A belt drive transmission is one of the cheapest options when it comes to transmitting power from the motor to the wheels of an electric vehicle, or any vehicle for that matter. They are also the most versatile, providing wider speed ranges than other transmission systems. Belt drive systems are also easy to service and adjust [108].

Although there are different types of belt drives for different applications, micromobility vehicles often make use of timing belts, which are flexible belts with grooves that fit onto geared pulleys. This ensures no slipping and a more precise transmission of power [109].

However, belt drive systems are not the most efficient, with their transmission efficiency being around 95%. While speed ranges are wide, belt drives have the drawback of not being able to transmit as much torque as other systems [108]. This has improved in the past years with the evolution of composite material technologies, like Balata Belts [109].

Belt drive systems have the advantage of being easily installed and maintained, as they don't require lubrication and can be easily fitted into geared pulleys. They can also be easily adjusted, a direct benefit of their flexible nature. They are also lighter than chain drive systems and make less noise because of their material [109].

On the other hand, belt drives are more propense to slipping if they aren't well adjusted, their use life is usually less than other transmission systems. Their operating temperature is also lower, and their degradation can be worse because of the materials used [109].

6.4.4 Gear drive

Gear drive transmission systems are a set of reduction gears, usually inside a gearbox. These gears contact each other instead of having a pulley system, as seen in Figure 27, transmitting power directly from one gear's teeth to the other.

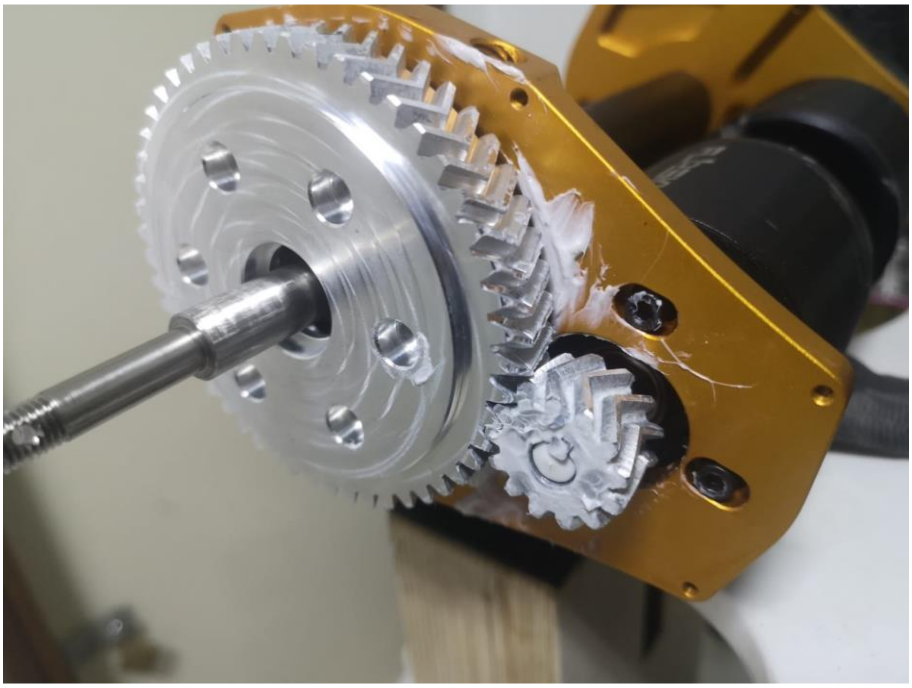

Figure 27: Illustration of an opened Gear Drive mechanism installed in a longboard's hanger

In micromobility, normally a simple design is used like a single reduction gear mechanism, where the reduction gearbox has a set of two gears, the smaller one called the pinion, which drives a larger gear tied to the wheel [110].

Gearboxes must be always enclosed and lubricated to ensure smoot power transfer between the gears. Any debris entering the gearbox could jam the mechanism.

Depending on the application, different gear types are available. The most notorious ones are the spur gear, seen in Figure 28, which is the simplest and most extensively used gear type. This kind of gear has straight teeth parallel to the rotation axis.

Figure 28: Spur gear visual

One issue with spur gears is the backlash, as seen in Figure 29. Backlash occurs when the gear mechanism has slack or play, which means that, between acceleration and breaking cycles, the gears' teeth can collide in a hardly manner with each other [111]. This also makes geared systems much harder to manufacture and install, as their fit needs to have extremely tight tolerances to avoid backlash and consequent degradation issues.

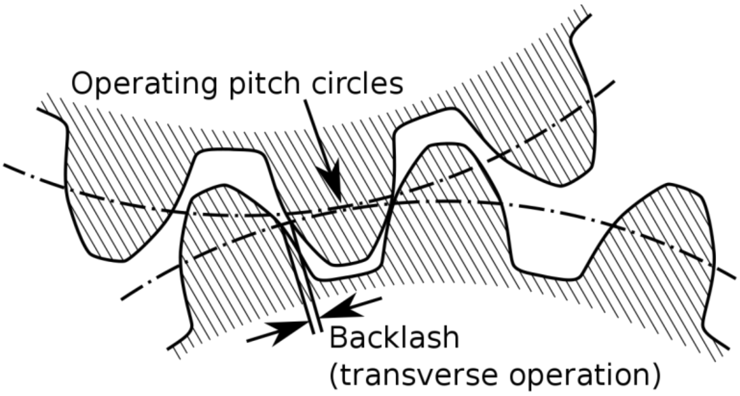

Figure 29: Backlash illustration

Helical gears are similar to spur gears, but their teeth are cut in a spiral way around the cylindric face of the gear body, as seen in Figure 30. Because of this design, helical gears have a smoother operation than spur gears. Because they have more contact area between teeth, they can also transfer more power while being quieter [110].

One drawback from this design is that, while transmitting high power, the angle of the teeth can cause excessive thrust load effects. This means that there are forces pushing the gears to the side, which if bad adjusted, can cause the gear to move axially.

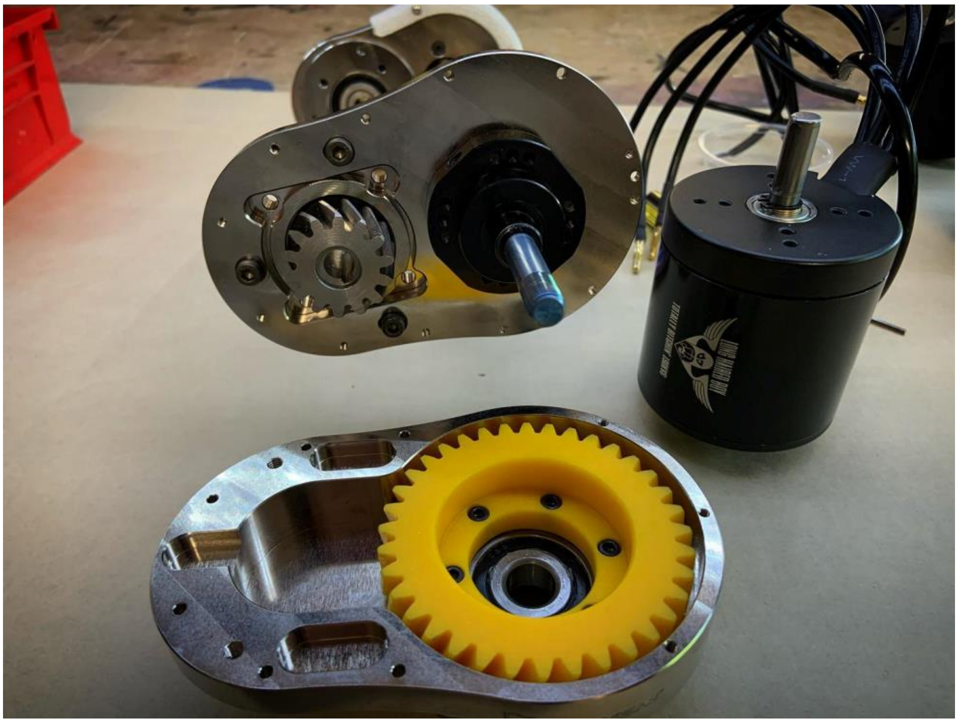

Figure 30: Helical gear drivetrain assembly from an e-longboard

Finally, there are herringbone gears, seen in Figure 31, which consist of two helical hears coupled together forming V-shaped teeth. By doing this, side thrust forces are compensated with each side of the gear, which helps center the gear and prevent it from moving axially [110].

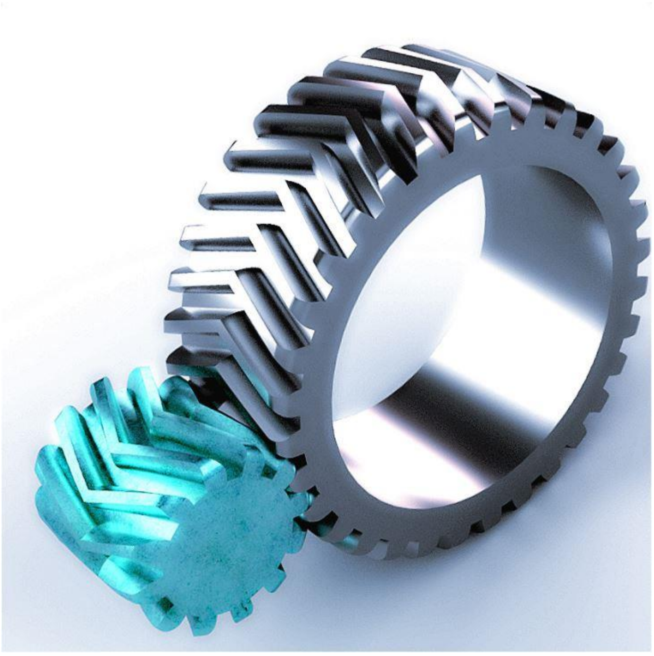

Figure 31: Herringbone gear set visual

Geared drivetrains have the advantage of being one of the most efficient and silent transmission systems. However, it requires a more cumbersome and expensive assembly and installation, as well as correct lubrication and maintenance. Gearboxes also have more deterioration over time due to friction between teeth [111].

6.4.5 Direct drive

Finally, direct drive transmissions are also popular in micromobility. The light weight of the vehicles allows for the ability of certain motors to provide the necessary power to the wheels directly, without transmission assemblies.

Electric motors for direct drive systems are often called “hub motors” because they usually are installed inside the hub of the wheel, with the outer part of the motor rotating. This can be seen in Figure 32.

Figure 32: Hub motor and wheel assembly

This system allows for less parts to be manufactured and installed, thus also avoiding deterioration, maintenance, and other issues.

The drawback is that de design is limited by the motor characteristics. While other transmission systems allow for tweaking of speed and torque, direct drives are bound by the speed and torque of the motor, which also limits the availability of choosing the correct motor for the application.

Because of this nature, usually these systems have less power. They can also suffer from faster degradation as the motor directly suffers the vibration from the road.

7. MICROMOBILITY VEHICLE DEVELOPMENT

In this section, a development process of a micromobility vehicle is described, including design, procurement, manufacturing, and assembly of the vehicle.

7.1 Motivation

Micromobility vehicles can sometime lack the speed, range and overall construction, to endure certain urban and suburban terrains, mainly on the outskirts of the city centers, where the pavement might not be as good as in the city center and the streets don’t usually have slow bike lanes, making it dangerous to be going at half or less than the allowed speed of the road.

These cases call for another micromobility platform, which has been growing in popularity in recent years, which include electric longboards and mountainboards, a type of platform like skateboards but better suited for longer transport journeys.

These platforms, as stated before, have the advantage of being more stable at higher speeds, being faster, more efficient, and enduring rougher terrain.

7.2 Platform

The platform of choice for this project is a mountainboard with hybrid street wheels. This will ensure rideability on rough roads while having a lower wheel diameter than bigger off-road wheels, thus providing more efficiency.

Although there are many brands around the world that produce mountainboards, TRAMPA [112] was chosen as the maker of the platform due to their high quality builds, customization options, which makes it easier to order a board with determined specifications such as hubs, wheels, suspension stiffness, board flexibility, etc. Some of their boards can be seen in Figure 33.

Figure 33: Sample models from trampaboards.com

This brand also makes it easier to build upon their platforms as they provide specific drivetrain components and parts, such as geared pulleys, bearings, hub adapters, etc. This, in turn, will also help save costs as more parts can be ordered from one manufacturer.

7.2.1 Platform configuration

Inside TRAMPA's boards, the platform of choice was a mountainboard on "Infinity" trucks. These trucks are made from heat-treated, CNC'd T6 aluminum, which is also heat-treated. While more heavy than other hollowed trucks, it's more solid and has more area to work on for machining, necessary to provide good anchorage to the motor mounts.

It has a 12mm solid steel axle, which provides good support for the wheels, as seen in Figure 34.

Figure 34: TRAMPA's "Infinity" trucks

The board's deck of choice is the 16ply (wood layers) model "Holypro 35 Electric". This deck has the longest wheelbase, at 945mm, which makes it more stable at higher speeds. The 16 layers were chosen in function of the rider's weight.

The hubs chosen are the 5 spoke "SUPERSTAR" hubs, seen in Figure 35. These hubs have a plastic outer rim with a T6 aluminium 5-spoke. They were chosen because the aluminium spokes provide sturdiness when the rear wheels are connected to the pulleys.

Figure 35: "SUPERSTAR" hub from TRAMPA

Finally, the tyres of choice are "6.5 Inch TRAMPA URBAN TREADS" Tyres, these are smaller than the usual 8-inch mountainboard wheels, which ensures better efficiency on less rough roads, whiles still being able to ride on rougher terrain.

The rest of the board's parts don't have anything specific to them and they are generic to any other board of the brand. The fully assembled board can be seen in Figure 36.

Figure 36: Fully assembled board

7.3 Powertrain

The board's powertrain can be divided in 4 different sections:

- Motors
- Battery
- BMS
- ESC (Motor controller)

7.3.1 Motors

The motors characteristics, as explained before, need to be a decision of both power and speed capabilities.

For this project the next constraints were set:

- Needs to reach speeds between 50 km/h and 70 km/h
- Needs to accelerate to 50 km/h in around 10 s, to be in pair with street cars.

- Needs to power a user between 60 kg and 80 kg with no speed loss.
- Note that the board will weight around 10 kg with all its systems installed.

For power assumptions, the usual power equation in Equation 3 is used.

$$P = \frac{W}{t} = F * v = m * a * v$$ Equation 3

Knowing that the average speed for city traffic is around 20 km/h [3], the power equation in Equation 4 is populated and the result calculated in Equation 5.

$$P = 90\ kg * \frac{50\frac{km}{h} * \frac{10^3 m * 1\ h}{1\ km * 3\ 600\ s}}{10\ s} * 20\frac{km}{h} * \frac{10^3 m * 1\ h}{1\ km * 3\ 600\ s}$$ Equation 4

$$P \approx 700\ W$$ Equation 5

If the user want's to continually operate at 50 km/h, the power is calculated in Equation 6 and Equation 7.

$$P = 90\ kg * \frac{50\frac{km}{h} * \frac{10^3 m * 1\ h}{1\ km * 3\ 600\ s}}{10\ s} * 50\frac{km}{h} * \frac{10^3 m * 1\ h}{1\ km * 3\ 600\ s}$$ Equation 6

$$P \approx 1\ 700\ W$$ Equation 7

Knowing that friction and drag forces act against the movement of the vehicle, the power needs to be a certain amount higher to properly power the vehicle. Although these can be calculated theoretically, a simple way to estimate a rough friction and drag force for this application is just to measure the force required to pull a user on the board at constant speed by means of a weight measurement device. This setup can be seen in Figure 37.

Figure 37: Friction force test setup

The results of this test provide an average pulling force of ≈ 35 N, which can be attributed to friction and drag forces. The power to propel the vehicle and user through friction forces should be around 200 W at 20 km/h and ≈500W at 50 km/h. With the purpose of giving the motor some slack so it's not riding at maximum power all the time, a motor of 4 000 W was chosen for this purpose.

Because of rougher roads and the ability to provide traction control, a dual motor configuration was decided. This won't only give the possibility of better traction, bit it will also make the board more stable and reduce the electric and physical load on the motors, dividing it by two. Still, the power of the motors will remain the same to give the availability of power and ride at reduced loads.

In terms of KV, the speed and voltage of the motors need to be considered. For the vehicle to be able to reach 70 km/h, the wheels should be rotating at 1124 rpm, as seen in Equation 8.

$$70\,\frac{km}{h} * \frac{10^3 m * 1\,h}{1\,km * 60\,min} * \frac{1\,wheel\,revolution}{2 * \pi * \ 0.1651\ \mathrm{m}} \approx 1\,124\,rpm \qquad \text{Equation 8}$$

The availability of reduction ratios from the geared pulleys from TRAMPA can be deduced from their pulley availability. Motor pulleys vary from 13 to 15 teeth. Slave pulleys for "SUPERSTAR" hubs have either 62 or 66 teeth. The different combinations can be seen in Table 4.

Motor Pulley Teeth	Wheel Pulley Teeth	Reduction Ratio	Max Motor Speed [rpm]
13	62	4.77	5360.62
13	66	5.08	5706.46
14	62	4.43	4977.71
14	66	4.71	5298.86
15	62	4.13	4645.87
15	66	4.40	4945.60

Table 4: Max Motor Speed by pulley combination

Electric skateboards brushless motors usually operate between 10s (37.0 V) and 12s (44.4 V), thus, their max KV values can be seen in Table 5.

Max Motor Speed [rpm]	Motor Voltage [V]	Max Motor KV
5360.62	37	144.88
	44.4	120.73
5706.46	37	154.23
	44.4	128.52
4977.71	37	134.53
	44.4	112.11
5298.86	37	143.21
	44.4	119.34
4645.87	37	125.56
	44.4	104.64
4945.60	37	133.66
	44.4	111.39

Table 5: Max Motor KV by Max Motor Speed

Looking at these values and at the availability of brushless motors, which have a range of 100 KV, 130 KV, 170 KV, 200 KV…, a 170 KV motor was selected so it can handle all pulley combinations.

Finally, the motor's brand of choice was APS [113] (Alien Power System). The bran was chosen due to its reputation amongst the electric longboard and mountainboard community as a quality manufacturer.

Two motors of the model "APS 6384S SENSORED OUTRUNNER BRUSHLESS MOTOR 170KV 4000W" was selected as it matches all the definitions provided above.

7.3.2 Battery

Battery characteristics to choose from are:

- Cell type
- Battery voltage (Cells in series)
- Battery capacity (Cells in parallel)

7.3.2.1 Battery specifications

The batteries cell type selected is lithium ion. As explained before, these cells are cheaper than LiPo cells, which can significantly reduce the cost of the battery pack.

Inside the lithium ion cells, the 18650 type was selected as it is the most common and available Li-ion cell in the retail market, which makes it more affordable.

Regarding brands, many like Samsung, Panasonic, Sony, etc.; are known and have a good reputation when it comes to cell manufacturing. In this case the choice was to go for a well-known model from Samsung, which has great documentation, the INR18650-30Q cell, seen in Figure 38.

Figure 38: Samsung's 18650 30Q cell

This cell has a nominal voltage of around 3.6 V, with a max voltage (100% SOC) of 4.2 V. It has a capacity of 3000 mAh and a max rated current of 20 A. This cell is tested to degrade to 72% SOC at 250 cycles as seen in Table 7. Its discharge capacity by cell voltage can be seen in Figure 39.

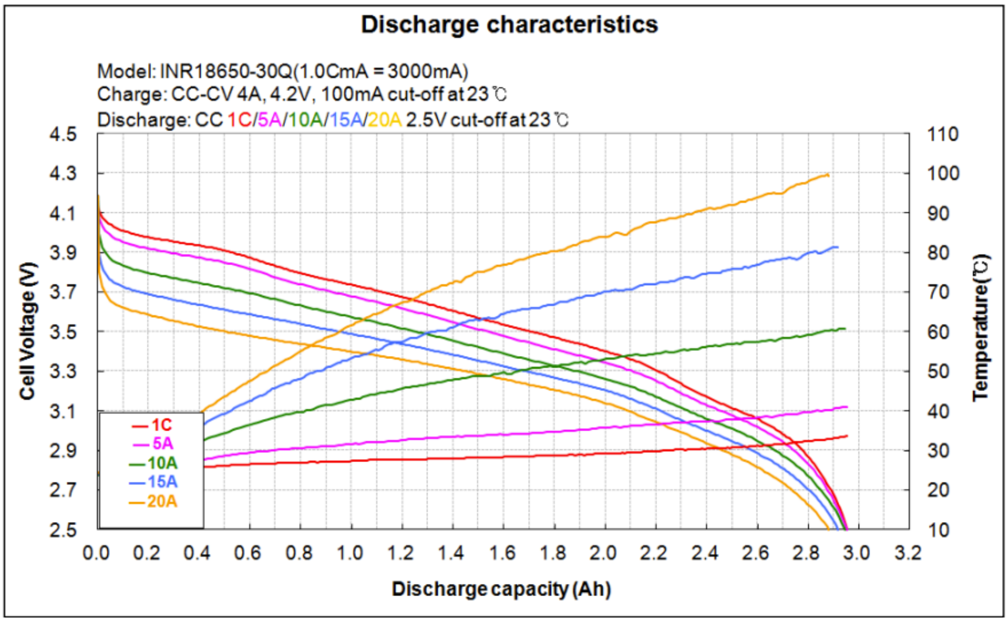

Figure 39: Voltage vs capacity characteristic curves for Samsung's 18650 30Q cell

Type		Spec.(Tentative)	Typical INR18650-30Q
Chemistry		NCA	NCA
Dimension (mm)	Diameter	18.33 ± 0.07	18.33 ± 0.07
	Height	64.85 ± 0.15	64.85 ± 0.15
Weight (g)		Max. 48.0	45.6
Initial IR (mΩ AC 1kHz)		≤ 18	13.13 ± 2
Initial IR (mΩ DC (10A-1A))		≤ 30	19.94 ± 2
Nominal Voltage (V)		3.60	3.61
Charge Method (100mA cut-off)		CC-CV (4.2±0.05V)	CC-CV (4.2±0.05V)
Charge Time	Standard (min), 0.5C	180min	134min
	Rapid (min), 4A	70min	68min
Charge Current	Standard current (A)	1.5	1.5
	Max. current (A)	4.0	4.0
Discharge	End voltage (V)	2.5	2.5
	Max. cont. current (A)	15	15
Rated discharge Capacity	Standard (mAh) (0.2C)	3,000	3,040
	rated (mAh) (10A)	2,700	2,983

Table 6: Samsung 18650 30Q specifications

The motors selected have a max voltage of 50.4 V, so 12 cells connected in series (12S) are needed to achieve maximum voltage of the motor. Thus, the battery pack is designed to have 12 groups of cells in series.

The cells in parallel will be bound by the desired battery capacity and the space on the platform.

In terms of space capacity, for the platform to avoid mass concentrations in certain points and retain a slim design, a cable chain was gathered to act as a battery pack housing.

Figure 40: Cable chain design as a battery pack enclosure

With both the bottom compartment and the top compartment, seen in Figure 40, it was found that a 12S 6P (12 in series and 6 in parallel) battery pack could fit into the platform.

This pack would have a total capacity of 216 Ah or 792 Wh approximately. Knowing that mountainboards have an average consumption of 10 Wh/km, this would give the board around 79 km. However, this board has a dual motor configuration with a lot of power, which might bring the consumption up and the range much lower.

7.3.2.2 Battery assembly

The battery was assembled along the board in groups of 2 bricks, for a total of 12 bricks and 12 modules. The way that 18650 cells are assembled into bricks is by spot welding nickel strips onto the negative and positive poles, grouping the cells together permanently. This process can be seen in Figure 41, Figure 42 and Figure 43.

Figure 41: Group of 6 18650 cells ready for welding

Figure 42: Six cells welded together to form a brick

Figure 43: All 12 bricks spot welded and ready for installation

While spot welding the cells into bricks is a secure way to ensure connection, thin nickel strips might not bear with the amount of current going through it and potentially heat up and cause other issues. For this reason, a bare copper cable was soldered on top of the nickel strips to ensure good current flow. This can be seen in Figure 44.

Figure 44: Copper cable welded on top of nickel strip

To ensure good connection between bricks and avoid short circuiting or isolation problems between modules, a 3D-printed protection assembly was designed and printed for every module of two bricks, seen in Figure 45.

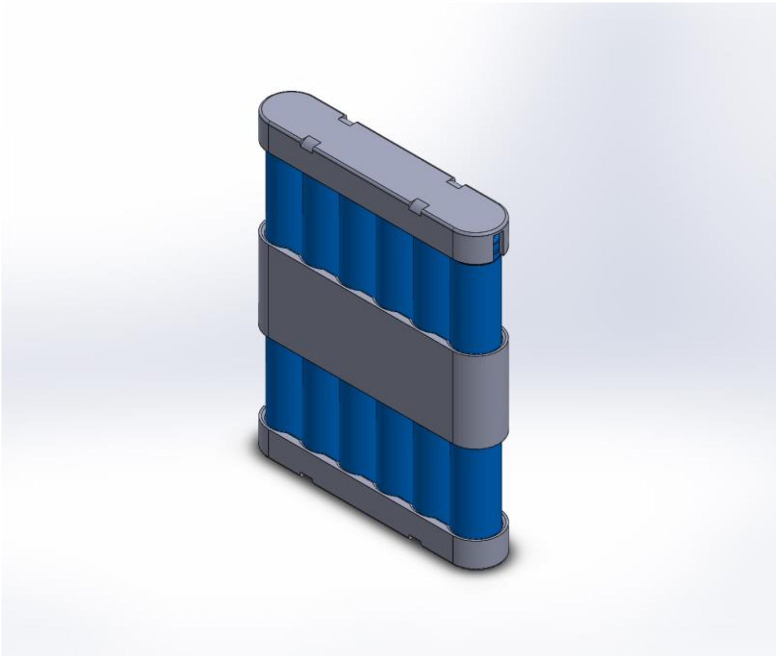

Figure 45: Protective 3D-printed assembly CAD design

Once all the modules were assembled, they were connected and placed into the cable chain, as seen in Figure 46.

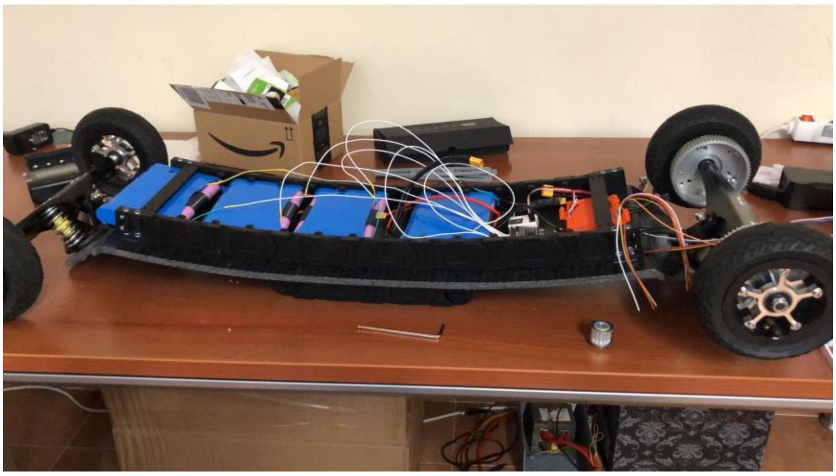

Figure 46: Battery pack assembled inside the cable chain

7.3.3 BMS

The BMS is the device ensuring proper voltage balance between cells, as well as prevention from over voltage or over discharge. In big systems, the BMS functions both when charging and discharging. Due to the low number of cells in micromobility vehicles, costs were cut down to acquire a BMS that would balance the bricks only every charge cycle.

Because of its low capacity, this battery would need several charge and discharge cycles to cause concerning imbalance. Balancing every charge cycle is enough in this case.

A 12S BMS was purchased and wired following the proper schematic referenced in Figure 47.

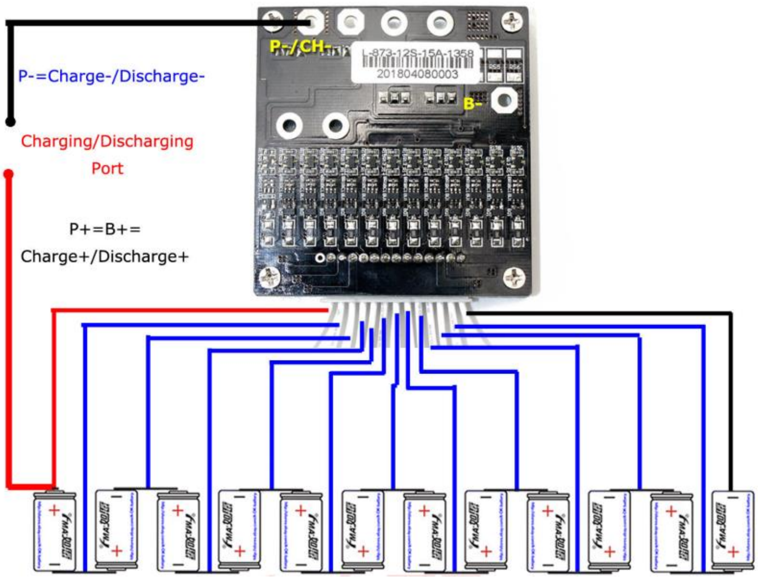

Figure 47: BMS wiring diagram

7.3.4 Motor controller

One of the most important components of an electric micromobility vehicle is the motor controller or ESC (Electronic Speed Control). This is considered as the MCU (main control unit) of these kind of vehicles as it handles all the telemetry and controls the motors of the vehicle.

One of the most famous types of motor controllers are VESC systems. VESC is an open-source ESC system, thus its popularity and great community support [114].

For this project, the Focbox UNITY was chosen as the motor controller, seen in Figure 48. This is a dual motor ESC developed by the brand Enertion, that is built upon VESC version 4.0. Its schematics can be seen in Figure 49.

Figure 48: Focbox UNITY

This was chosen due to its innovations and capabilities. This ESC has PPM, Analog, UART and USB C communication ports for both monitoring telemetry, configuration purposes and control purposes. It also uses the CAN-bus protocol and has Bluetooth connectivity.

In terms of electric specifications, it can provide 80 A continues motor current with 300 A max system current. It accepts batteries ranging from 3S to 12S.

It provides electrically delivered braking, reverse and traction control for dual motor configurations.

The motor controller is directed by a 2.4 GHz PPM wireless trigger remote.

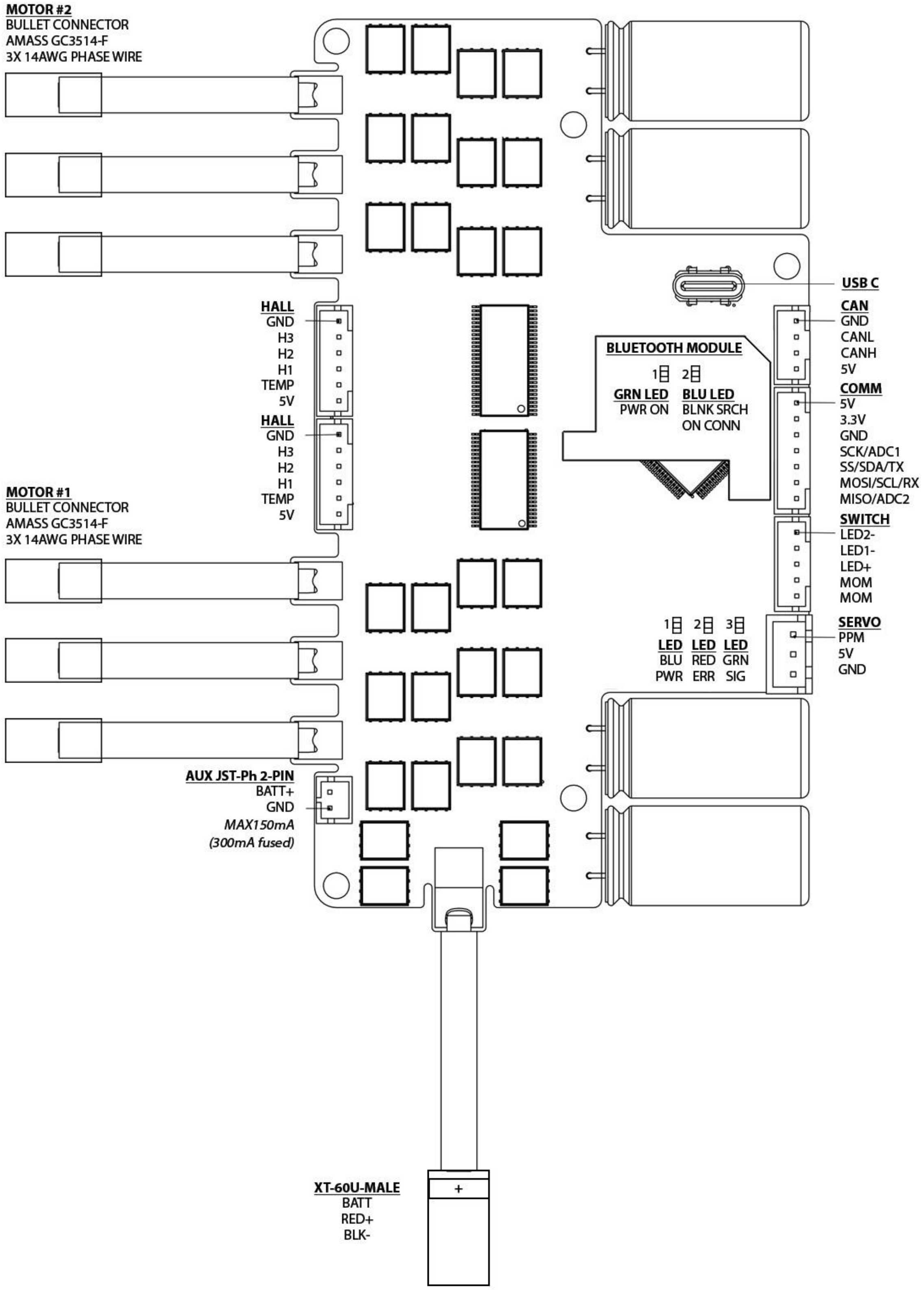

Figure 49: Wiring diagram of Focbox UNITY

7.4 Drivetrain

7.4.1 Gearing

It was decided to go with a belt drive system as it provides great flexibility and low maintenance to the vehicle. It’s also lest costly and easier to install.

From Table 4, a combination of a 15 teeth motor pulley and a 66 teeth wheel pulley were chosen, together with a 460mm long belt.

This system uses 5M HTD (High Torque Drive), which is a type of gear tooth design optimal for high torque applications. 5M states the spacing between teeth, in this case 5 mm. Knowing this data, the distance between center points for both pulleys can be calculated using an online calculator [115]. Distance between center points for an optimal belt tension is 122 mm. Knowing this value, a motor mount can be designed.

7.4.2 Motor mounts

First, two faces of the rear hanger were machined flat to ensure a proper fit of the motor mounts, as seen in Figure 50.

Figure 50: Machined rear right hanger

7.4.2.1 Version 1.0

Version 1 of the motor mount was designed to be CNC machined from a single piece of aluminum. The 3D-printed prototype of this version can be seen in Figure 51. Vertical slots were cut for the motor mounting points, so it could slide and tension the belt as needed.

Figure 51: Motor mount version 1.0 3D-printed prototype

While being an easy and sturdy design due to its lateral surface area contact with the trucks, as seen in Figure 48, proved challenging to manufacture as CNC services are extremely costly.

Thus, this design had to be quickly abandoned.

7.4.2.2 Version 2.0

Version 2.0 of the motor mount was designed for manufacturing, more specifically laser cutting. Laser cutting is much cheaper than CNC machining, which reduced costs drastically. Its CAD design can be seen in Figure 52.

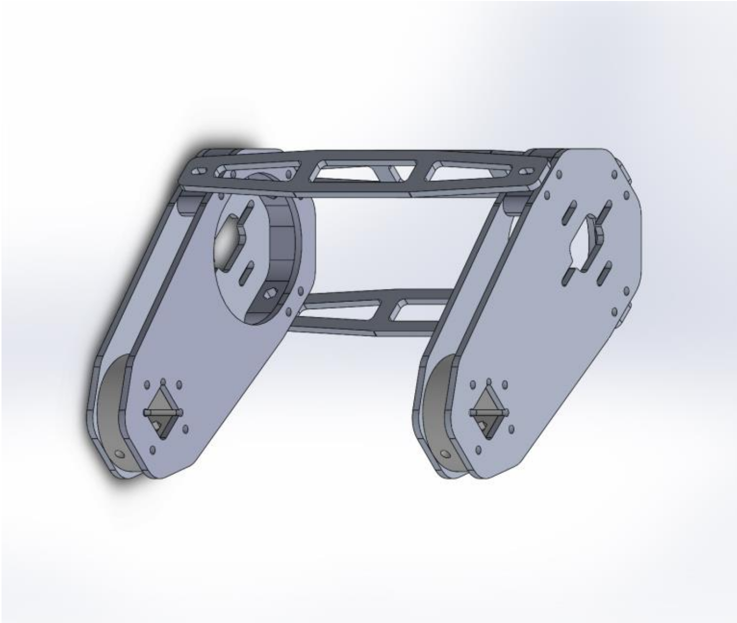

Figure 52:CAD design of Motor Mount version 2.0

This setup was 3D-printed in PLA and tested on the rear trucks to check its fitment and tolerances, as seen in Figure 53.

Figure 53: Drivetrain assembly PLA prototype

Once the M4 screws were procured, the design was 3D-printed in PETG, a material similar to ABS. This prototype can be seen in Figure 54. Even with a fully 3D-printed prototype, the strength of the assembly as exceptional, where the vehicle was already able to be ridden.

Figure 54: 3D-Printed prototype of Motor Mount version 2.0

The spacers that separate the two plates were designed to be made out of PETG, in the end, these prototype parts could be used in the final assembly.

7.4.2.3 Finite element analysis

To make sure this type of aluminum was the correct choice, a finite element analysis was carried out.

7.4.2.3.1 Design

The material of choice for laser cutting was Aluminum 5083 which has exceptional strength and is also resistant to salts and other chemicals, which is extremely important as these parts are exposed to the elements [116].

Note that for this analysis, the design doesn't include the backplates, which were added later for improved stabilization both dynamic and modal.

The thickness chosen for the aluminum plate was 5 mm. And the mounting points were extruded cut as in Figure 54 and Figure 55.

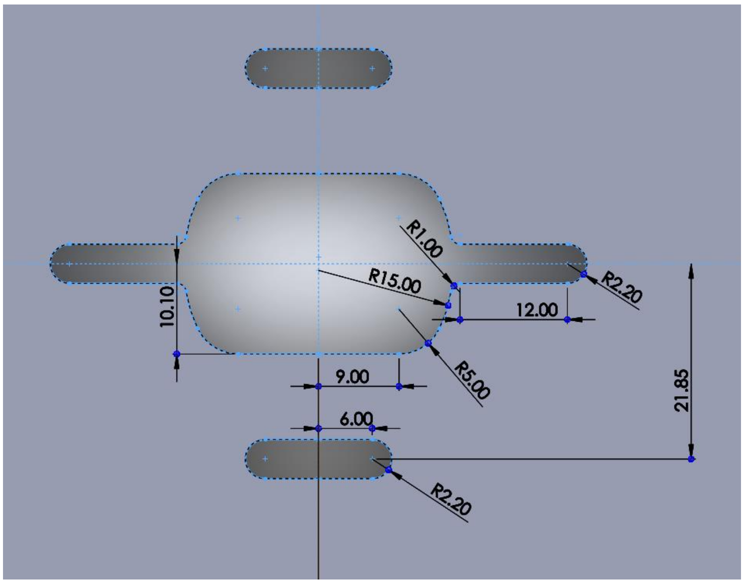

Figure 55: Motor mounting holes

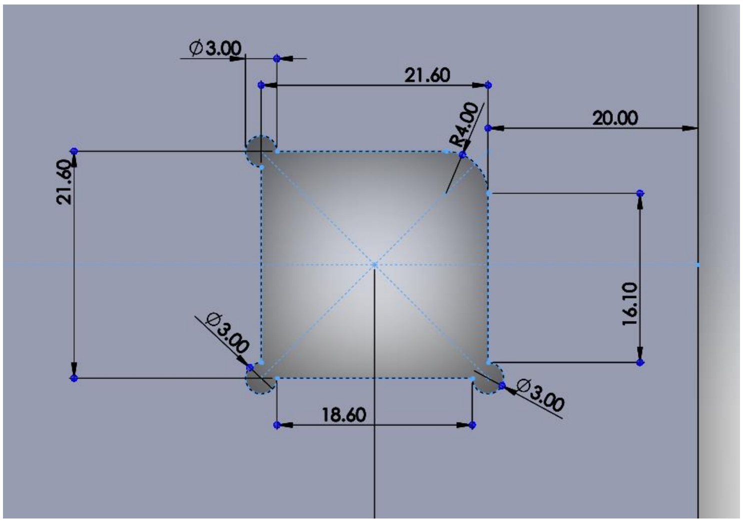

Figure 56: Truck mounting holes

Holes are made to fit M4 screws, which is the measure that the chosen motors use. Same M4 screw size was used along the motor mounts for simplicity purposes. The full plate design can be seen in Figure 57.

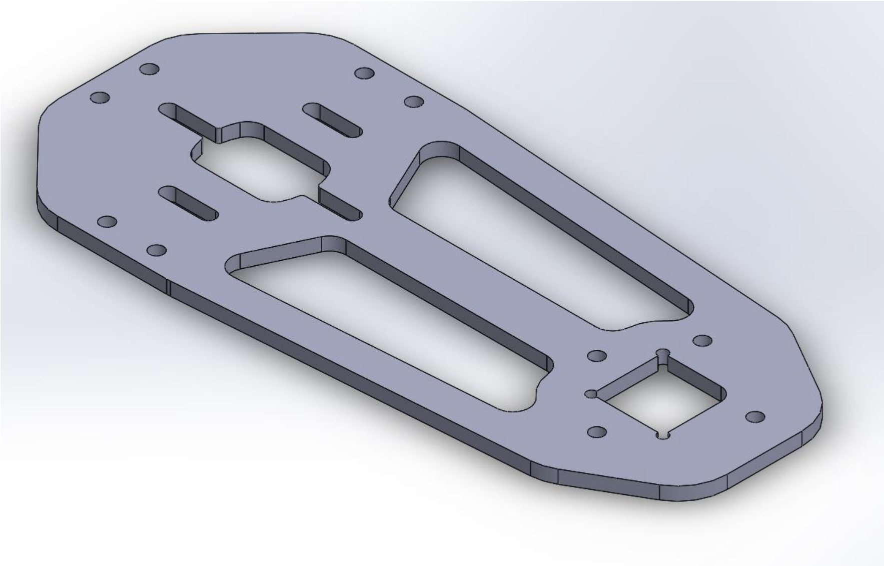

Figure 57: Front motor mount piece

7.4.2.3.2 ANSYS modeling

The front mounting plate was the part studied in ANSYS, the model was imported into the software. The mesh was done using the SmartSize tool, with a size of 4 in a scale of 1 to 10, where 1 is very fine and 10 is very coarse [117]. This provides enough detail to the part, without exhausting computer resources. The result of this import can be seen in Figure 58.

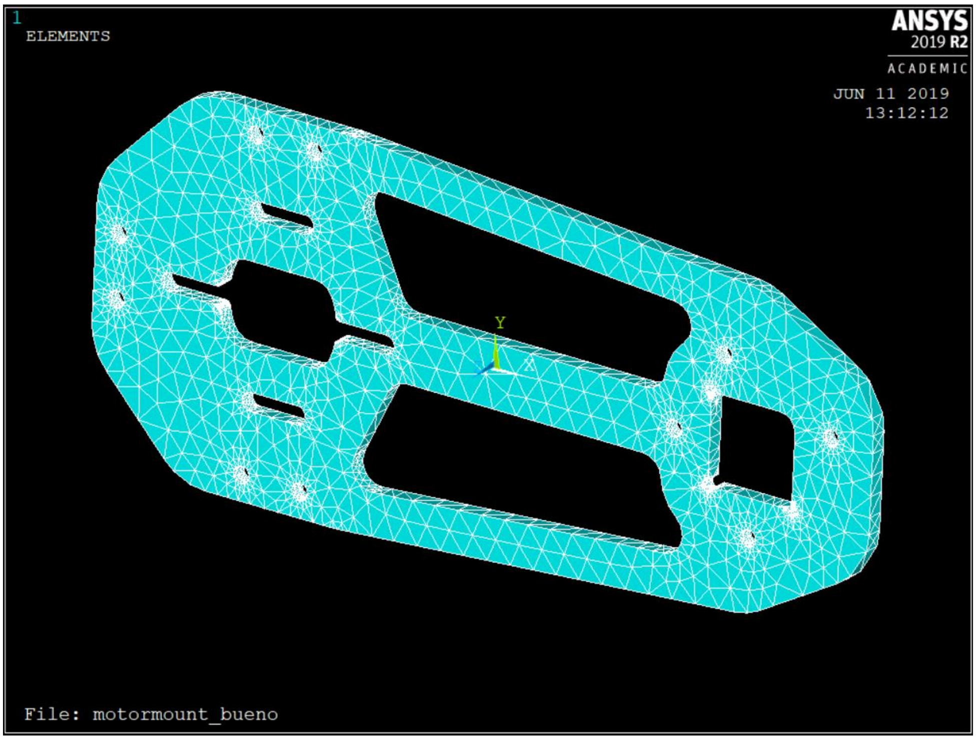

Figure 58: Front motor mount plate ANSYS model

The model is then constrained by the truck-mounting point and the four screw points at the bottom, as seen in Figure 59.

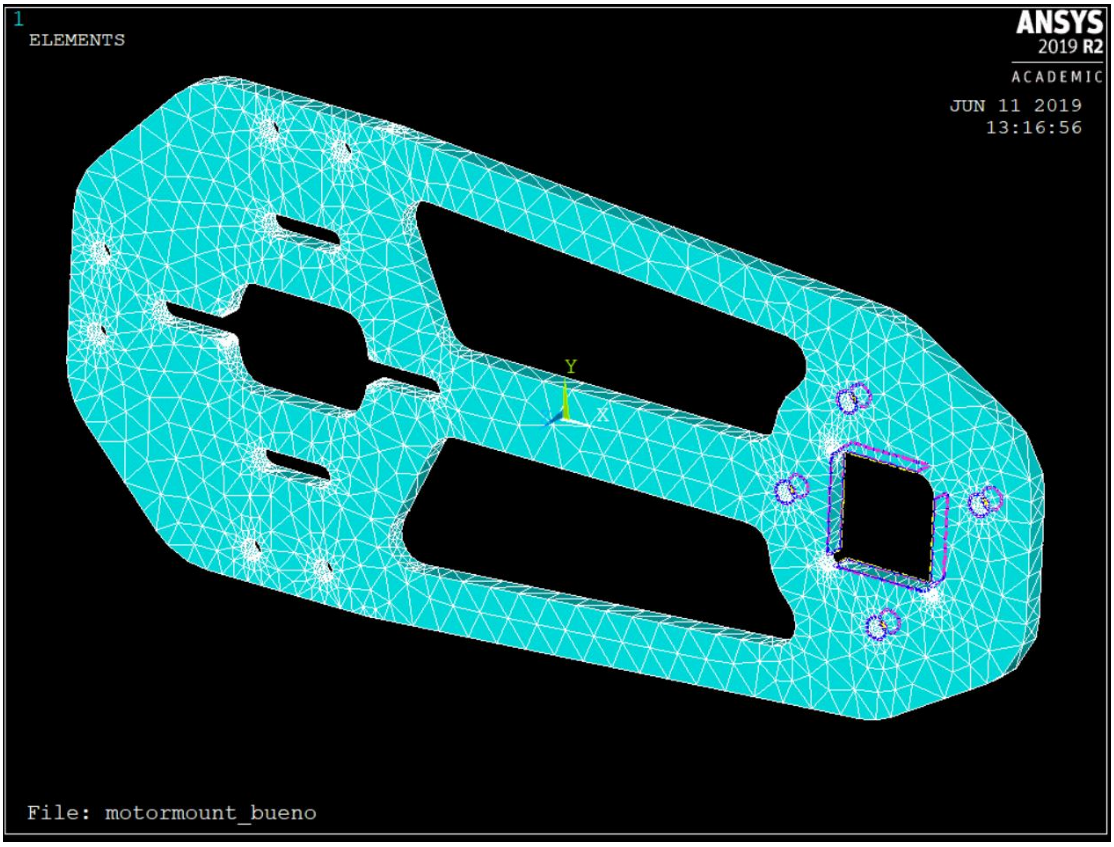

Figure 59: Front motor mount plate constrained ANSYS model

Static forces were calculated from the motor's mass, 0,955 kg, which applies ≈ 9,37 N to the motor mount in the direction of gravity. Because the motor is mounted on one side, it also applies a torque on the four mounting points. These forces can be seen applied to the model in Figure 60 and Figure 61.

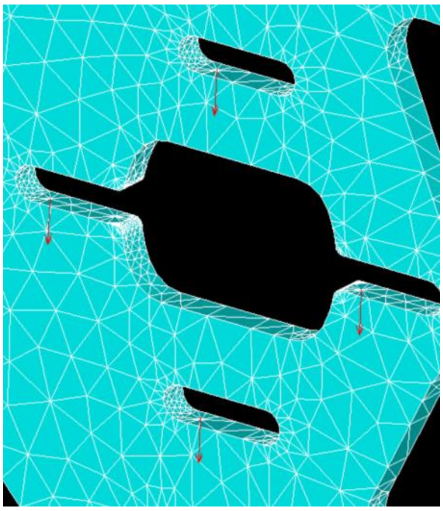

Figure 60: Vertical mass forces on the front plate motor mount plate

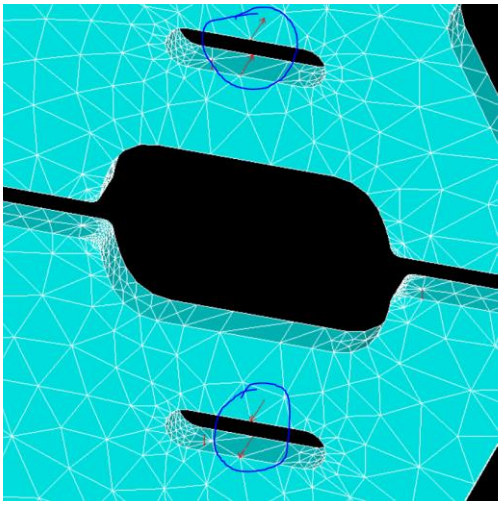

Figure 61: Mass-caused torque forces on the front plate motor mount plate

Further static forces are estimated by means of the maximum torque of the motor, which can be gathered from the specification sheet and it’s 5.8 Nm. This is also applied to the model, as seen in Figure 62.

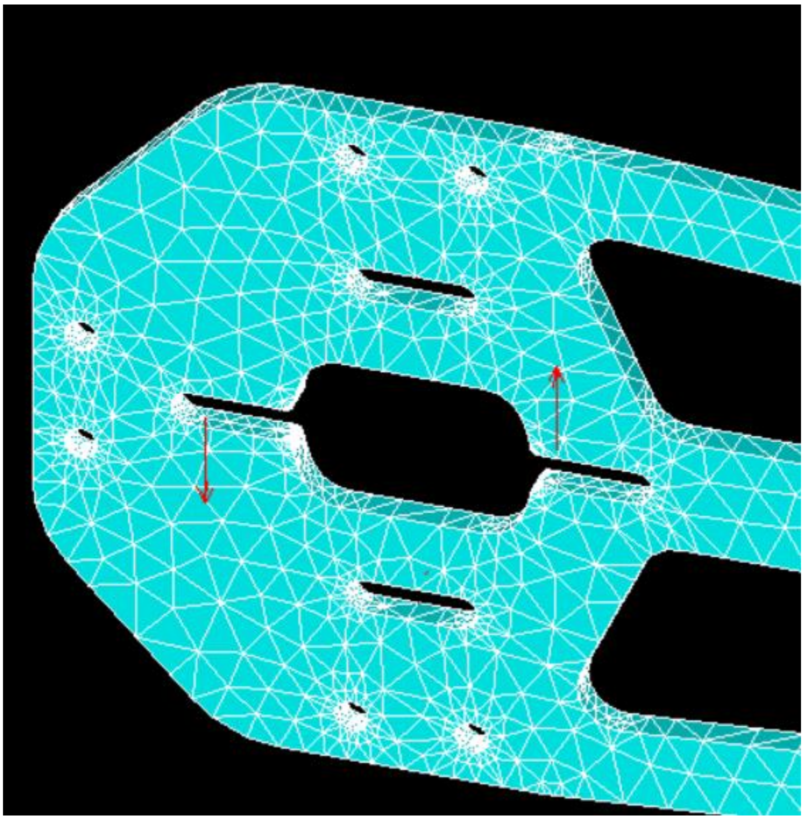

Figure 62: Dynamic forces acting on the front plate motor mount plate

7.4.2.3.3 ANSYS results

It was first interesting to see the effects of the stabilizing bars, that connect the two motor mounts on either side of the axle. For these, two scenarios were made, where only the motor mass effects were considered, as these forces are the only transversal ones. One without the bars connected, as seen in Figure 63, and one with the bars connected, as seen in Figure 64.

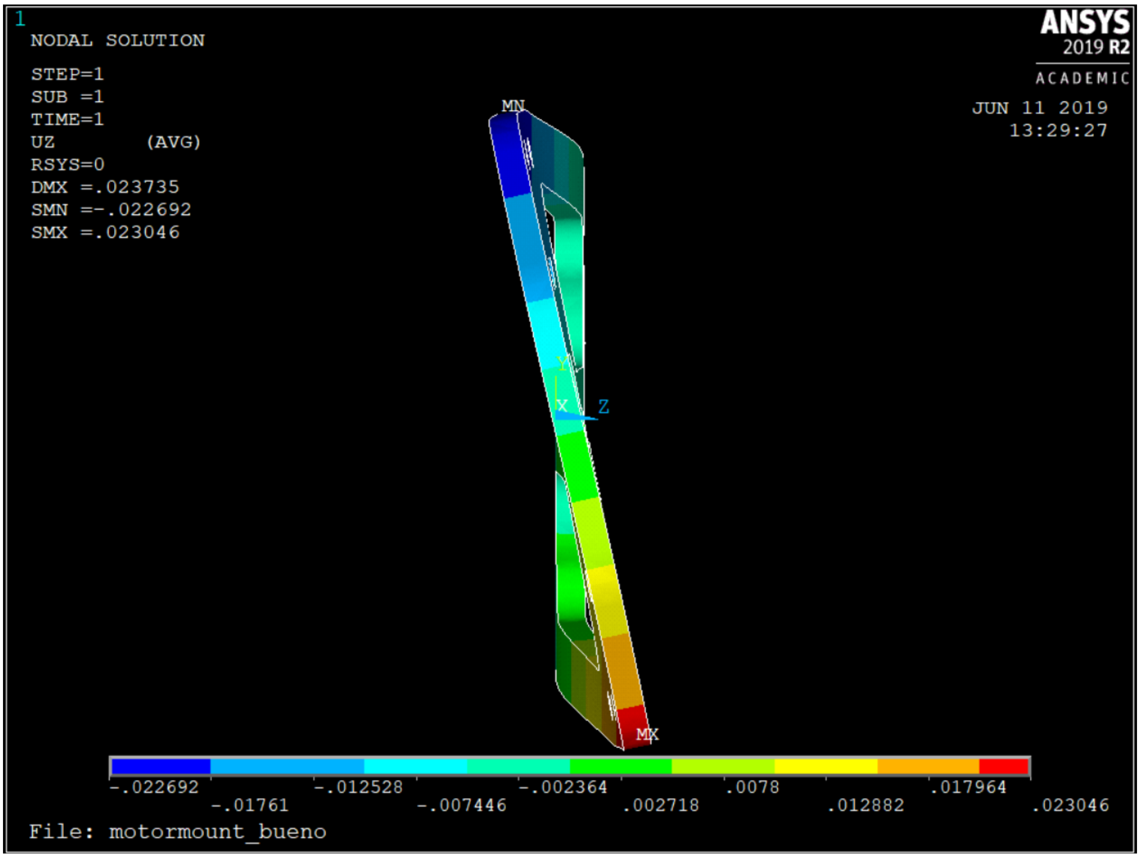

Figure 63: Elastic deformation of the front motor mount plate without stabilizing bars (Static forces) [m]

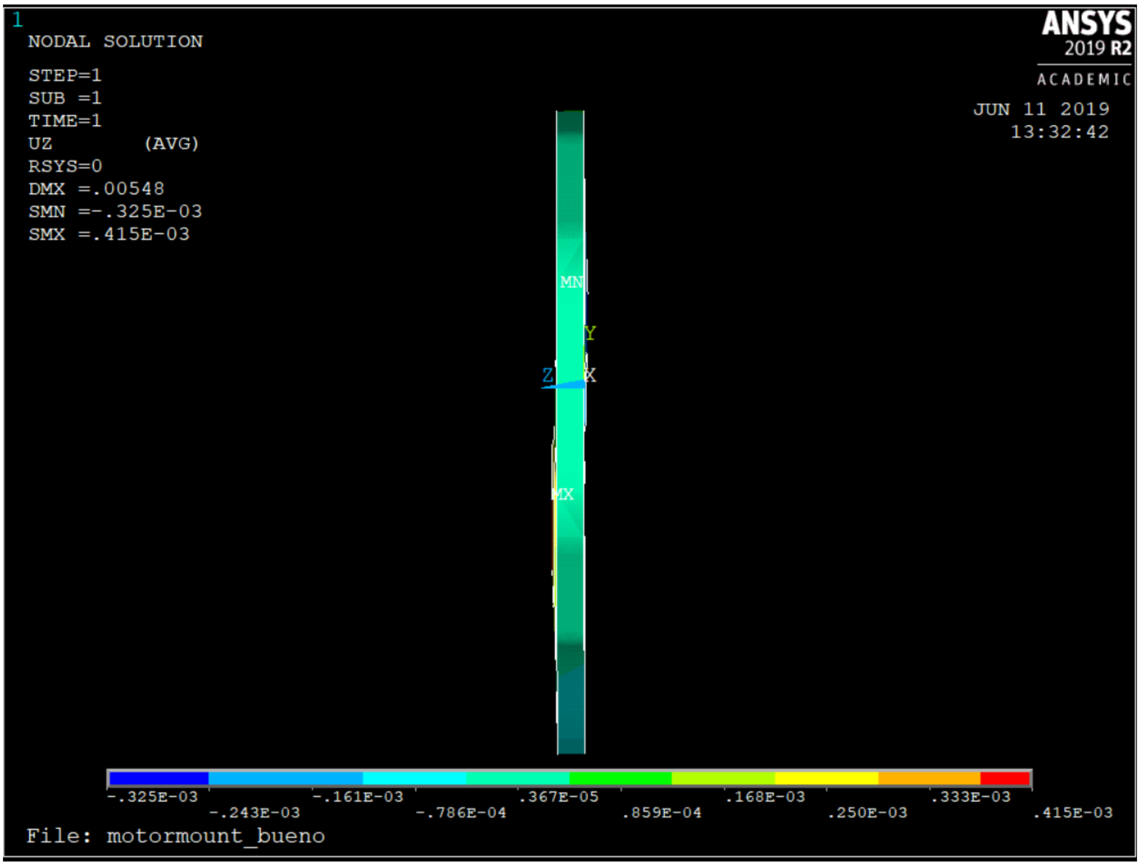

Figure 64: Elastic deformation of the front motor mount plate with stabilizing bars (Static forces) [m]

It can be seen how the stabilizing bars can improve the deformation of the plate by a magnitude of 10000.

Next, the effects of the maximum motor torque were considered. Because of its magnitude, these are the most critical forces acting on the motor mount. The results can be seen on Figure 65.

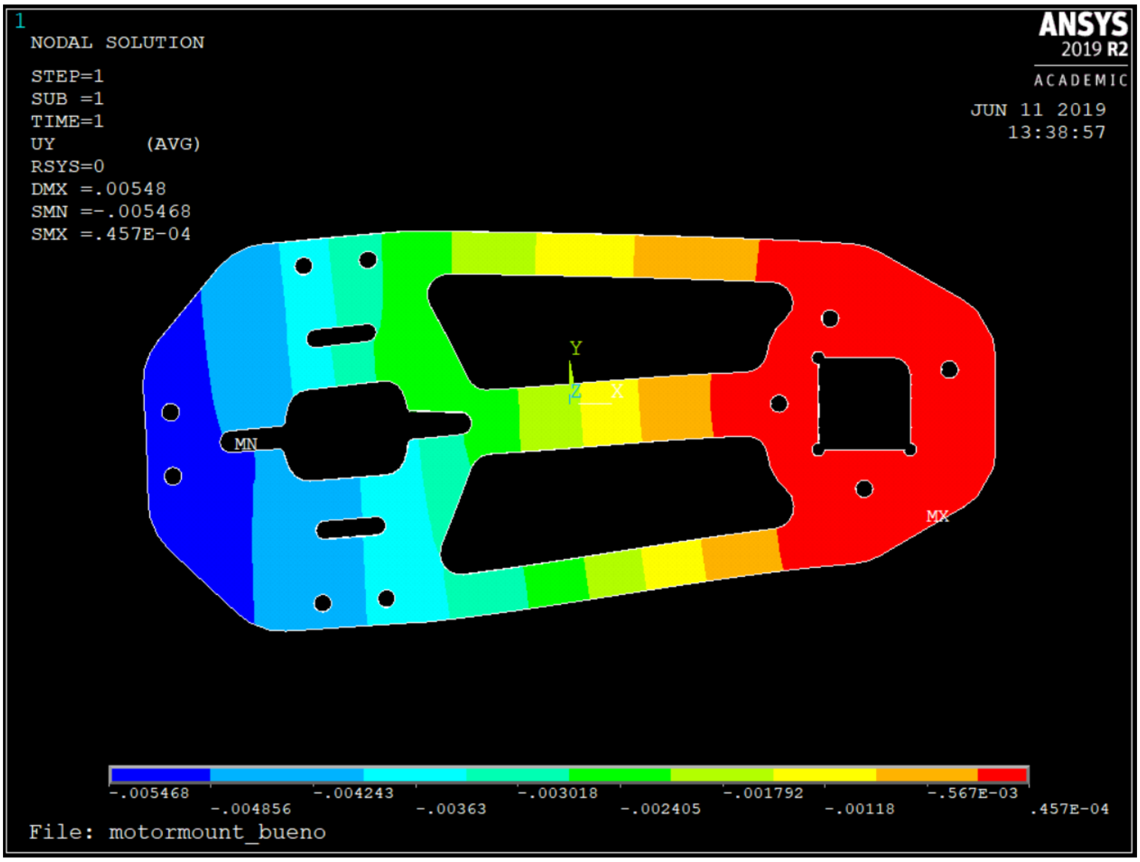

Figure 65: Maximum motor acceleration torque effects on the front motor mount plate [m]

Maximum elastic displacement occurs on the furthest point from the anchor points, and its value is ≈ 5 mm. This is one of the main reasons that the backplate was later added in the design.

Von Misses stress was also analyzed, and it's greater where the mounting screws contact the mounting plate, as seen in Figure 66. Note that the anchoring of the screws have been set at one point, thus the greater values, these values would be less in reality as the screw has a contact surface with the plate and not a point.

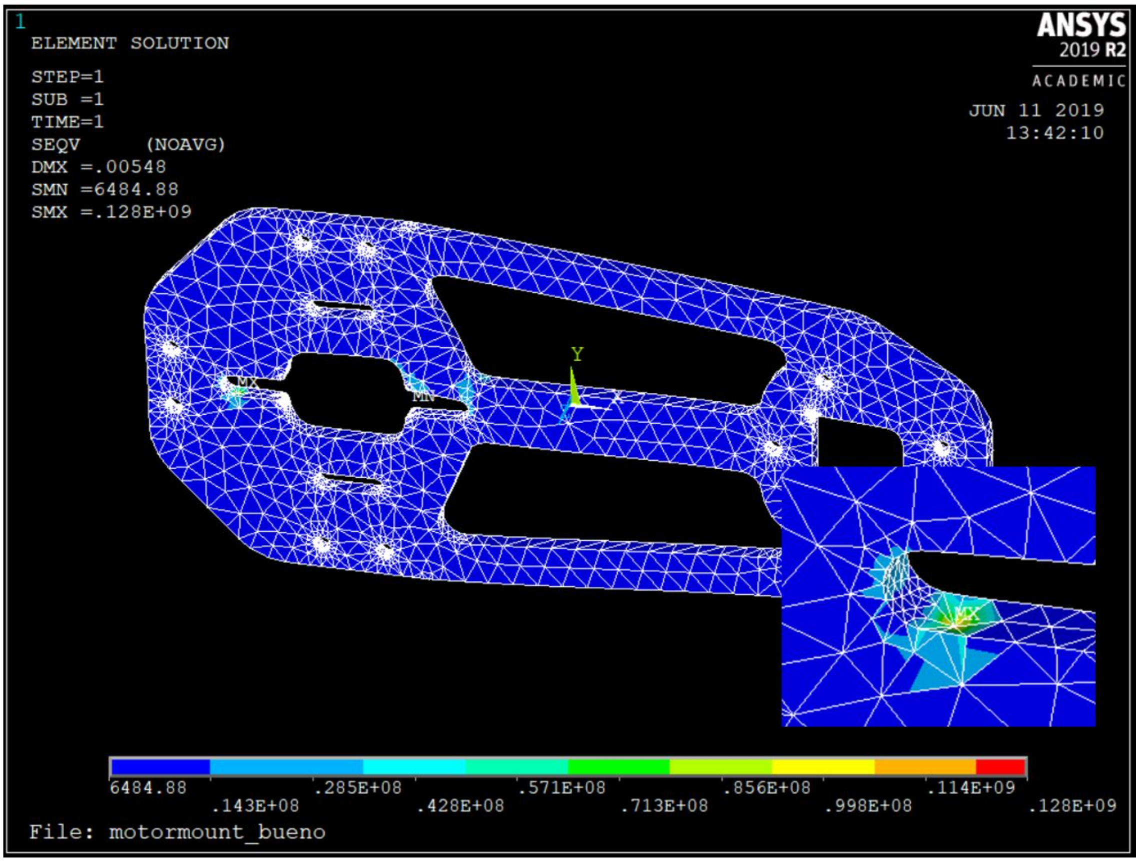

Figure 66: Front motor mount plate Von Misses stress caused by static forces [Pa]

Lastly, for static forces, in case of maximum breaking, the motor would apply the same maximum torque but in opposite direction. Resulting in the deformation model seen in Figure 67.

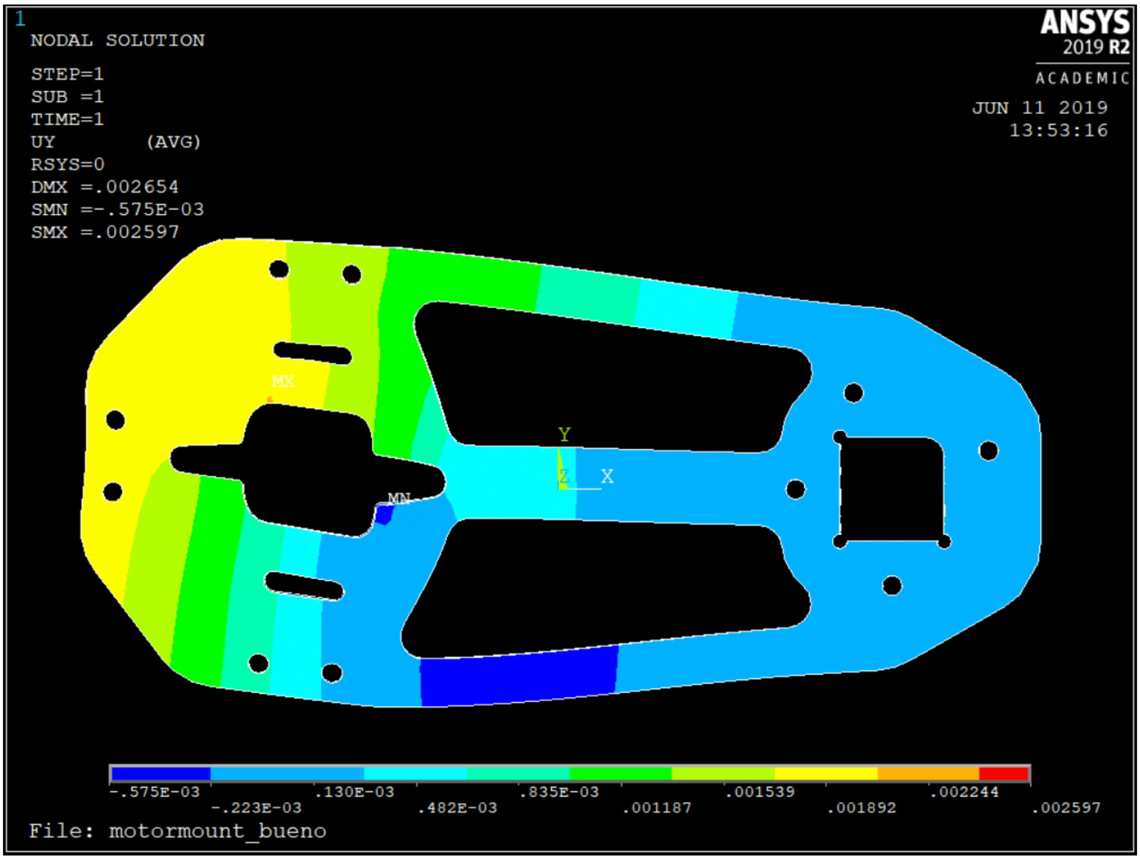

Figure 67: Maximum motor braking torque deformation effects on the front motor mount plate [m]

For a dynamic forces analysis, the following was considered:

- 0.01 s → Maximum acceleration torque
- 4 s → Acceleration ends
- 4.01 s → Maximum braking torque
- 7 s → Braking ends

This sequence results in a maximum elastic deformation which can be seen in Figure 68.

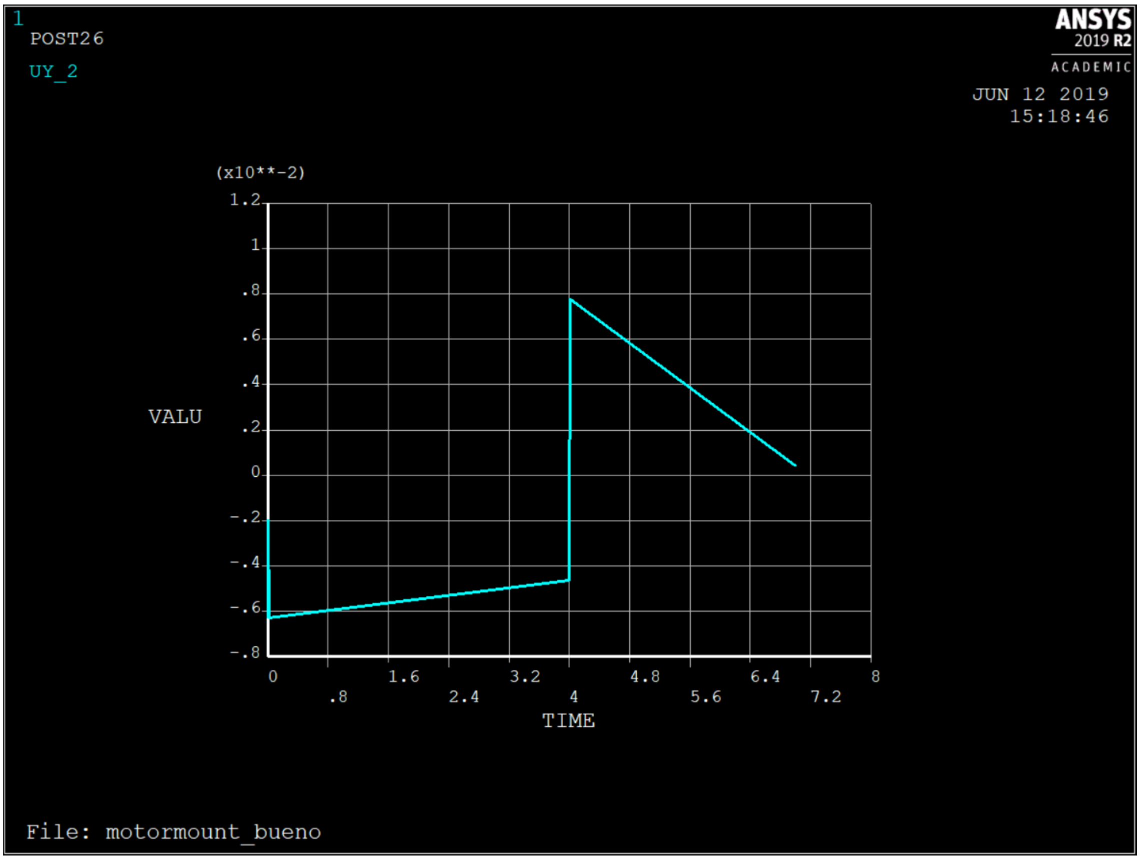

Figure 68:Maximum elastic deformation of the front motor mount plate while accelerating and braking [m]

Both transient Von Misses stress and deformation was modelled for each period's maximum value. These results can be seen in Figures 69 and 70.

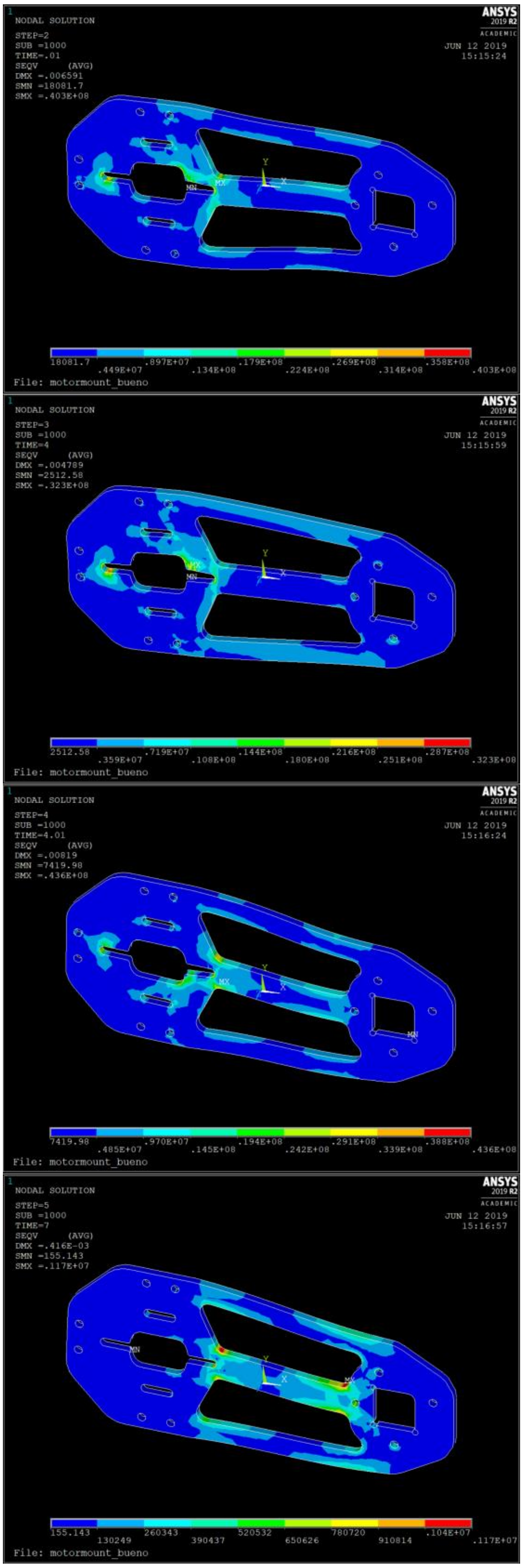

Figure 69: Von Misses stress on the front motor mount plate (Transient analysis)

Figure 70: Front motor mount plate deformation (Transient analysis)

7.4.2.3.4 Finite element analysis conclusions

While analyzing maximum forces and torque applied to the front motor mount plate resulted in little elastic deformation and stress, taking into account the stabilizing bars; it was decided to design and incorporate a backplate to improve the mounting plate rigidity both transversal and axially.

7.4.2.4 Final assembly

The material chosen for the spacers was 3D-printed PETG, which has similar properties as ABS but is easier to print [118]. M4 screws, spacers and nuts were ordered in different lengths to fit the assembly. The manufactured parts for the assembly can be seen in Figure 71. Their assembly process can be seen in Figure 72 and Figure 73.

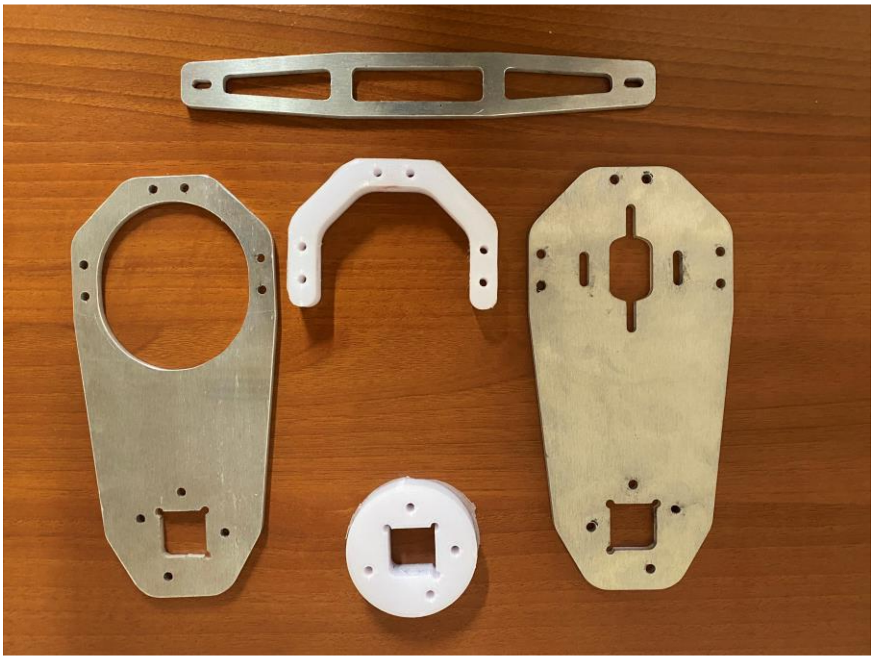

Figure 71: Manufactured parts for the motor mount

Figure 72: Rear Right motor mount assembly

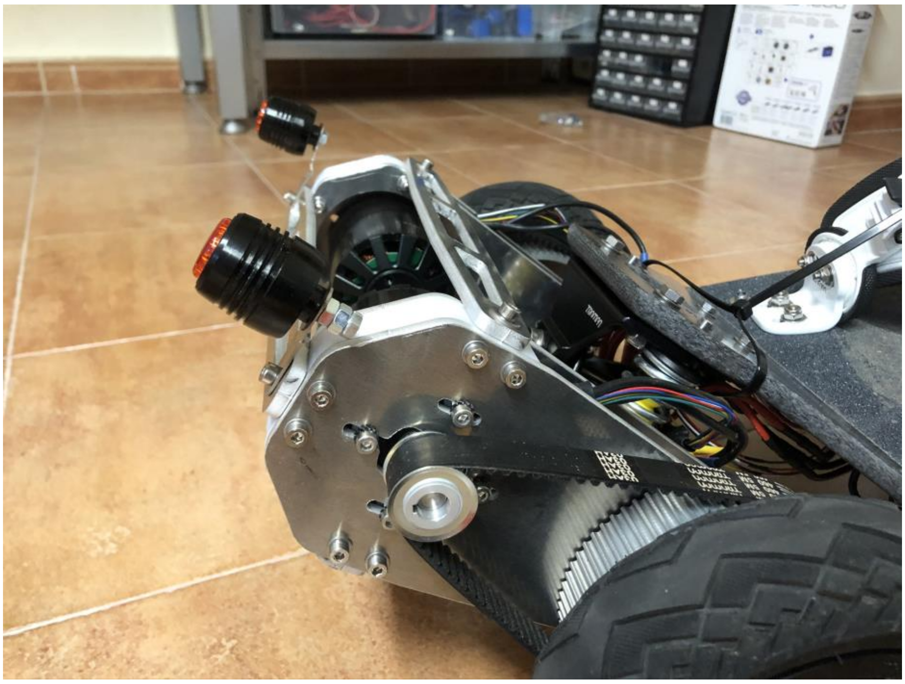

Figure 73: Motor Mount version 2.0 assembly

8. VEHICLE DEVELOPMENT RESULTS

The vehicle was tested in several scenarios.

8.1 Flat surface results

After assembly, the vehicle was tried on a flat surface, for almost 2 km, results can be seen in Figure 74.

Figure 74: Result telemetry from flat surface

The maximum speed reached was 30 km/h, more speed seemed subjectively dangerous. The board efficiency was found to be 14.5 Wh/km. This would put the vehicles range in around 54 km. The vehicle seemed stable and didn't de-stabilize at any moment.

Turning radius was measured to be near 2m, which isn't great. This was later improved by tweaking the suspension system on the trucks.

8.2 Hilly surface results

The vehicle was tested on a hilly surface next.

With slopes up to 10% the vehicle had enough power to accelerate through them. Regeneration going downhill on 10% slopes was also enough to bring the vehicle to a standstill. Results can be seen in Figure 75.

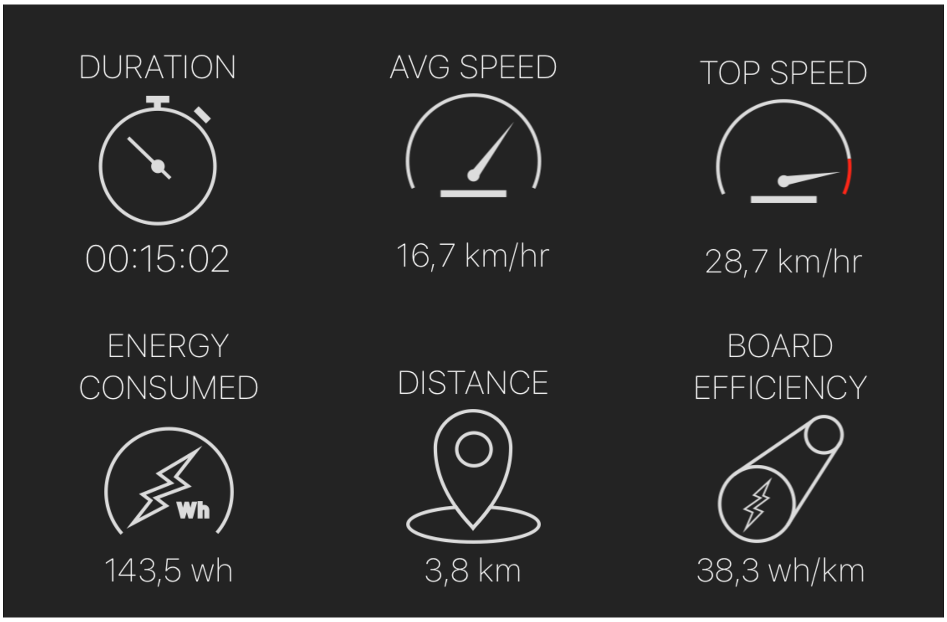

Figure 75: Result telemetry from hilly surface

However, the efficiency was affected greatly, and it was more than double what the flat tests results showed, while maximum speed remained the same. This is thought to be a direct cause of hard acceleration and regeneration cycles on significant slopes, where the ESC isn’t as efficient when changing current constantly.

Max battery current when going 20 km/h uphill on a 10% slope street was around 20 A. This would be around 3.33 A per cell, which is well below its peak current capacities, helping reduce de load on the battery and extending its life.

Rougher roads were also tested without major concerns. Only relevant moment to mention is going through a deep pothole of ≈5 cm. Were the lowest point of the battery enclosure touched the ground. However, this is what the enclosure is for.

For riding on rougher terrains high height deltas, 8-inch wheels would be recommended, as these would elevate the platform around 2 cm and prevent the lowest points to touch the ground when going through potholes or running into rocks.

8.3 Racetrack results

The vehicle was also ridden on Madrid's most famous racetrack, Circuito del Jarama, seen in Figure 76. This was a great opportunity to test the vehicle's limit capabilities in a controlled environment.

Figure 76: Aerial shot of the racetrack "Circuito del Jarama", Madrid, Spain

The racetrack is a 3 850 m long track situated at the north of Madrid. It is 12 m wide and has a total of 13 turns. A total of 3 laps were made around the track at high speed, with a total distance of 11.5 km.

The results of riding on this track can be seen in Figure 77.

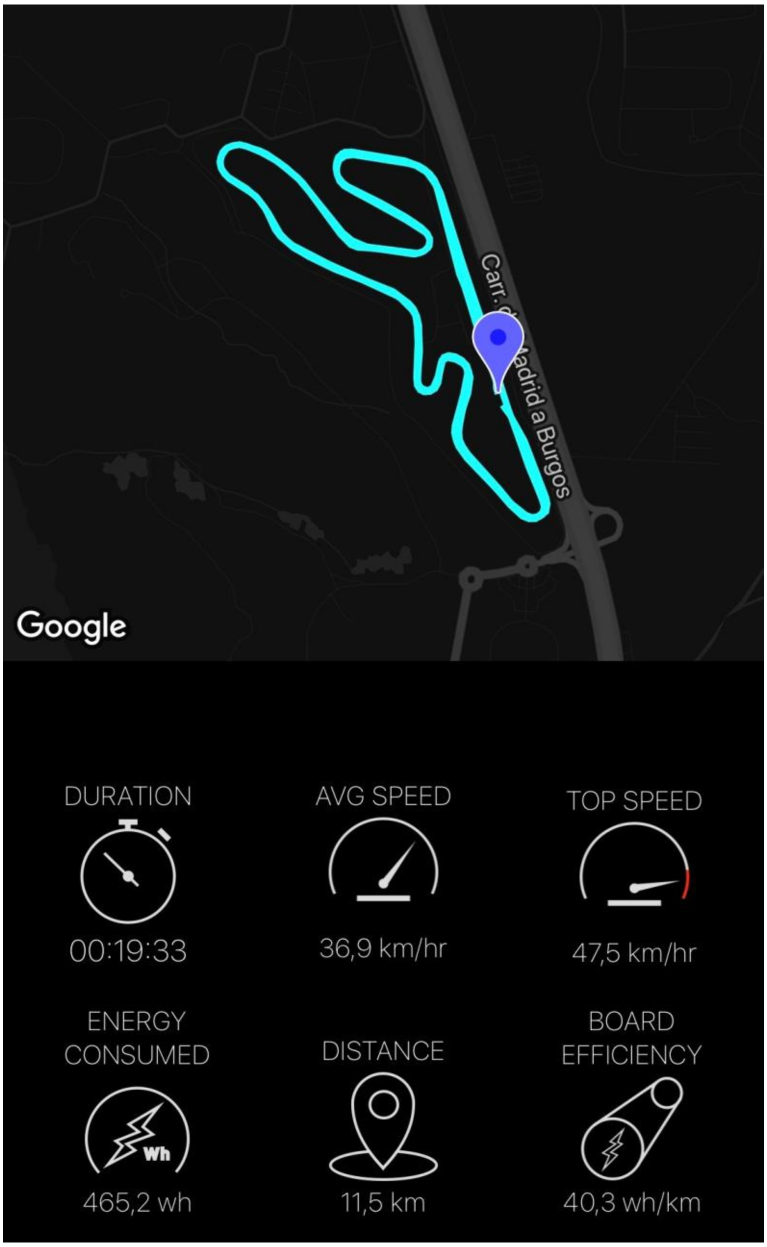

Figure 77: Telemetry results from the vehicle's test at the "Circuito del Jarama"

In this case, the board could be ridden faster, reaching almost 50 km/h. This wasn't the board's limit but rather felt uncomfortable to ride faster considering the little previous riding experience.

This time, because high speed and acceleration cycles, the efficiency of the board dropped and consumed 40.3 Wh/km. This is three times more than riding at slower speeds on normal streets. This efficiency would give the board around 24 km of range, which is still impressive compared to other manufacturers boards with less power.

The current didn’t reach more than 30 A, and the motor temperatures didn’t reach more than 50 degrees, although the ambient temperature was around 10 degrees, which helped cool the systems.

This goes to show that the board is over-designed for urban speeds, as the motor’s load isn’t close to their maximum capabilities.

Although 50 km/h were reached, the board hasn’t been fully tested to its potential and it will require more riding experience to feel subjectively comfortable in doing so.

9. CONCLUSIONS

Overall, micromobility vehicles can help with the transition of urban transport to a more sustainable system.

With cities becoming more densely populated with time, traffic congestion is one of the biggest problems in modern transportation systems, affecting not only private vehicles but also public transport. Micromobility platforms are light, efficient vehicles that can help greatly with traffic congestion as they occupy a fraction of the road and parking space that cars and other bigger vehicles use.

Furthermore, the positive environmental impact micromobility vehicles have has been proven time and time again. Even with the dependable variable of how the electricity at a particular location is generated, causing indirect emissions when charging electric vehicles, the benefits of using micromobility can already help in great measure to health risks derived from ICE emissions in modern cities.

Not only this, but they can also reduce traffic noise in great measure, reducing even more the health and cognitive risks that can ultimately cause anxiety.

Micromobility vehicles are also beneficial for the end user, providing the user with accessibility not only to a private means of transportation, but also to places that could before being unreachable or unavailable for certain people.

Depending on the vehicle, micromobility can also benefit the end user by multitasking during daily commutes and providing the user with a physical activity routine.

It’s because of this last reason, that the development of a more suburban fitting micromobility vehicle was made, in the form of an electric mountainboard. These kinds of vehicles can provide access to places and increase travel time savings for people that live on the outskirts of cities or, also, those that live in the center and have to commute to places on the outskirts.

Results of the development proves that a faster, more efficient and more range achievable transportation method can be constructed, albeit more costly, it can provide with professional and personal opportunities to the users that live outside the city center, have to travel through rougher terrains and have public transport stops further away.

This could also mean a improvement in life quality, not only because of the better travel time, but also because people can find a more affordable means of housing out of the more expensive urban centers.

In conclusion, micromobility offers a wide range of benefits that makes it a great transportation alternative as a standalone and also as a combination mode with other transport modes.

Bibliography

[1] G. Lyons, "Transport and society," *Transp. Rev.*, vol. 24, no. 4, pp. 485–509, Jul. 2004, doi: 10.1080/0144164042000206079.

[2] M. A. Aasness and J. Odeck, "The increase of electric vehicle usage in Norway—incentives and adverse effects," *Eur. Transp. Res. Rev.*, vol. 7, no. 4, 2015, doi: 10.1007/s12544-015-0182-4.

[3] M. F. Chang and R. Herman, "Attempt To Characterize Traffic in Metropolitan Areas.," *Transp. Sci.*, vol. 12, no. 1, pp. 58–79, 1978, doi: 10.1287/trsc.12.1.58.

[4] R. Salas, M. J. Perez-Villadoniga, J. Prieto-Rodriguez, and A. Russo, "Restricting traffic into the city centre: Has Madrid Central been effective to reduce NO2 levels?" [Online]. Available: https://ssrn.com/abstract=3495440.

[5] J. M. Baldasano, "COVID-19 lockdown effects on air quality by NO2 in the cities of Barcelona and Madrid (Spain)," *Sci. Total Environ.*, vol. 741, no. 2, p. 140353, 2020, doi: 10.1016/j.scitotenv.2020.140353.

[6] G. Oeschger, P. Carroll, and B. Caulfield, "Micromobility and public transport integration: The current state of knowledge," *Transp. Res. Part D Transp. Environ.*, vol. 89, no. November, 2020, doi: 10.1016/j.trd.2020.102628.

[7] Cambridge Dictionary, "'Transport' definition," 2021. https://dictionary.cambridge.org/dictionary/english/transport (accessed Oct. 15, 2021).

[8] M. Rosemberg, "Largest cities throughout history," *ThoughtCo*, Aug. 27, 2020. https://www.thoughtco.com/largest-cities-throughout-history-4068071 (accessed Oct. 15, 2021).

[9] G. Duranton and D. Puga, "The growth of cities," 2013.

[10] T. Goldman and R. Gorham, "Sustainable urban transport: Four innovative directions," *Technol. Soc.*, vol. 28, no. 1–2, pp. 261–273, 2006, doi: 10.1016/j.techsoc.2005.10.007.

[11] T. Eccarius and C. C. Lu, "Adoption intentions for micro-mobility – Insights from electric scooter sharing in Taiwan," *Transp. Res. Part D Transp. Environ.*, vol. 84, p. 102327, 2020, doi: 10.1016/j.trd.2020.102327.

[12] Various, "Boosted (Company)," 2021. https://en.wikipedia.org/wiki/Boosted_(company) (accessed Oct. 16, 2021).

[13] S. Pfeiffer, "Participation in the sharing economy : What determines the adoption and use of technology-enabled shared mobility ? University of Mannheim Chair of SME Research and Entrepreneurship."

[14] Cromwell Schubarth, "Scooter startups break unicorn speed records to $1 billion valuations," *Silicon Valley Business Journal*, Jun. 15, 2018.

[15] R. L. Abduljabbar, S. Liyanage, and H. Dia, "The role of micro-mobility in shaping sustainable cities: A systematic literature review," *Transp. Res. Part D Transp. Environ.*, vol. 92, no. February, p. 102734, 2021, doi: 10.1016/j.trd.2021.102734.

[16] J. Lazarus, J. C. Pourquier, F. Feng, H. Hammel, and S. Shaheen, "Micromobility evolution and expansion: Understanding how docked and dockless bikesharing models complement and compete – A case study of San Francisco," *J. Transp. Geogr.*, vol. 84, no. November 2019, p. 102620, 2020, doi: 10.1016/j.jtrangeo.2019.102620.

[17] S. D. Parkes, G. Marsden, S. A. Shaheen, and A. P. Cohen, "Understanding the diffusion of public bikesharing systems: Evidence from Europe and North America," *J. Transp. Geogr.*, vol. 31, pp. 94–103, 2013, doi:

10.1016/j.jtrangeo.2013.06.003.

[18] "Lime (transportation company)," *Wikipedia*, 2021. https://en.wikipedia.org/wiki/Lime_(transportation_company)#:~:text=7 External links-,History,Rosen in March 2017.

[19] G. McKenzie, "Spatiotemporal comparative analysis of scooter-share and bike-share usage patterns in Washington, D.C.," *J. Transp. Geogr.*, vol. 78, no. March, pp. 19–28, 2019, doi: 10.1016/j.jtrangeo.2019.05.007.

[20] N. Merino, "Los patinetes de Lime ya están disponibles en la app de Uber en Madrid," 2021. https://www.autofacil.es/movilidad/apps/patinetes-lime-disponibles-app-uber/189472.html (accessed Oct. 23, 2021).

[21] "Xiaomi Mi Electric Scooter 1S," *Idealo*, 2021. https://www.idealo.es/precios/200792852/xiaomi-mi-electric-scooter-1s-25-km-h.html.

[22] Dan, "How Long Do Electric Scooters Last?," *eScooter Rider*. https://escooterrider.com/how-long-do-electric-scooters-last/#:~:text=Rideshare electric scooters have an,likely much longer than that. (accessed Oct. 23, 2021).

[23] L. Poultney, "Electric scooter maintenance: the essential guide to keeping your e-scooter running," *T3*. https://www.t3.com/features/how-to-maintain-an-electric-scooter (accessed Oct. 23, 2021).

[24] Daniel Foley, "XIAOMI 1S ELECTRIC SCOOTER REVIEW," *Scooter Guide*, 2021. https://scooter.guide/xiaomi-1s-electric-scooter-review/ (accessed Oct. 23, 2021).

[25] "Consulta el precio de la luz (€/kWh): tarifas y comparativa," *Tarifasgasluz*, 2021. https://tarifasgasluz.com/comparador/precio-kwh (accessed Oct. 23, 2021).

[26] "Evolución del precio Gasolina 95," *Clickgasoil*. https://www.clickgasoil.com/c/evolucion-del-precio-gasolina-95 (accessed Oct. 23, 2021).

[27] C. S. Smith and J. P. Schwieterman, "E-Scooter Scenarios: Evaluating the Potential Mobility Benefits of Shared Dockless Scooters in Chicago," 2018, Accessed: Oct. 17, 2021. [Online]. Available: https://las.depaul.edu/centers-and-institutes/chaddick-institute-for-metropolitan-development/research-and-publications/Documents/E-ScooterScenariosMicroMobilityStudy_FINAL_20181212.pdf.

[28] O. Zirn, K. Sagert, and M. Rüther, "Foldable Electrified Ultralight Vehicles on Public Walkways for Sustainable Traffic Chains," *Int. J. Civ. Infrastruct.*, 2018, doi: 10.11159/ijci.2018.001.

[29] "BiciMAD," 2021. https://www.bicimad.com/ (accessed Oct. 17, 2021).

[30] "citibike," 2021. https://www.citibikenyc.com/ (accessed Oct. 17, 2021).

[31] M. L. Smidt, "Reduction of NO 2 by Hydrocarbons over H-form Zeolites," *Zeolites*, 2003.

[32] Z. Naukowe, P. Śląskiej, and S. Transport, "Scientific Journal of Silesian University of Technology . Series Transport – PROBLEMS AND ISSUES," vol. 108, no. 27, pp. 133–140, 2020.

[33] "eCO2 mic - CO2 emissions per kWh of electricity generated in France," 2021. https://www.rte-france.com/en/eco2mix/co2-emissions# (accessed Oct. 17, 2021).

[34] "Are E-Scooters Good or Bad for the Environment?," Mar. 20, 2020. https://www.itf-oecd.org/are-e-scooters-good-or-bad-environment (accessed Oct. 17, 2021).

[35] EEA, "EN15 Accidental oil spills from marine shipping," *Eur. Environ. Agency*, p. 6 pp., 2006.

[36] E. S. Han and A. goleman, daniel; boyatzis, Richard; Mckee, “Oil Supply chain,” *J. Chem. Inf. Model.*, vol. 53, no. 9, pp. 1689–1699, 2019.
[37] A. Cretì and F. Fontini, “Electricity Systems and the Electricity Supply Chain,” *Econ. Electr.*, pp. 35–49, 2019, doi: 10.1017/9781316884614.004.
[38] G. Erbach, “Understanding electricity markets in the EU,” *Eur. Parlimentary Res. Serv.*, no. November, pp. 1–10, 2016, [Online]. Available: http://www.europarl.europa.eu/RegData/etudes/BRIE/2016/593519/EPRS_BRI(2016)593519_EN.pdf.
[39] Donald W. Aitken, “Transitioning to a Renewable Energy Future Introduction-10 A Global Energy Transition, Steering the Correct Course.” [Online]. Available: http://whitepaper.ises.org.
[40] J. A. Turner, “A Realizable Renewable Energy Future.” [Online]. Available: www.hypercar.com.
[41] A. Franco and A. Russo, “Combined cycle plant efficiency increase based on the optimization of the heat recovery steam generator operating parameters,” 2002. [Online]. Available: www.elsevier.com/locate/ijts.
[42] M. Masoud, M. Elhenawy, M. H. Almannaa, S. Q. Liu, S. Glaser, and A. Rakotonirainy, “Heuristic Approaches to Solve E-Scooter Assignment Problem,” *IEEE Access*, vol. 7, pp. 175093–175105, 2019, doi: 10.1109/ACCESS.2019.2957303.
[43] R. Zarif, D. Pankratz, and B. Kelman, “Small is beautiful Making micromobility work for citizens, cities, and service providers Part of a Deloitte series on the Future of Mobility 2.”
[44] U. Pacific, “From the Auto Factory to Your Local Dealership,” *Track record*, 2020. https://www.up.com/customers/track-record/tr050520-auto-factory-to-dealership.htm (accessed Oct. 23, 2021).
[45] L. Gaines, “The future of automotive lithium-ion battery recycling: Charting a sustainable course,” *Sustain. Mater. Technol.*, vol. 1, pp. 2–7, Dec. 2014, doi: 10.1016/j.susmat.2014.10.001.
[46] U. Mildenberger and A. Khare, “Planning for an environment-friendly car,” *Technovation*, vol. 20, no. 4, pp. 205–214, 2000, doi: 10.1016/S0166-4972(99)00111-X.
[47] V. Technology, “Voi Technology.,” no. September, 2019.
[48] E. Comission, “Air Quality and Noise Legislation.” https://ec.europa.eu/environment/legal/law/5/e_learning/module_1_5.htm (accessed Oct. 23, 2021).
[49] L. NÚÑEZ-VILLAVEIRÁN and L. F. DURÁN, “Los patinetes ya invaden las calles de Madrid: 22 accidentes, 18 heridos, dos de ellos graves,” *El Mundo*, Madrid, Nov. 02, 2018.
[50] José Domingo Méndez, “Peligro: patinete por la acera a toda velocidad,” *El Dia*, Santa Cruz de Tenerife, Jul. 30, 2021.
[51] L. Á. SANZ, “El Ayuntamiento de Madrid multiplica por cuatro las multas por aparcar mal en las aceras patinetes, bicis y motos compartidas en 2021,” *El Mundo*, Madrid, Apr. 19, 2021.
[52] T. Jones, L. Harms, and E. Heinen, “Motives, perceptions and experiences of electric bicycle owners and implications for health, wellbeing and mobility,” *J. Transp. Geogr.*, vol. 53, pp. 41–49, 2016, doi: 10.1016/j.jtrangeo.2016.04.006.
[53] J. Woodcock, M. Tainio, J. Cheshire, O. O’Brien, and A. Goodman, “Health effects of the London bicycle sharing system: Health impact modelling study,” *BMJ*, vol. 348, no. February, 2014, doi: 10.1136/bmj.g425.

[54] B. Gojanovic, J. Welker, K. Iglesias, C. Daucourt, and G. Gremion, “Electric bicycles as a new active transportation modality to promote health,” *Med. Sci. Sports Exerc.*, vol. 43, no. 11, pp. 2204–2210, 2011, doi: 10.1249/MSS.0b013e31821cbdc8.

[55] A. Badeau, C. Carman, M. Newman, J. Steenblik, M. Carlson, and T. Madsen, “Emergency department visits for electric scooter-related injuries after introduction of an urban rental program,” *Am. J. Emerg. Med.*, vol. 37, no. 8, pp. 1531–1533, 2019, doi: 10.1016/j.ajem.2019.05.003.

[56] E. M. Thomas Holm Møller, John Simlett, “Micromobility: Moving cities into a sustainable future,” *Ernst & Young*, pp. 1–34, 2020.

[57] A. Rau, “E-Scooters in Germany,” *The Germany Eye*, 2019. https://thegermanyeye.com/e-scooters-in-germany-3707.

[58] “Electric Scooter Database + Performance Testing,” *ELECTRIC SCOOTER GUIDE*, 2021. https://electric-scooter.guide/comparisons/compare-electric-scooters/.

[59] EMESA, “Normativa para patinetes eléctricos en Madrid: actualización 2021,” 2021. https://www.emesa-m30.es/normativa-para-patinetes-electricos-en-madrid/.

[60] M. Figueras, “Nuevos patinetes eléctricos con ‘alcoholímetro’ que no se desbloquean si has bebido,” *La Vanguardia*, 2021.

[61] B. Gardner and C. Abraham, “What drives car use? A grounded theory analysis of commuters’ reasons for driving,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 10, no. 3, pp. 187–200, 2007, doi: 10.1016/j.trf.2006.09.004.

[62] T. W. Simpson, “HENRY FORD AND THE MODEL T: LESSONS FOR PRODUCT PLATFORMING AND MASS CUSTOMIZATION,” pp. 1–8, 2016.

[63] A. L. Handman, “INTERMODALISM A SOLUTION FOR HIGHWAY CONGESTION AT THE MILLENNIUM?”

[64] K. Storchmann, “On the depreciation of automobiles: An international comparison,” *Transportation (Amst).*, vol. 31, no. 4, pp. 371–408, 2004, doi: 10.1023/B:PORT.0000037087.10954.72.

[65] R. Nijskens, M. Lohuis, P. Hilbers, and H. Willem, *Hot Property: The Housing Market in Major Cities*, vol. 206, no. 3. 2018.

[66] L. D. Frank and G. Pivo, “Impacts of mixed use and density on utilization of three modes of travel: single-occupant vehicle, transit, and walking,” *Transp. Res. Rec.*, pp. 44–44, 1994.

[67] J. Gobind, “Transport anxiety and work performance,” *SA J. Hum. Resour. Manag.*, vol. 16, pp. 1–7, 2018, doi: 10.4102/sajhrm.v16i0.943.

[68] B. Propfe, M. Redelbach, D. J. Santini, and H. Friedrich, “Cost analysis of plug-in hybrid electric vehicles including maintenance & repair costs and resale values,” *World Electr. Veh. J.*, vol. 5, no. 4, pp. 886–895, 2012, doi: 10.3390/wevj5040886.

[69] O. Bitsche and G. Gutmann, “Systems for hybrid cars,” *J. Power Sources*, vol. 127, no. 1–2, pp. 8–15, 2004, doi: 10.1016/j.jpowsour.2003.09.003.

[70] Z. S. Gelmanova *et al.*, “Electric cars. Advantages and disadvantages,” *J. Phys. Conf. Ser.*, vol. 1015, no. 5, 2018, doi: 10.1088/1742-6596/1015/5/052029.

[71] CITROEN, “NEW CITROËN AMI 100% ËLECTRIC,” 2021. https://www.citroen.co.uk/models/future-models/ami.html.

[72] P. Kopp, “The unpredicted rise of motorcycles: A cost benefit analysis,” *Transp. Policy*, vol. 18, no. 4, pp. 613–622, 2011, doi: 10.1016/j.tranpol.2011.03.002.

[73] “El carril bus-VAO: ¿qué vehículos pueden circular por él?,” *RACE*, 2020. https://www.race.es/carril-bus-vao-vehiculos-circulacion (accessed Oct. 24, 2021).

[74] M. R. Domingo, "Madrid prueba el carril 'avanza moto' para esquivar coches en semáforos," *ABC*, Madrid, Apr. 15, 2021.

[75] R. ALONSO, "Coche o moto, ¿qué es más barato en ciudad? Ésta es mi experiencia," *SOYMOTOR.COM*, 2019. https://soymotor.com/coches/articulos/coche-o-moto-que-es-mas-barato-en-ciudad-964321 (accessed Oct. 24, 2021).

[76] A. Ali, J. Mehraj, S. Mhmood, Z. Mirza, and M. Tahir, "Frequency of Risk Factors Associated with Road Traffic Accidents of Motorbike in a Big City of a Developing Country," *Angew. Chemie Int. Ed. 6(11), 951–952.*, pp. 5–24, 1967.

[77] S. CARPENTER, "Motorcycles and emissions: The surprising facts," *Los Angeles Times*, California, Sep. 16, 2014.

[78] M. Paviotti and K. Vogiatzis, "On the outdoor annoyance from scooter and motorbike noise in the urban environment," *Sci. Total Environ.*, vol. 430, pp. 223–230, 2012, doi: 10.1016/j.scitotenv.2012.05.010.

[79] A. Millard-Ball, M. Gail, and J. Ter Schure, *Car-Sharing: Where and How it Succeeds*. 2005.

[80] J. L. de Benito, "Estos son los servicios de carsharing de los que dispone Madrid (ACTUALIZADO 2021)," *mobilidadelectrica.com*, 2021. https://movilidadelectrica.com/comparativa-carsharing-madrid/ (accessed Oct. 30, 2021).

[81] "Una flota de 110 taxis eléctricos para la ciudad de Madrid," *eSMARTCITY.es*, 2016. https://www.esmartcity.es/2016/11/24/una-flota-110-taxis-electricos-para-ciudad-madrid (accessed Oct. 30, 2021).

[82] T. G. Crainic and K. H. Kim, "Intermodal Transportation," *Handbooks Oper. Res. Manag. Sci.*, vol. 14, no. C, pp. 467–537, 2007, doi: 10.1016/S0927-0507(06)14008-6.

[83] "Introducing, the VanMoof V," *VANMOOF*, 2021. https://www.vanmoof.com/en-ES/vanmoof-v (accessed Oct. 30, 2021).

[84] "Over 450 Electric Bikes Compared! What does an ebike cost?," *eBikesHQ.com*. https://ebikeshq.com/cost-of-an-ebike/ (accessed Oct. 30, 2021).

[85] Micah Toll, "The truth: How far can an electric bicycle really go on a single charge?," *electrek*, 2020. https://electrek.co/2020/06/12/how-far-can-an-electric-bicycle-really-go-on-a-charge/ (accessed Oct. 30, 2021).

[86] M. V Hornea and D. Dobre, "The conceptual design of an ultralight electric scooter," *J. Ind. Des. Eng. …*, pp. 5–12, 2018, [Online]. Available: http://www.sorging.ro/jideg/index.php/jideg/article/view/94.

[87] E. R. DE LUIS, "El mejor patinete eléctrico: guía de compra y comparativa," *xataka*, 2020. https://www.xataka.com/analisis/mejor-patinente-electrico-guia-compra-comparativa (accessed Oct. 31, 2021).

[88] "Longboard vs Skateboard. Everything You Need To Know," *hamboards*, 2021. https://hamboards.com/blogs/news/longboard-vs-skateboard-everything-you-need-to-know (accessed Oct. 30, 2021).

[89] Daniel, "Electric Skateboard Comparison Table," *e-skate boarder*, 2021. https://e-skateboarder.com/comparison-table-and-tool/ (accessed Oct. 31, 2021).

[90] Spike, "Mountain Boarding for Beginners: The Ultimate Guide," *REVIEW LONGBOARDS*, 2016. http://reviewlongboards.com/mountain-boarding-for-beginners/ (accessed Oct. 31, 2021).

[91] A. Mahmoudzadeh Andwari, A. Pesiridis, S. Rajoo, R. Martinez-Botas, and V. Esfahanian, "A review of Battery Electric Vehicle technology and readiness levels," *Renew. Sustain. Energy Rev.*, vol. 78, no. February, pp. 414–430, 2017,

doi: 10.1016/j.rser.2017.03.138.
[92] H. Berg, *Battery technologies for electric vehicles*. 2017.
[93] H. Berg, *The electrochemical cell*. 2015.
[94] C. Honsberg and S. Bowden, "Battery Voltage," *pveducation*. https://www.pveducation.org/pvcdrom/battery-characteristics/battery-voltage (accessed Oct. 31, 2021).
[95] C. Honsberg and S. Bowden, "Battery Capacity," *pveducation*. https://www.pveducation.org/pvcdrom/battery-characteristics/battery-capacity (accessed Oct. 31, 2021).
[96] C. Honsberg and S. Bowden, "Battery Charging and Discharging Parameters," *pveducation*. https://www.pveducation.org/pvcdrom/battery-characteristics/battery-charging-and-discharging-parameters (accessed Oct. 31, 2021).
[97] "Battery states: State of charge (SoC), State of Health (SoH)," *BioLogic*, 2021. https://www.biologic.net/topics/battery-states-state-of-charge-soc-state-of-health-soh/ (accessed Oct. 31, 2021).
[98] K.-C. Moeller, "Lithium-ion batteries: Basics and applications," *Lithium-Ion Batter. Basics Appl.*, pp. 1–413, 2018, doi: 10.1007/978-3-662-53071-9.
[99] "Lithium-ion Battery vs Lithium-polymer Battery," *robu.in*, 2020. https://robu.in/lithium-ion-battery-vs-li-po-battery/ (accessed Oct. 31, 2021).
[100] "EV Powertrain Components - Basics," *EV Reporter*. https://evreporter.com/ev-powertrain-components/.
[101] J. G. Hayes and G. A. Goodarzi, *Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric and Fuel Cell Vehicles*. John Wiley & Sons Ltd., 2017.
[102] "What are Brushless DC Motors," *Renesas*. https://www.renesas.com/us/en/support/engineer-school/brushless-dc-motor-01-overview.
[103] A. Solovev and A. Petrova, "BLDC Motor Controller: How It Works, Design Principles & Circuit Examples," *INTEGRA SOURCES*, 2021. https://www.integrasources.com/blog/bldc-motor-controller-design-principles/ (accessed Oct. 31, 2021).
[104] "What's the Difference Between Powertrain and Drivetrain?," *Maxwell Ford*. https://www.maxwellford.com/powertrain-and-drivetrain.html (accessed Oct. 31, 2021).
[105] "Developing the Gear Ratio Formula." https://www.sae.org/binaries/content/assets/cm/content/learn/education/motortoycar-samplelessonplan.pdf (accessed Oct. 31, 2021).
[106] G. Turner, "Simple Gear Ratio Explained," *SCIENCING*, 2017. https://sciencing.com/calculate-speed-ratio-7598425.html (accessed Oct. 31, 2021).
[107] "Types of Chain Drive: Mechanism, Uses, Design, Applications, Advantages & Disadvantages," *Engineering Learn*, 2021. https://engineeringlearn.com/types-of-chain-drive-mechanism-uses-design-applications-advantages-disadvantages/ (accessed Nov. 01, 2021).
[108] Raymond Kulwiec, "Materials Handling Handbook , 2nd Edition .," p. 1454, 1985.
[109] "Types of Belt Drive: Material, Applications, Advantages & Disadvantages," *Engineering Learn*, 2021. https://engineeringlearn.com/types-of-belt-drive-material-applications-advantages-disadvantages/.
[110] "Gear Drive (Speed Reducers)," *Industrial Quick Search directory*.

https://www.iqsdirectory.com/articles/gearbox/gear-drive.html (accessed Nov. 01, 2021).

[111] M. Hilton, "What's the Difference Between Geared and Direct-Drive Actuators?," *MachineDesign*, 2018. https://www.machinedesign.com/mechanical-motion-systems/article/21836346/whats-the-difference-between-geared-and-directdrive-actuators (accessed Oct. 31, 2021).

[112] "TRAMPA," *trampaboards.com*, 2021. https://trampaboards.com/.

[113] "Alien Power System," 2021. https://alienpowersystem.com/.

[114] "VESC PROJECT," 2021. https://vesc-project.com/.

[115] "Timing Pulley Distance Between Centres Calculator," *Technobots*, 2021. https://www.technobotsonline.com/timing-pulley-distance-between-centres-calculator.html.

[116] "5083 aluminium alloy," *Wikipedia*, 2021. https://en.wikipedia.org/wiki/5083_aluminium_alloy#:~:text=5083 aluminium alloy is an,retains exceptional strength after welding.

[117] ANSYS, "Static Mixer : Basic and Inflation Introduction to ANSYS Meshing," no. March, pp. 1–19, 2010.

[118] "WHAT IS PETG? (EVERYTHING YOU NEED TO KNOW)," *twi-global*. https://www.twi-global.com/technical-knowledge/faqs/what-is-petg#:~:text=Polyethylene terephthalate glycol%2C known as,durability%2C and formability for manufacturing.