POLITECNICO DI TORINO

DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING

Master's Degree in Automotive Engineering

Master's Degree Thesis

CONCEPT DESIGN PROCESS OF A NOVEL MODULAR VEHICLE

Supervisor:
Prof. Andrea Tonoli

Candidate:
Mapimí Tosolini

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ABSTRACT

In this project, a new type of architecture for modular vehicles has been developed to better respond to the needs and demands of the mobility of tomorrow.
Literature studies have been conducted on the current modular vehicle prototypes, examining the benefits and criticalities offered by modularity.
The proposed solution which includes a vehicle consisting of three modules, one of which in a central position, called cargo module, dedicated to the transport of goods or passengers, and two modules dedicated to traction, placed on the front and rear of said central module, defined drive modules.
This construction offers numerous advantages, including complete autonomy of the drive modules, a broad choice of dimensions and customizations of the cargo module, ease of access and loading and carefree user experience, without vehicle management constraints.
The large van segment has been identified as the best one to exploit the full potential of modular construction. Taking as reference the characteristic dimensions of this class, the position of the various components was defined. The project therefore focused on the structure of the vehicle frame and on the coupling system between the different modules.
To verify the functioning of the various proposed solutions, a series of prototypes were built, one for the mechanism of the coupling system and another as a scale model of the entire modular vehicle.
It is essential to keep in mind that this project has been carried out on a conceptual level within the framework of a degree project.
This master thesis aims to provide a solid benchmark for further development and research within the subject.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 TRENDS OF MOBILITY

The extended global automotive industry is undergoing an unprecedented transformation to a new mobility ecosystem, as technological innovations in the form of electrification, connectivity, and autonomy advance, the way people and products move around is set to change dramatically.

Given the continuous population growth, urbanization and increasing environmental concerns, new forms of mobility are critical to support tomorrow's population hubs and economic activity [1].
Today's mobility systems suffer from congestion, inefficiency, accidents, and high prices. But the future promises convenient, safe, and economic mobility, with less impact to health and the environment.
To stay on top of the mobility industry trends, manufacturers explore ways to create smart automated vehicles.

The transformation of the mobility sector can be divided into four major disruptive trends: Connected and autonomous vehicles, shared mobility, and electrification of vehicles.
Taken independently, each would significantly disrupt the ecosystem; but in combination, they should drive unprecedented change.
For this reason, the acronym C.A.S.E. was assigned starting from the initials of each of these trends.

Connected

The technology for connectivity, thanks to the continuous developments in the IT sectors, is ready for a breakthrough.
Dramatic improvements will soon shift the connectivity experience from reactive to predictive. Occupants will be offered personalized infotainment through voice and hand gestures and have a dialogue with the vehicle to receive proactive recommendations on services and functions. The connectivity systems will become a "virtual chauffeur," in which cognitive artificial intelligence (AI) can anticipate and fulfil riders' needs.

Over time, the road infrastructure will equally be involved in this change and smart infrastructure is widely acknowledged as one of the core components of smart cities. It extends not only to smart roads, automated parking, and IoT, but also to all the various signals and signs along the roadside that provide information to drivers and AVs.
The Vehicles will exchange data with a central hub, Vehicle-control centres (VCCs), as well as each other, through cellular, Wi-Fi, and satellite communications allowing cars to travel much closer together and shortening travel times significantly.

Routes will be optimized almost instantly and will be able to react to any eventuality presented, like adverse weather conditions or any city emergency.

Traffic rationalization and control will accurately determine the preventive maintenance of both the infrastructures, like bridges and highways and for the vehicles themselves, analysing the wear and tear data and timely planning the maintenance cycles.

The fact is: in the future, digitalization with such applications will penetrate ever deeper into the core areas of vehicles. However, large amounts of data are produced that must be processed in a stable and secure manner. The connected car also needs continuous network availability with short latency times, which are mandatory for road traffic. Many of the future connected car use cases therefore require the new 5G mobile communications standard. Connected cars must also be protected against hacker access. This requires new security solutions and particularly secure IT and cloud environments [2].

Autonomous

Autonomous driving technology has always been one of the most promising areas within the mobility industry in the last years and it continues to grow. This mobility trend aims to minimize human negligence and errors to create safer roads.
Autonomy, expressed along a framework from the Society of Automotive Engineers ranges from level 0 (full driver control at all times) to level 5 (the full-time performance of an automated driving system of all aspects of driving under all roadway conditions) [3], is presently being pursued by numerous companies at different levels.

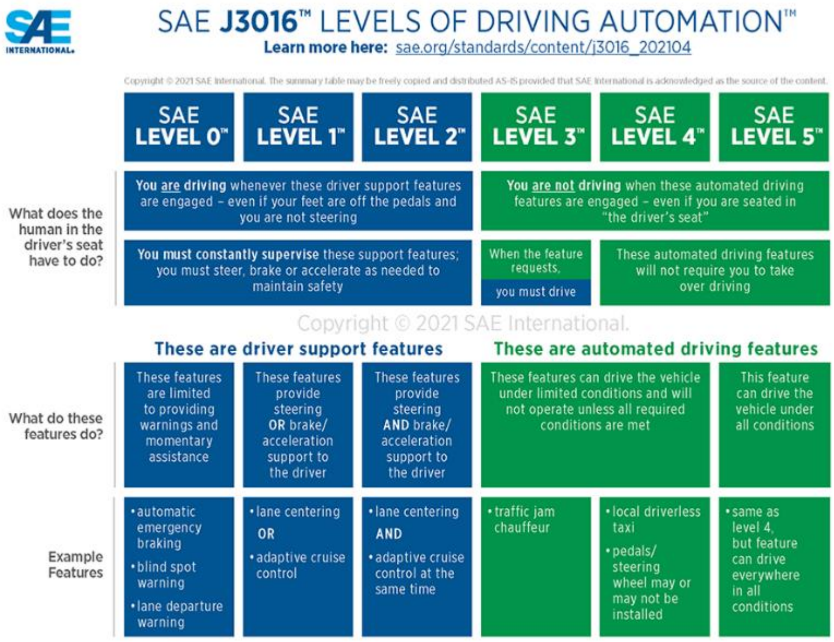

Figure 1 Levels of driving automation [3]

Fleets of AVs expand the scope of first and last mile commute and make public transportation safer and more efficient. Artificial intelligence, combined with smart sensors, accelerate advancements in the mobility industry.

Shared & Services

Integrating various modes of transportation into a single mobility service presents a user-centric approach to mobility. To achieve this, start-ups are building a range of mobility-as-a-service solutions MaaS. Customers use a sole payment channel instead of multiple ticketing and payment operations, allowing for convenience and efficient planning. MaaS also introduces new business models to operate different transport options, reduce congestion and remove capacity constraints. Among the multiple benefits that MaaS offers, easy route planning and simplified payments represent the keys that make this an emerging mobility trend.

If ride-sharing AVs eventually remove the driver from the equation, they could make riding more affordable. AVs will travel much more than the privately owned vehicles, lowering the total cost of ownership due to lower variable cost, despite higher fixed cost (the original price of the car). In addition, today's automobiles are designed for a vast number of use cases, narrowing it down to a more purpose-built vehicle for ride-sharing will also reduce the purchase price. Finally, advances in design should help overcome some potential riders' understandable resistance to sharing rides with strangers; in-vehicle pods will allow for greater privacy, more engaging entertainment, and productivity capabilities that approach what one would have at the office.

Electric

Significant improvements in battery technologies and the use of renewables, plus evident regulatory will from many governments to impose regional and global carbon limits, means the likely end of ICE's technology predominance.
That spells new opportunities for those in the energy and metals and mining industries, among others.
While government-funded subsidies for EVs are expected to be phased out over time in the United States, Europe, and China, electrification mandates appear here to stay.
European regulators are actively working to reduce CO2 emissions of vehicles and ratchet up penalties for noncompliance. China is targeting seven million electric-car sales by 2025. Although the country's targets have so far been more of a suggestion than a rule, we expect China to put in place enforcement mechanisms over the next decade, with insiders highlighting the potential intention to leapfrog the technical and manufacturing challenges of modern ICE drive trains.
Currently, absent subsidies, a typical entry-level luxury EV saloon costs a significant premium above the price of an ICE vehicle. Unsurprisingly, most consumers are unwilling to pay it. The cost of EVs—largely (but not solely) a function of their batteries' dollars per kilowatt-hour—will need to continue to decline substantially in order to generate the consumer pull essential for widespread EV adoption beyond specific EV-preferring segments and use cases.

Reinforcing effects [4]

The adoption of shared mobility will accelerate electrification, as increased use favours the economy of electric vehicles.

Autonomous driving could merge shared mobility business models into a single competitive proposition with private car ownership and public transport.

Self-driving vehicles, private and shared, are likely to increase mobility consumption, in which case electric vehicles offer a lower total cost of ownership.

The adoption of shared mobility will affect public transport.

Large-scale production of electric vehicles would accelerate the reduction of battery costs, with multiple effects.

Self-driving electric vehicles will have a variety of uses and will impose new requirements for the charging infrastructure.

Increased renewable energy production will make electric vehicles more attractive as a means of reducing carbon intensity in the transport sector.

Self-driving vehicles could accelerate the adoption of IoT applications.

2 MODULAR VEHICLES

Having clarified which are the development areas of the mobility sector, the question arises spontaneously to identify which vehicle will best match these emerging technologies.

Which type of vehicle can make the most of autonomous driving, electric mobility and sharing solutions?

Preamble

A vehicle is part of the user's life, it’s often even an extension of their personality, and like all the products the focal point is the pursuit for the best possible user experience.

There are several points of friction in the ownership of a vehicle, generally they concern the quality of life on board, which can be compromised by suboptimal ergonomics or bad interfaces, and the management of the vehicle itself, which includes, for example, charging and the maintenance.

Electric vehicles already mitigate many of these aspects, offering quieter and more comfortable journeys, more modern and updated on-board interfaces and reduced maintenance.

Autonomous driving allows the driver to free himself and carry out other activities during the journey, definitively distancing himself from the use case of a traditional vehicle.

Ride-sharing was originally introduced to increase the utilization rate of vehicles, which spend most of their life parked, and to share travel costs with other users.

To unlock the full potential of these technologies and further enhance the flexibility of the vehicle user experience, the next step is to physically separate the user's environment from the mechanical component one. In this context, the definition of the modular vehicle is intended as the ability to disjoint the modules directly on the field of use.

From the separation of mission between the vehicle parts, arises the concept of modular vehicle that will offer a solution for the future challenges of mobility.

2.1 Advantages of the modular architecture

The modern cars are so closely integrated that the potential for modularization is not apparent, and the advantages are unappreciated. Here's why modularity makes sense:

1. Mission flexibility
In a traditional vehicle its intended use is assigned at the beginning of its life and can hardly be changed, while for a modular vehicle the operation is reduced to the simple interchange of modules. A possible scenario is that the modular vehicle, during rush hours, can be dedicated to the transport of passengers, while the remaining time can carry goods.

2. Modularity makes the electric vehicle practical
The weak point of electric vehicles remains the charging speed, which is not yet sufficient to compete with traditional ice cars. The modularization of the vehicle allows a quick exchange with a charged driving module, enabling a seamless operation.
An autonomous vehicle can drive itself to a recharge station, and recharge at the most convenient time, if the vehicle is also modular, the user has always access to his passenger compartment module even when the drive modules are not present.
The possibility of exchanging drive modules allows for slow recharges, increasing the battery life and reducing the power line stress.

3. Modularity enhances autonomous mobility
When daily passenger transport wanes or rests, it is difficult for a robo-taxi to provide other services. It is simply not designed for it. As a result, valuable resources sit around idly.
The modularity physically separates the functions of the vehicle, allowing the autonomous part to be shared with other users, increasing the total working hours.

4. Personalization
Given the construction of a modular vehicle, the customizations of the passenger compartments are considerably greater than that of a traditional vehicle, both in terms of overall dimensions and equipment.

5. Sharing
In the modular vehicle there is the possibility to share the passenger compartment with other users like a traditional vehicle, but it's also possible to share the drive module, reducing the total number of vehicles necessary for the transport of everyone.

6. Infostructure integration
In addition to mobility activities, passenger modules can also serve other purposes and for example be used stationary as an integral component of smart cities.

7. Lower maintenance time and costs
Being able to interchange the drive module, the maintenance time is reduced to a minimum. Furthermore, knowing the rate of use of the vehicles, thanks to the automatic information collection, the maintenance can be strategically planned.

8. Optimized running costs
Most users do not travel long daily trips and only rarely travel considerable distances. To meet this need, the modules can be equipped with battery packs of various sizes, offering the optimal range. This allows to reduce weight and consequently consumption to a minimum.

9. Production
The productions of the units can be separated, even different manufacturers could produce the various modules. This flexibility allows to adapt more quickly to market demand.

10. Update
If the mechanical parts of the drive modules need to be updated for any reason, such as a more advanced electronics or sensors, depending on the complexity of these the module can be improved or changed entirely.
This does not affect the passenger compartment module in any case, and therefore extends the operational life of the vehicle.

11. Longer lifespan
Dividing the vehicle into modules allows to utilize of the life of each component more effectively, especially if the utilization rates of each module are different.
Even in the event of light impacts, the change of damaged components is easier.

2.2 Current modular vehicles concepts

Recognized as one of the first modern modular vehicles, the Ridek vehicles consist of two main parts, a bottom one that contain all the mechanical parts called Modek and an upper body called Rideon [5]. This modular division concept was patented by Dr Gordon Dower in 1997.
Here is shown the **Ridek III**, a mock-up prototype presented in Vancouver, in December 2005.

Figure 2 Ridek III modular vehicle

This vehicle has already an electric powertrain and the exchange between modules should be executed in a dedicated station, but these can be transported on a trailer like shown on the figure (2).

A reworking of the same concept was presented by General Motors with the prototype AUTOnomy in 2002 [6].

Figure 3 GM AUTOnomy 2002

This vehicle also offers a universal lower platform defined as skateboard, and a series of car bodies that can be installed on top of it. This vehicle was imagined as a fuel cell with drive by wire driving controls.

An evolution of the skateboard solution was proposed by Mercedes-Benz with the Vision Urbanetic light commercial vehicle concept.

Figure 4 Mercedes-Benz Vision Urbanetic 2018 [7]

This prototype is already designed to adopt autonomous driving and electric mobility.
The goal of the prototype was to eliminate the separation between people moving and goods transport. To do this, it adopts a rear track widening system and to perform the exchange of bodies it needs to travel to dedicated warehouses.
The difficulty in the exchange of the body modules is the main problem that all these three concepts have in common.

The solution proposed by Rinspeed [8] overcomes this limit by installing a lifting system in the structure of the passenger compartment.

Figure 5 Rinspeed Snap 2018

The concept Rinspeed Snap allows an easy sharing of the skateboard platform with other road users. Moreover, this solution allows the lower skateboard module to recharge autonomously without the need of moving the customer's pod that will remain always available.

One of the critical points of this solution is the space occupied by the lower module on the road, because the skateboard in the plan view takes up the same space in both configurations of loaded and unloaded passenger compartment.
In addition, the passenger compartment bodywork must be shaped taking into account the space required for the wheels and all other powertrain components, which means that once parked, not all the volume available in a parking lot is used efficiently.

2.3 New modular vehicle proposal

The critical factors of the present prototypes are the difficulty of exchanging the modules during normal operation on the road and the efficient use of the volume of the passenger module.

To overcome the limitations of current prototypes, that rely on the skateboard concept, a novel type of architecture is needed. Thus, was born the idea of dividing the vehicle with respect to two vertical axes.

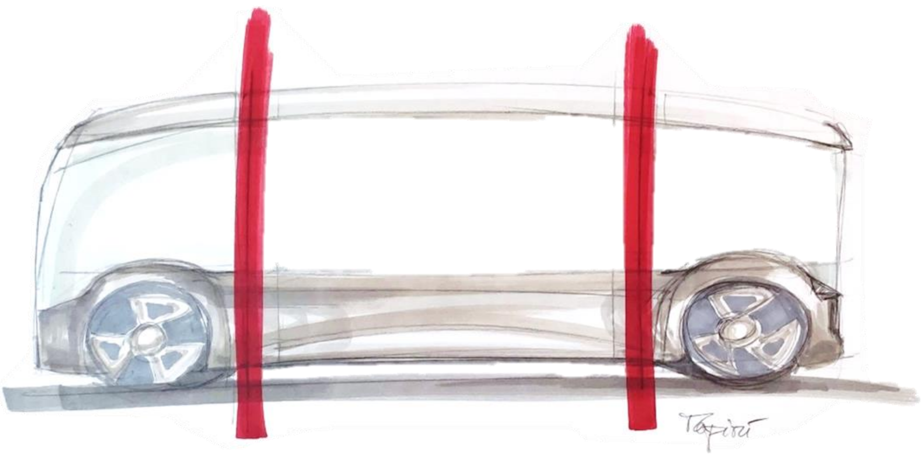

Figure 6 Modular vehicle vertical subdivision

The resulting vehicle is therefore divided into three parts, of which the central module is designed for transport while the modules at the ends contain all the mechanical systems necessary for the propulsion and the autonomous drive.

Description

The vehicle includes the central module dedicated to containing what the user needs to transport, whether they are goods, people, or custom fittings. To make the most out of this module, its volumetric efficiency must be maximized so its shape should be as regular as possible (cuboid). In this project this module will be referred to as the "cargo module".

The vehicle must include at least two wheel axles to allow movement of the cargo module. Each wheel axle is included in a module that also carries all the other drivetrain components of the respective wheel axle, which will be referred to in the following as the "drive module".

To allow the mechanical parts to be separated from the cabin in any place without the use of external equipment, these wheel axles are independent of each other and also from the cargo module.

Therefore, the vehicle consists of a cargo module to which two independent drive modules are associated.

To achieve this result, the vehicle's drive modules must be able to couple with the cargo module without overlapping it in the side and top view.

In summary, the vehicle proposed in this thesis can make the most out of autonomous driving, electric mobility, and a better use of the ground space, it includes a cargo module and two independent drive modules that couple to the cargo module without causing overlap between them.

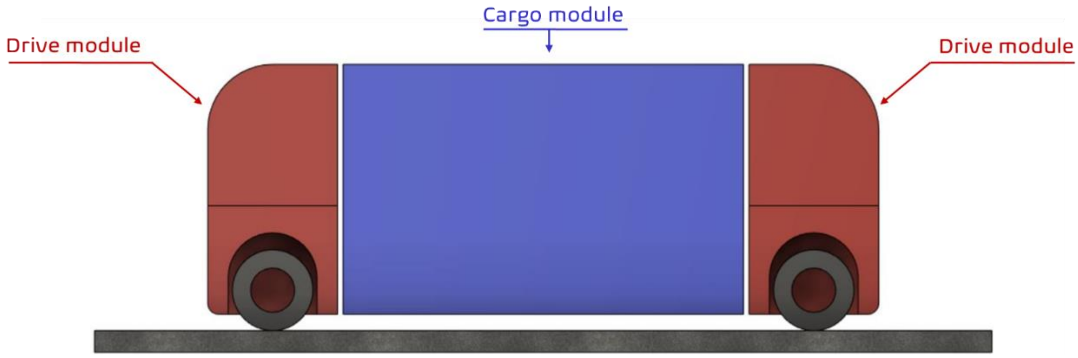

Figure 7 New modular vehicle architecture

In addition to the advantages already presented for modular vehicles, this configuration offers:

Two identical drive modules, which can be standardized, simplifying production and favouring economies of scale.

The dimensions of the cargo module do not depend on those of the drive module, in particular the length with the skateboard architecture would be constrained, while in this solution it is unrestricted.

The loading surface of the cargo module is closer to the ground, making access easier.

The cargo module maximizes the internal space compared to its external volume.

The drive modules can operate independently in self-balancing, occupying less space on the road and participating in the overall reduction of traffic.

Only the one drive unit that should present problems must be replaced, unlike the skateboard that must be replaced in its entirety.

The standard drive modules are equipped with a minimum battery pack for normal vehicle operation, this to reduce the excessive weight, but if a user needs a longer autonomy, larger batteries may be available. By having two modules, the possible combinations are increased.

The cargo module can be equipped with an additional battery which increases the autonomy of the entire vehicle. Moreover, this battery can power all the utilities that the customer needs.

3 MARKET PLACEMENT

After identifying the characteristics of the proposed modular vehicle, it becomes necessary to define its dimensions and which class of vehicles to compare with.
Since the module coupling system requires a space that is not normally occupied, the larger the vehicle, the less significant the volume loss will be.
The choice fell on the category of multipurpose vehicles, in particular commercial vehicles with large dimensions, like large vans.

3.1 Large VAN

Large vans stand at the upper edge of the light commercial vehicle class, LCVs, are motor vehicles with at least four wheels, used for transporting goods or people [9].
In the European Union, the vehicles that a driver can operate are limited by the driving licence class. These classes are closely related to the gross vehicle weight rating and include (among others) B for general motor vehicles, C for large goods vehicles, D for large passenger vehicles (buses).
Class B permits the use of vehicles with GVWRs of not more than 3500 kg and covers both standard passenger cars of all sizes as well as the LCV.
In England, new rules have recently been introduced for the electric Vans, raising the weight threshold up to 4250 kg to compensate for the additional weight of the batteries and in this way maintaining the overall transportable payload.
Van manufacturers offer versions of their vehicles with higher payloads to satisfy the most demanding users. These versions are equipped with reinforced frames and can reach up to 7 tons GVWR.

A fundamental characteristic that distinguishes the vans from other vehicles, is the variation in the body styles that they are offered.
Even just looking at the vans dedicated to freight transport, they can be optioned with different lengths, wheelbases, heights, type, and number of doors.
In addition, variants dedicated to transporting people or with special equipment are also built, which can include ambulances, campers, or tow trucks.

Figure 8 Mercedes-Benz Sprinter line-up

Electric LCV

As the electric drive of vehicles gradually gains momentum across the world, the next phase of growth is expected to be driven mainly by vans and trucks.
To capture this demand, traditional manufacturers are presenting various models to cover the entire range of the Van line-up.
The strategy currently adopted by the OEMs is to use as much as possible the structures of the vehicle that they have already available, adapting the powertrain to an electric one. The battery packs are inserted between the main rails adapting the available frames.

Figure 9 Mercedes-Benz E-Sprinter chassis

This strategy is adopted to save the initial investment costs and reduce the time on the market.

As with the automotive sector, the introduction of electric vehicles has created the opportunity for new players to enter the market.
These start-ups embrace the possibility to develop new van platforms starting from a blank sheet, allowing them a superior integration of the components of the electric powertrain, thus reducing the suboptimal used spaces that leads to a more ergonomic and spacious final product.
Among these companies, some of them have specialized in vans designed specifically for deliveries, focusing on the modularity of the platforms and on the reduction of the costs over the entire life cycle of the vehicles.
Examples are Rivian, which has among its investors has the e-commerce Amazon, and Arrival a UK company with a partnership with UPS.

Figure 10 Amazon delivery van by Rivian [10]

3.2 Customer segmentation

As already mentioned before, one of the features of commercial vehicles is their possibility of customization, for this reason it becomes necessary to identify all the various distinctive characteristics by segmenting the vans into different classes.

By mission
The first way in which vans can be divided is based on how they are utilized by customers. The first major distinction is established if the van is intended for the transport of people or goods.
An increasingly narrow distinction can be stated, as illustrated in Figure 11, is possible to reach up to eighteen distinct classes.

Figure 11 Van segmentation by mission [11]

Not all these classes have the same number of users [12], and the main ones are general haul, delivery, and construction.

General haul includes the transport of goods or tools as a non-core activity of an individual or a small enterprise; it represents almost 40% of large segment sales. The daily mileage is usually between 50 and 400 km a day [12] and typical users are craftsmen, retail merchants, short-term rentals and utilities, involving both services and municipalities.

Another category, accounting for 25% of sales of the large segment is Delivery: professional freight logistics including post & urban delivery, food & beverage and thermo controlled or refrigerated vehicles. In this market segment the distance covered each working day ranges from 80 to 250 kilometres and daily routes are scheduled in advance.

Construction represents up to 16% of large vans sales. These vehicles are used to move construction materials and equipment from or to a job site and cover distances from 50 to 200 kilometres with heavy loads every working day.

An important point that needs to be stressed for all these groups is the high utilization rate they have. Statistics say that the less used category is general haul, with an average of 200-250 working days a year, while the highest utilization rate is reached by delivery, with an average of 300 working days a year and peaks, for example for the food delivery sub segment, up to 360. For this reason, reliability is a critical aspect for an LCV customer.

By ownership

This criterion divides customers in two groups: fleets and private owners. The first category represents almost 70% [13] of sales every year, and as the main customer is another company, they generally buy more than one van, moreover they know exactly the type of goods that have to be moved, the daily route covered, the number of passengers, and can optimize the choice of characteristics precisely for their needs. For medium and large fleets, OEMs can provide dedicated service programs and specific vehicles' functions. Brand and model selection are based on how much a particular vehicle fits customer specific needs, reliability, safety, and purchase and operational costs.
Private owners pay attention to these parameters too, but, in addition, their decision process involves also other aspects: since usually they are directly involved in driving, design and comfort become important criteria to make the decision. These customers often have a very limited number of vehicles that need to perform a range of different tasks, so flexibility is indispensable.

3.2.1 Customer needs and decision factors

To determine the characteristics of the product, it is necessary to comprehend what the requirements and needs of the customer are.
Unlike a car that is purchased irrationally, the choice of a van is evaluated according to more rational criteria that maximize the profit for the customer and minimize friction and inconvenience.
The main buying factors that customers of large van vehicles consider have been synthesized [14].

Payload capacity

The load capacity represents a fundamental aspect of the characteristics of a van and quantifies the amount of usable weight that can be carried.
It's defined by the difference between the empty weight of the vehicle and the total mass allowed, i.e., the payload capacity that the van can safely carry as specified by the manufacturer.
Considering the business daily needs, allows the customer to decide which van size is the most suited. The dimensions do not always correspond to the load capacity, and as a result, a smaller van can also support a greater load than a larger van.
For now, since there has not yet been the introduction of autonomous mobility, the payload that a vehicle can carry is also influenced by the type of driving licence that the user has.
The vans that are currently available on the market are offered in the following sizes that are based on the maximum gross vehicle weight:

GVWR - 2T - 3.5T - 4.5T - 5T - 7T

Cargo volume

The load space of the vehicle is conditioned by the type of cargo that it has to carry and usually is provided in litres or cubic metres by the manufacturer.
One aspect that determines the useful volume of the vehicle is the length and height of the loading floor.
To meet all customer uses, manufacturers offer different vehicle lengths, identified with an L, ranging from L1 to L5 and are divided as follows:

L1 lower than 5.35 m
L2 between 5.35 m and 5.7 m
L3 between 5.7 m and 6.27 m
L4 between 6.27 m and 7.05 m
L5 greater than 7.05 m

For the height of the vehicle there are several options and usually they are indicated with the letter H:

H1 Low roof ≈ 2300 mm
H1 Medium roof ≈ 2600 mm
H1 High roof ≈ 2800 mm

The height is indicated measuring from the ground.

Easy loading/ easy access

This parameter is linked to the ease of entering and loading objects into the vehicle.
It depends on the access restrictions to occur in the workplace environment, for example, narrow streets or ceiling height constrains.
The position and door type also influence the usability of the van, and in a city, vans with dual sliding doors that allow for curbside loading would be a appropriate choice.
The rear doors can be optioned with hinges that allow a greater opening angle.
Another aspect to consider is the sill height, that will influence the loading technique of the van and the driver's effort of getting on and off the vehicle.

Customization

Some businesses require specialist commercial vehicles to cope with day-to-day operations.
Van interior setups can vary widely based on customer requests, and can go from simple additions such as extra attachment points to fully bespoke interiors.
The van manufacturers are increasing their offer more and more to be able to cover the requests of the customer.

Type of mission

As already specified in the previous chapter, one of the ways to divide vans is based on use by the customer.
Apart from the various classes already illustrated, it is critical to consider the length of the daily routes and the hours of use of the vehicle. Furthermore, the choice of the van will also affect how much load is transported and the type of travel.
It is also very important to evaluate performance and engine when buying a van or commercial vehicle. Consider that most of the time you will have a full van, so the engine must be capable to support a certain type of weight.

Range

For an electric van, the distance that can be travelled is limited by the size of the battery.
This will directly affect the maximum transportable load. The customer will have to carefully evaluate which factor he wants to prefer.

Manoeuvrability

For a user, the ease of driving the van can be decisive. Reduced steering radius increases the ability to move in city traffic and makes parking easier.
The wheelbase length is directly correlated with the turning radius and the bigger the worse the performance becomes.
The manoeuvrability is influenced by the maximum turning angle of the wheels, generally vans with front-wheel drive have a limited angle in respect of those with rear-wheel drive, because they must account for the drivetrain components.

Total cost ownership TCO

The cost of a vehicle is not determined solely by the purchase price but must include the expenses incurred during its entire life cycle.
If we take as a reference a TCO study for a van used for 150 days and 160000 km [13], the main cost items are divided as follows:

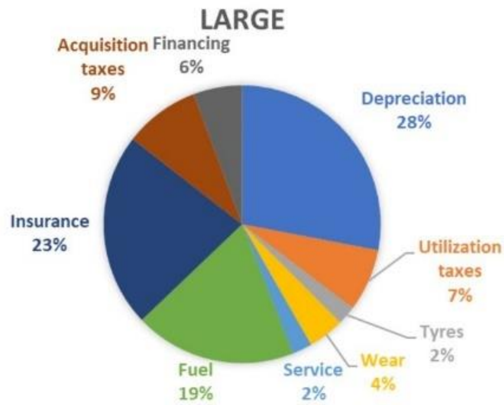

Figure 12 TCO composition for a large LCV

Many OEMs provide online TCO calculator tools. With reference to figure 12, starting at the top and moving clockwise, from depreciation to fuel are all voices on which the OEMs should focus to reduce customers' costs and obtain a competitive advantage in a market where information about total costs of ownership is almost perfect.

Downtime maintenance
Commercial vehicles must provide maximum reliability since their use is daily, and they are subjected to greater stress than a car. Reliability is, therefore, the keyword. The commercial vehicle constitutes the primary source of the customer profit: it cannot lose a job opportunity due to a problem caused by the van.

Durable / rugged
Predicting the life span of a vehicle represents an important factor for companies that decide to use a particular van from a manufacturer. In addition to the quality of the components, a robust design and the availability of spare parts ensure that a vehicle lasts longer and thus cuts down the costs of fleets.

4 PRODUCT CHARACTERISTICS

The proposed vehicle will be autonomous, electric, and modular.
The vehicle class is the multi-purpose one, and reference dimensions will be those of large Vans. The drive modules will have a single size, while the cargo module will be offered in different sizes.
Since the development time for this vehicle is limited, to determine its mission, the sales data have been taken as a reference, and the results reported that the most common use is general haul, the customers are fleet companies, and the subtype of vehicles is panel vans [12].
For this reason, the cargo module will be specialized only for the transport of objects, while a version dedicated to the transport of people is left for future developments.

Satisfy customer needs

To identify the technical characteristics of the vehicle, it is necessary to respond to the customer's requests and needs.
The same list of needs of Chapter 3.3 is again proposed and for each point the technical characteristic that satisfies the customer is identified.

Payload capacity
The load capacity of the vehicle can be divided into the part of the drive module and the one of the cargo module.
The weight of the vehicle directly affects the payload that can be carried, and for an electric vehicle the component with the greatest influence is the battery pack.
Considering that the cargo module can be equipped with different dimensions and weights of battery packs, the payload is directly affected.

Cargo volume
The total cargo volume is given by the sum of the available space on the drive and cargo modules. The external shape of the vehicle can be influenced by aesthetic, functional or aerodynamic demands that can reduce the theoretical maximum volume of the vehicle.

Easy loading/ easy access
Access to the vehicle is a critical aspect for the ergonomics of use of a van. The position of the doors, their size, and the type of opening mechanism must align with the use by the customer.
The proposed modular vehicle has the possibility of facilitating the access by lowering the cargo module to the ground thanks to the suspension system. Another aspect is linked to the manoeuvrability of the vehicle and its ability to position itself as requested by the customer.

Customization - Tailored cargo module
Compared to a traditional van, the cargo module allows greater customization.
The primary choices are related to the dimensions of the cargo module, the balance between the vehicle capacity and the battery size, the number of doors and their position and the interior fittings related to the field of use.

Type of mission
This aspect is linked to the specific use and the type of route that the vehicle must perform during the working day.
Vehicle requirements change if the majority of the kilometres are travelled on a highway or if the van moves mainly in the city.

Range
The distance that can be travelled depends on the efficiency of the vehicle and on the battery pack sizes.
As far as efficiency is concerned, this is linked to the reduction of resistance, both in terms of rolling resistance and aerodynamic drag. Autonomous driving can reduce the energy consumption by trying to optimize routes and driving style.
As far as the batteries are concerned, as mentioned above, it is possible to choose various sizes for the drive module

Manoeuvrability
Thanks to the construction with two specular drive modules, the vehicle has four wheels steering which improves the turning radius.
Moreover, the combination of autonomous driving and the presence of an electric motor on each individual wheel allows to control the torque and slip of each tire.
The control of the height from the ground allows the vehicle to easily overcome obstacles that are encountered on the path.

Total cost ownership
The cost of ownership is made up of various parts
The devaluation is one of the most onerous costs and is linked to ageing and the consumption of components. The modular vehicle allows to mitigate this aspect, because the different rate of wear of the modules doesn't affect each other.
As far as energy consumption is concerned, these depend on the size and load carried by the vehicle. To reduce costs, it is possible to share the use of the drive modules with other users.

Downtime maintenance
The vehicle can go autonomously to the workshop to carry out scheduled maintenance. To minimize the time lost as a customer, a replacement drive module can be loaned.

Durability
A very important aspect is the lifespan of the product.
In any vehicle, the various components that make it up wear at different time rates, generally the parts making up the drive train are more critical than those of the structure.
The modular vehicle being able to separate the drive module which has all the most critical components allows the customer to use the cargo module for more years than a normal van.

5 OPERATION

Given the flexibility of the modular vehicle platform, it is necessary to explain the way it operates, for this reason, this chapter will identify the main working conditions and which operations the vehicle must perform to remain operational.

The main operating modes have been summarized in this list:

1. Road driving operation
2. Self-balancing
3. Coupling phase
4. Recharging phase
5. Service and maintenance
6. Dive module recovery

1.Road driving operation

When the vehicle moves on the road and has the modules connected, its operating mode will be the same as that of a commercial vehicle that adopts autonomous driving. Level 5 autonomous driving offers considerable advantages in terms of safety, optimization of the energy consumption which leads to a reduction in overall emissions. Furthermore, advanced traffic management leads to a reduction in congestion.
To adopt autonomous driving, it’s necessary to coordinate the operation of the two driving modules, maintaining continuous communication. To do this, either a wireless communication system can be adopted, or a physical connection can be established through a coupler system.

Four-wheel steering is a distinctive feature that increase the vehicle's agility by reducing the turning radius, improving the ability to move in traffic and park. They also allow the vehicle to perform peculiar manoeuvres such as moving diagonally or turning on a point.

As far as the autonomy of the vehicle is concerned, each drive module has a sufficient battery for short distances. If the customer's use is more intensive, he can choose to set up the cargo module with a dedicated battery to fulfil his needs.

The vehicle is equipped with an active suspension system that manages the height of the vehicle. This height from the ground is adjusted according to the conditions of use and for example will be in a raised position during city operation, to compensate for any disconnected terrain, while on the motorway a lowered position reduces aerodynamic drag.

2.Self-balancing

When the drive module is disconnected it must remain balanced on a single wheel axis.
This mode its also used for the approach phases for the coupling with the cargo module.

For longer trips, the drive modules can also connect to each other to give the necessary stability at the composed vehicle

3.Coupling phase

Since the proposed vehicle has a modular construction, the coupling system represents the most critical system of the structure.
Starting from the position with disconnected modules, several steps are necessary to complete the coupling phase:

a) Approach
The drive modules approach the cargo module operating in self-balance mode.

b) Opening third arm
The next step is to open the mechanical system to stabilize the drive module and prevent it from falling during subsequent manoeuvres.

c) Alignments
To proceed with the coupling phase, the drive module must be aligned in front of cargo module. Particular attention is paid to lateral alignment in width direction, which must be fully managed by the autonomous driving system.
The modules bring the coupling system to the same level by working on the height control systems present on both the driving and cargo parts.
Height control systems of both the drive and cargo modules will compensate for the misalignments in other directions.

d) Contact
Once aligned, the drive module come close to bringing the coupling system into contact.

e) Coupling phase main locks
Once the right distance is reached, the coupling system can be activated. From this moment the modules are mechanically connected.

f) Coupling connectors power-systems
Any other systems such as power lines, data lines, compressed air will have their own dedicated coupling system.

g) Closing third arm balancing system and cargo height control
The vehicle being completely stable can retract both the balancing system of the drive module and the feet of the height control of the cargo module.

h) Height adjustment for driving
At this point the vehicle is ready, the ground clearance is adjusted according to road condition and normal operation begins.

4.Recharging phase

The vehicle being autonomous and modular opens up the possibility of using different charging strategies that can best adapt to the user's needs.

If a company has many vehicles, it can take advantage of a strategy of exchanging drive modules with charged ones, reducing the time lost to recharge to almost zero. Moreover, in this way the recharge do not necessarily have to be of the fast type, with the effect of increasing the lifespan of the batteries.
To fully automate the process, charging stations can be set up with an automatic engagement system for charging, removing the need for an operator to supervise the process.
If the modular vehicle is mainly used during the day and remains idle at night, overnight charging is a good option. This approach assumes that the vehicle runs for only one shift a day, are idle throughout the night, and usually have a battery that is large enough to support the daily required range when fully charged.

The dedicated charging station can use the same coupling system already present between the modules. Then the drive module will then simply lean against the wall and connect to the charging station.
The operational steps for an autonomous charging system are:

a) approaching
b) alignments
c) coupling
d) charging

The vehicle will also have a standardized charging port available so that it can also be plug into traditional charging columns.

5.Service and maintenance

Since the critical components are all on the drive module, it can drive itself to a facility to undergo scheduled maintenance.
To minimize the time losses that the customer has to endure, different solutions can be adopted.
If the drive modules are rented, then they will simply be exchanged with an operated unit, in this way the management of working hours for maintenance can be scheduled in an optimal way. The modular vehicle platform enables to remotely identify and resolve the service needs proactively, preventing downtime.

6.Dive module recovery

If a module as any problem, it can be switched with a rescue module provided by the leasing contractor.
Two drive module rescue: one for the non-functioning one and one for the customer to conclude his operations.
In this case, the two drive modules will come to the rescue, one to be exchanged with the non-functioning one and one to bring the exhausted one back to the base or recharge.

In work operations such as on construction sites the cargo module, once it has arrived, tends to remain stationary, while the drive modules, being independent, can still help to transport objects by exploiting their load capacity.

6 DESIGN AND PACKAGE IDEATION

The vehicle by state is composed of three modules, the external geometry must be as simple as possible, in order to maximize the internal volumes.
For this reason, the cargo volume has the priority over the drive module dimensions, and for the latter is preferable to be as short as possible.

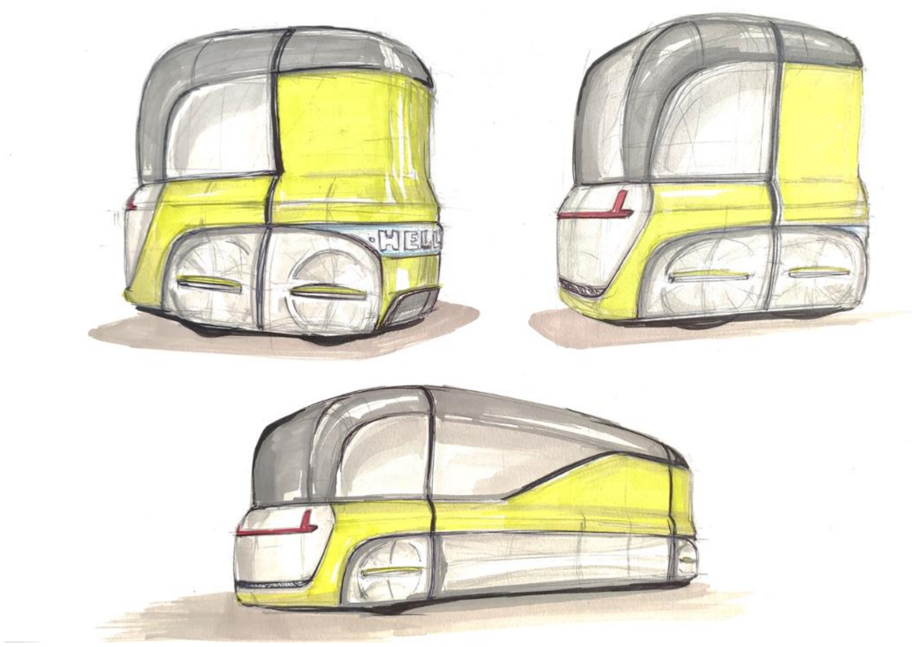

Figure 13 Sketch different coupled configurations for the modular vehicle

To fully exploit the potential of the vehicle's modularity, the cargo module will be available in many different sizes and variants.

Figure 14 Sketch cargo module with different types and dimensions

A simple diagram is presented which includes the intended use of each available space of the vehicle.

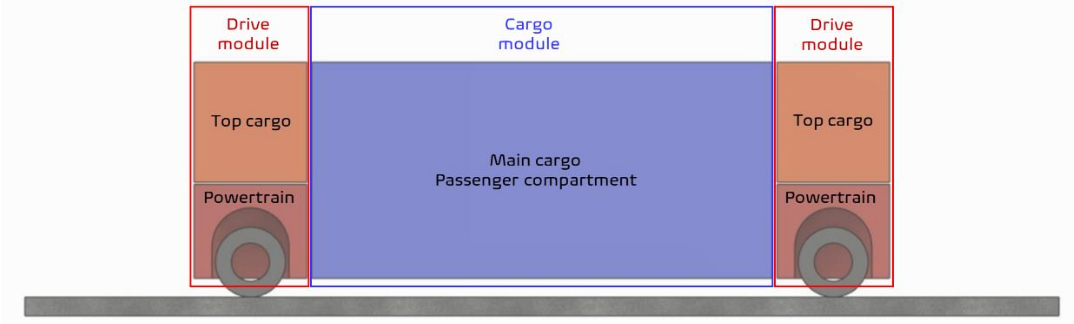

Figure 15 Modular vehicle side view layout

To appreciate the actual dimensions, the vehicle is presented together with a mannequin with a height corresponding to the 95th percentile for men in Europe.
The details of all these specifications are presented in the following chapter.

6.1 Functional Requirements

Dimensional
To compete with large vans, the dimensions of the vehicle, both external and internal, are the main comparison parameter.
From the research carried out, a series of measures are proposed, these are considered a good compromise between the offer for the customer and production complexity. It should be recalled that for a modular vehicle the construction of special parts is simpler, so alternative dimensions are possible.

Length
As already explained in chapter 3 large vans can be classified according to their external length, and the current manufacturers follow the subsequent classes:

L1 lower than 5.35 m
L2 between 5.35 m and 5.7 m
L3 between 5.7 m and 6.27 m
L4 between 6.27 m and 7.05 m
L5 greater than 7.05 m

For the proposed vehicle, the overall size is given by the sum of two drive modules with a cargo module. While the length of the driving module is fixed, the cargo modules can have different dimensions which depend on the needs of the end user.
For this reason, the vehicle is designed starting from the inside to the outside, making sure the final measures fall within the classes already defined.

Cargo module length
The internal length of the cargo module has been set to the number of standard EU pallets that can be transported.
The flat loading floor allows to obtain a clear advantage over traditional vans, where a part of the space is occupied by the rear wheel arches.
Playing with the possible dispositions of the pallets, a set of viable final configurations has been achieved, and as illustrated in the figure 16, for each length class, an extra pallet could be loaded.

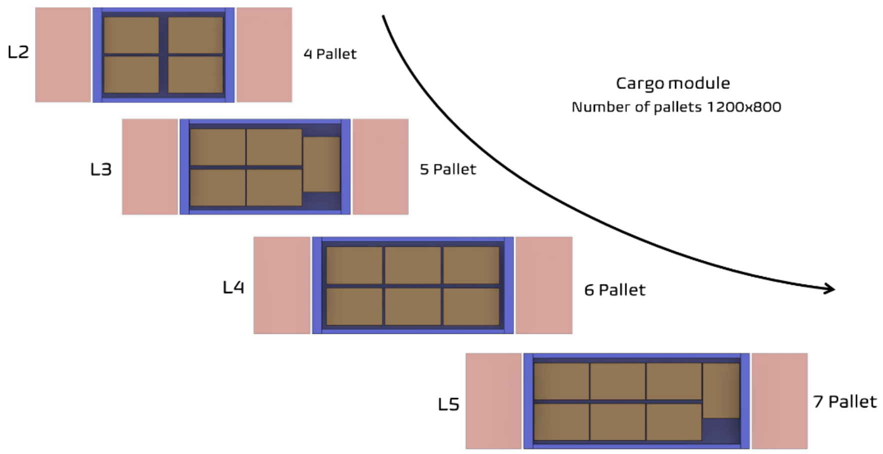

Figure 16 Loadable number of pallets in the cargo module

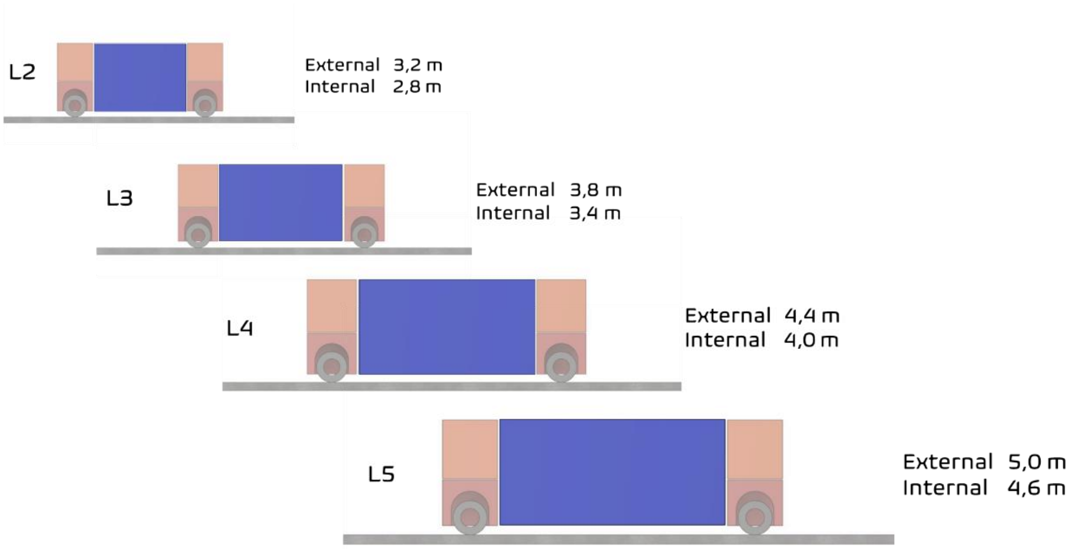

Figure 17 Length classes cargo module

Adequate spaces have been added from the dimensions of the loading surface to consider the structure of the module, thus defining the final internal and external measures.

Drive module length
The drive module must be as short as possible to reduce the overall dimensions of the vehicle. This minimum size is limited by the space necessary to accommodate the internal components.
To define the final length, the frontend of the current vans was taken as reference, and it has been chosen to set this measurement to 1.2 m.
Overall vehicle length
Knowing the measurements of the various modules, the length of the whole vehicle is therefore defined. It was verified that the obtained measurements correctly belonged to the assigned length classes.

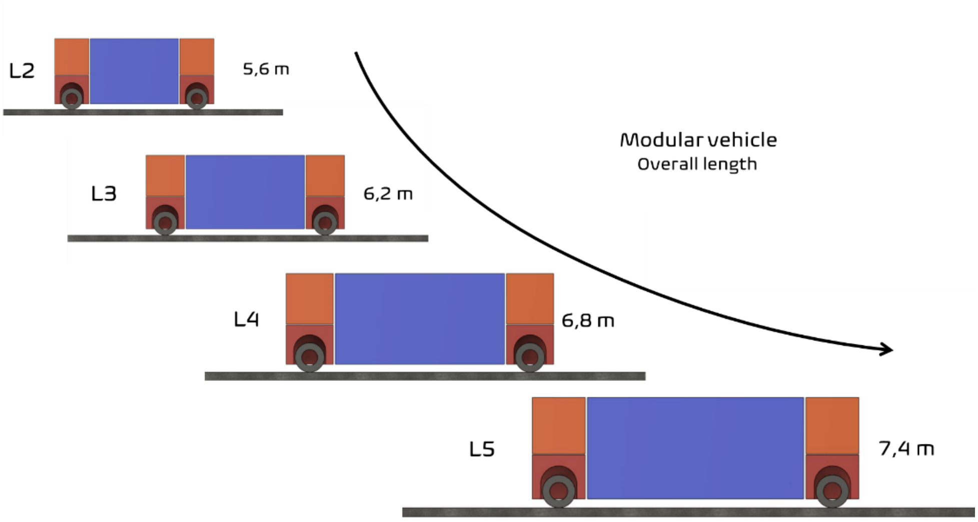

Figure 18 Overall vehicle lenght

	Overall m	Wheelbase m	Load compartment m
L2	5,6	4,4	2,8
L3	6,2	5,0	3,4
L4	6,8	5,6	4,0
L5	7,4	6,2	4,6

Table 1 Modular vehicle lenght

Width

Cargo module width

The width of the vehicles is a compromise between the internal load capacity and the ability to operate on narrow streets such as those of the city.
The maximum allowed width by EU regulation is 2.6 m while the width of vans is generally 2.1 m without considering the mirrors.
The base width chosen is 2.07 m and is in line with that of the other van manufacturers. This size allows to easily load two EU pallets side by side, as shown in the figure 19.

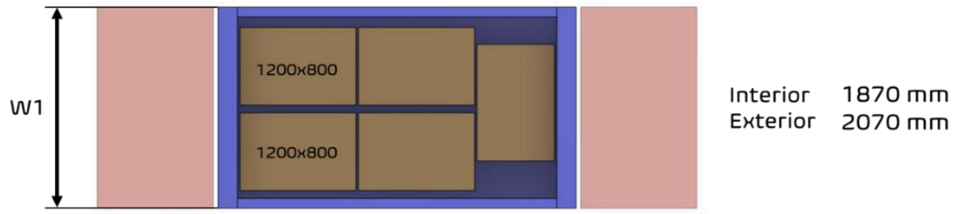

Figure 19 Cargo L3 standard width

For users who need to have more internal space, an additional measure was chosen, again based on the dimensions of the pallets, but this time considering a non-standard 1200x1200, with this configuration the internal width is set at 2.1 m and the external one at 2.3 m as shown in the figure 20 conf.A.
It's also possible to rearrange the standard pallets in alternative disposition, like in conf.B.

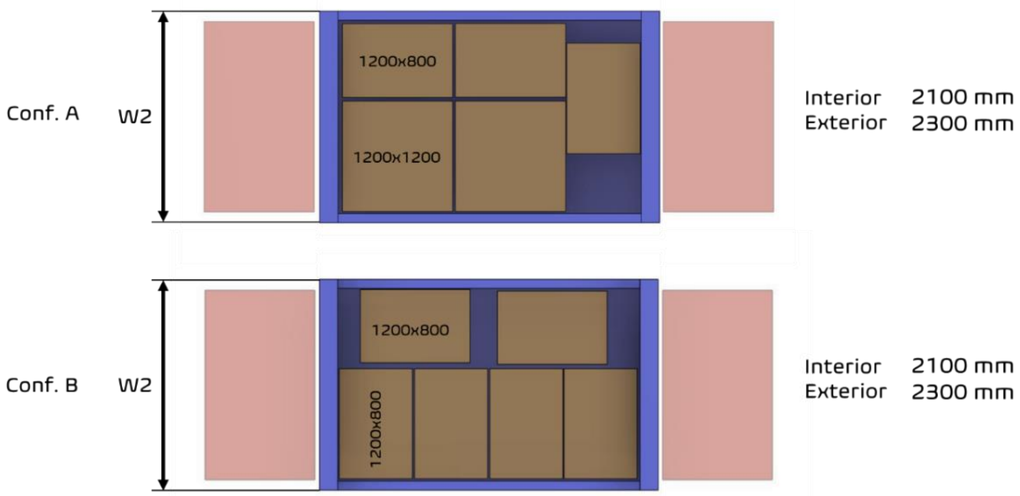

Figure 20 Cargo module extended width, with different pallet disposition

Payload area
Having defined the internal measurements of the cargo module, you can simply calculate the payload surface in the various possible configurations.

	Load surface m^2	
	W1	W2
L2	5,2	5,9
L3	6,3	7,1
L4	7,4	8,4
L5	8,5	9,7

Table 2 Cargo module load surface as function of length and width class

Drive module width
The width of the drive module is set to be the same as that of the cargo module in the narrowest configuration, and this will limit the possible dimensions of the suspensions and drivetrain components.

Height

Cargo module Height
The minimum height of the cargo module has been chosen so that most of the people can stay inside in an upright position.
Considering that in Europe the height of the 99th percentile man is 191 cm the proposed minimum interior height is 2 m.
Smaller dimensions are unnecessary, thanks to the active suspension system, the height from the ground is lower compared with a traditional van, this leads to a consequent lower overall external height. As for the other cases, a cargo module with greater height is provided for special needs with final internal height is 2.3 m.

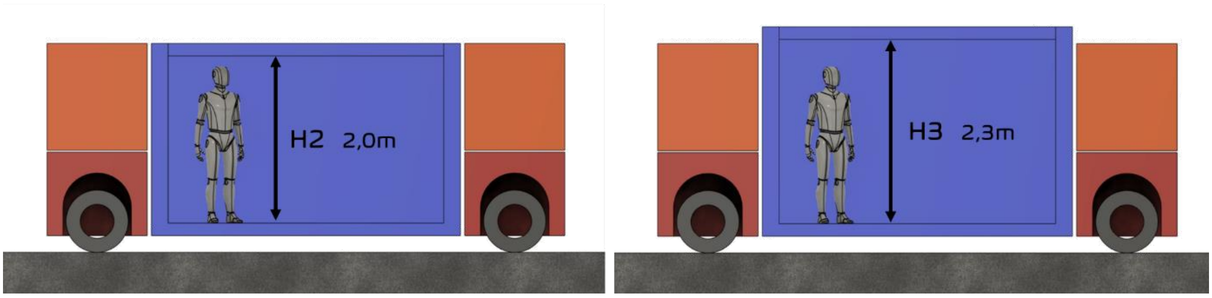

Figure 21 Cargo module interior height class

Ground clearance
The relationship of the body and underbody components to the ground should be appropriate to the use of the vehicle.
In addition to the height from the ground, to easily overcome the obstacles found while driving, the approach, departure and ramp over angle are also to be taken into consideration.
The SAE J1100 standard is used as a reference for the definition of the various angles like shown in the figure 22.

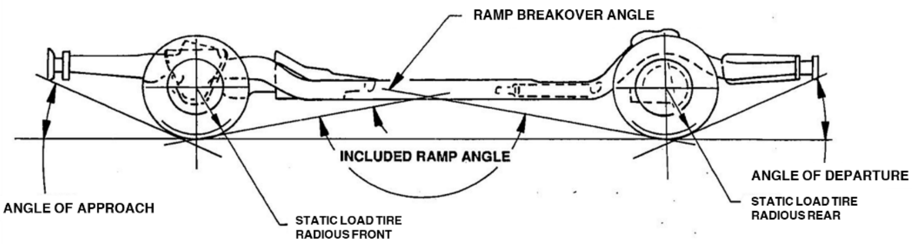

Figure 22 Ground clearance dimensions SAE J1100

Large vans usually have long wheelbases, and this tends to compromise the ability to overcome obstacles like ramps. Furthermore, given the package of the proposed modular vehicle which pushes the wheels outward, this problem worsens.

To overcome this, the vehicle is equipped with high travel suspension which allows it to rise considerably.
In addition, the suspension is required to lower the vehicle to the ground, both to facilitate any coupling phases between the modules and the loading and unloading operations of the cargo.

The average height from the ground of the vans currently available on the market is between 150 and 230 mm, it is therefore chosen to set the standard height at 200 mm and a maximum height from the ground of 400 mm to overcome the most challenging obstacles.

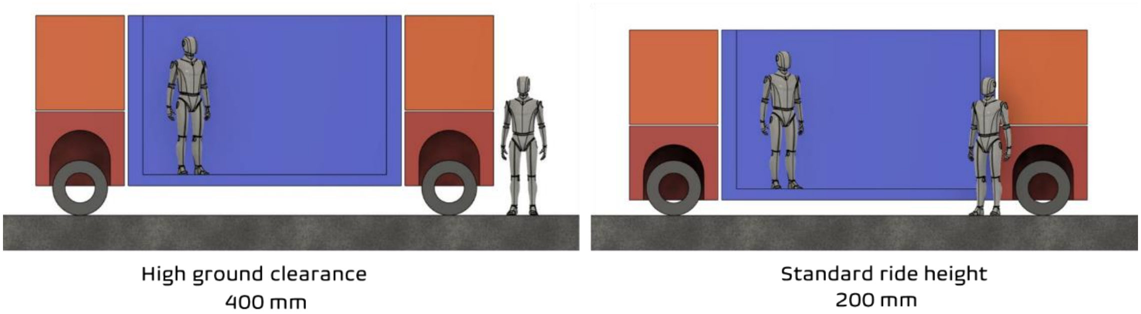

Figure 23 Ground clearance ride height

Given the nature of the modular vehicle, the ramp breakover angle is strictly correlated with the length of the cargo module and therefore to the wheelbase.

Length classes	Wheelbase	Standard height 200 mm		Lifted height 400 mm	
		Ramp breakover angle	Included ramp angle	Ramp breakover angle	Included ramp angle
L2	4400	10,4	169,6	20,6	159,4
L3	5000	9,1	170,9	18,2	161,8
L4	5600	8,2	171,8	16,3	163,7
L5	6200	7,4	172,6	14,7	165,3

Table 3 Approach angle and breakover gangle as function ground clearance and length class

The figure 24 shows an example of a configuration for the length L3 which has Cargo module exterior length of 3.6 meters, that implies a wheelbase of 5 meters.

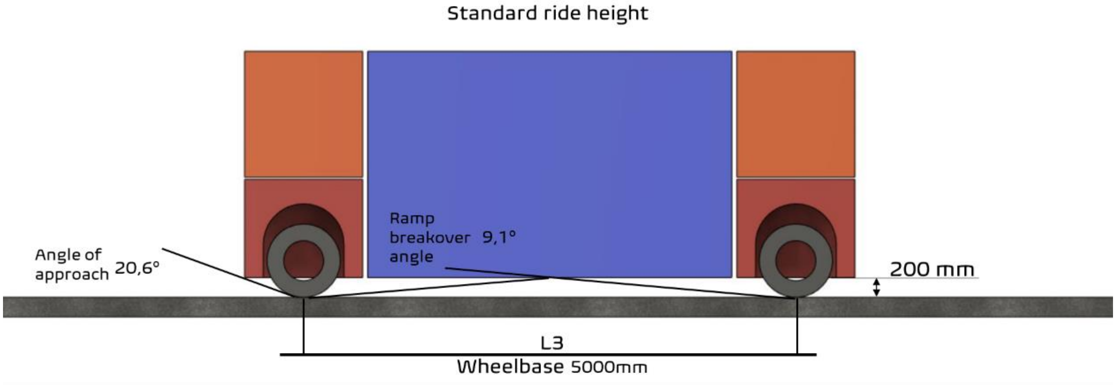

Figure 24 L3 configuration characteristic approach angle

Since the drive module is the same front and rear, the approach angle will be equal to the departure angle and depend only on the vehicle height from the ground.
For 200 mm the angle of approach is 20.6 deg and for the raised height the value increases to a maximum of 40.9 deg.
The considerable travel required by the suspension demands an active control system to be implemented. This system has the advantage of being able to continuously control the movements of the car body and adapts the height from the ground according to different needs.
For example, from the standard position, the vehicle can be lowered to improve aerodynamic efficiency, reducing the overall drag.
Another feature already mentioned above is that of having the possibility of placing the modules on the ground, minimising the distance from the ground of the loading surface.

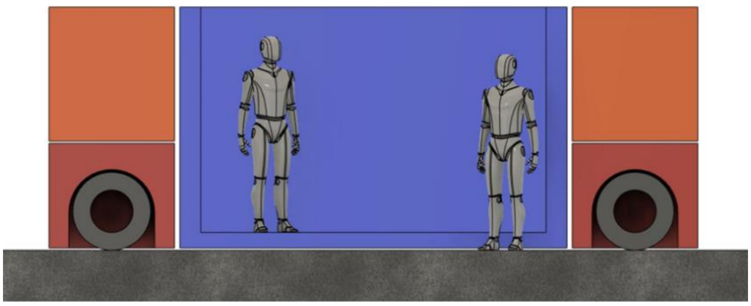

Figure 25 Modular vehicle lowered configuration

A sill height of 150 mm and an integrated ramp opens up the possibility of being able to load the module employing only a pallet jack without the need to use a forklift.
Even in a hypothetical version dedicated to passenger transport, this feature makes access possible for people with limited mobility.

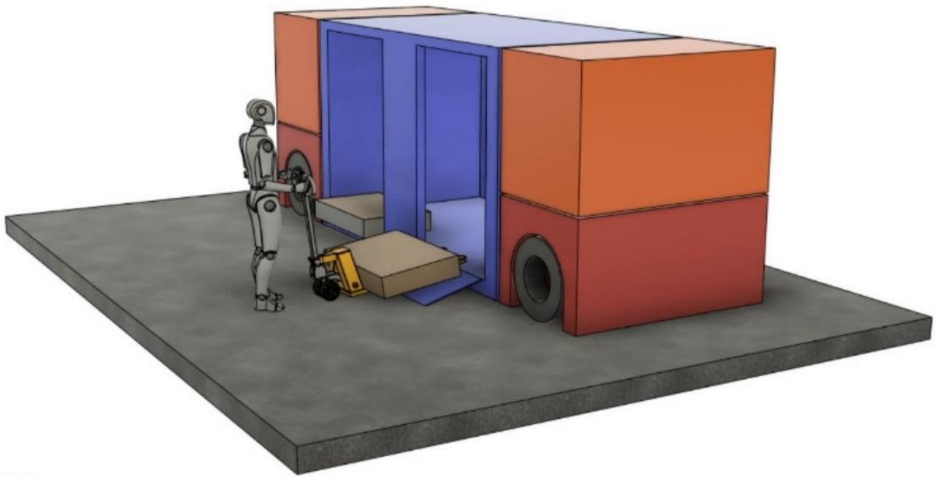

Figure 26 Modular vehicle unloading operation

Cargo module lift system

Another component required for the operation of the modular vehicle is a lifting system for the cargo module.
This component is necessary because it allows the modules to be brought to the same height during the coupling phase, and is especially critical when the terrain is uneven.
When the module is parked, the system allows the floor to be kept level at all times, facilitating on-board operations.

Figure 27 Cargo module lifting system

The proposed solution is to integrate in each corner of the cargo module a lifting system that has the same excursion as the suspension of the drive module.

Functional

The autonomous driving technology is necessary for the operation of the modular vehicle, since in this configuration the drive module does not provide space for passengers.
The general dimensions and positions for all the components necessary for level 5 of autonomous driving must therefore be considered.

Self-Balance system

For the vehicle to function correctly, it is necessary to have a balancing system for the drive module for when the modules are disconnected.
This system can be obtained by controlling the speed of single wheels and keeping the engine in equilibrium.
A similar operating principle is already adopted by products like the Segway or various robots such as the Ascento [15].
This way of working consumes a lot of energy to maintain equilibrium, so a mechanical solution is also employed.
In the figure 28 a mechanical arm that extends on the front is proposed, but different solutions could also be used, such as a third support wheel that moves vertically as used by the Gapo tractor.

Figure 28 Drive module balancing systems

Since the front and rear drives are the same, the vehicle has four steering wheels. This considerably increases the manoeuvrability of the vehicle, reducing the turning radius and being able to move diagonally (crab walk).
Since autonomous driving is managed by a computer, there is the possibility of having an independent control system between the right and left wheels. This allows for an improvement in dynamics and simplifies the design of the steering geometry.
With current trucks as a reference, the maximum wheel steering angle that can be obtained is 45 deg, and this parameter is limited by the articulation of the CV joints.

Doors

The side doors should be wide enough to be able to load a pallet from the long side, so the chosen width is 1250mm.
Vans generally only have a single sliding door, as they have easy access to the rear as well. While for the modular vehicle if the driving modules are connected only the sides are free, for this reason, possible configurations with two side doors are proposed figure 29:
One with a double door on the single side and one with a door on each side of the vehicle.

Figure 29 Cargo module door side configuration

The number of side doors directly depends on the length of the cargo module class.

If the customer needs to load very long objects and the side doors are insufficient, front doors are available, but only with the cargo module disconnected.
The width of these front doors is limited by the coupling system position and design.

Figure 30 Cargo module door front configuration

Powertrain

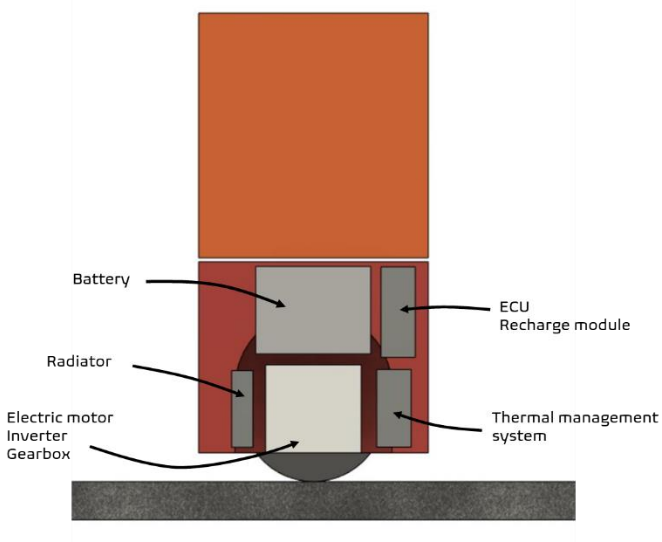

Figure 31 Powertrain configuration

The architecture of the powertrain will depend on the exact components chosen. In this phase a configuration is proposed that includes two electric motors installed on the wheel axle, a battery pack placed directly above, a thermal management system, connected to its radiator and finally the space necessary for all the on-board electronics, especially the ones dedicated to the autonomous driving.

Coupling System

The coupling system represents a fundamental part of the design of this modular vehicle. The arrangement of the coupling systems on the vertical faces of the modules makes this technical solution unique compared to the other existing prototypes.
For this reason, it is important its design is robust and allows a quick and easy coupling operation.

Figure 32 Couler system configuration

7 BENCHMARKING SIZING AND PROPORTIONS

After defining the macro systems of the vehicle, the next step is to compare with competitors already present on the market and other relevant vehicles.

From the market research carried the best-selling vans in Europe were identified, these manufacturers were selected to represent the benchmark for the project.
In this phase of transition to electric mobility almost all manufacturers have presented at least an electric version of their products even if they are currently only available in limited variants and do not yet include all the body styles available for the ice versions.
Moreover, these electric vehicles are born on the basis of their ice counterparts, and not utilizing a dedicated structure they have to make compromises in the geometries that reduce the overall efficiency of the vehicle.

For this reason, as regards the geometric dimensions, the traditional variants have been taken as a reference, while as regards the powertrain part and the electric variant they have been considered.
The list of models of vans of these brands is presented:

- Ford transit and E-transit [16]
- Mercedes Benz Sprinter and E-sprinter [17]
- Renault Master and Ze-master [18]
- Fiat Professional Ducato and e-Ducato[19]
- VW Crafter [20]
- Iveco Daily [21]

To refer to this group of brands, they will be referred to as legacy manufacturers in this document.

In recent years, several companies have appeared on the market that promise to produce better vans by adopting an electric platform from the start.

The Arrival van [22] was chosen as the representative for these companies because at this time (March 2022) there are not enough specifications available regarding other companies such as Rivian, Canoo and Brightdrop.

The vehicles are compared to the main geometric dimensions and in the principal characteristics, such as weight and power.
The research data was obtained directly from the respective manufacturers' sites.
Overall dimensions, cargo storage, powertrain package.

7.1 Geometrical dimensions benchmark

The classes proposed for the van refer to those in chapter 3.2.1 and range from L2 which corresponds to a medium-sized van to L5 which corresponds to an extra-long length.

The plots are divided classes that correspond to the multiple lengths offered by manufacturers. These classes are necessary because they fill different needs of the users:

L2 between 5.35 m and 5.7 m
L3 between 5.7 m and 6.27 m
L4 between 6.27 m and 7.05 m
L5 greater than 7.05 m

The proposed modular vehicle is indicated in the graphs as "New modular"

Overall vehicle length

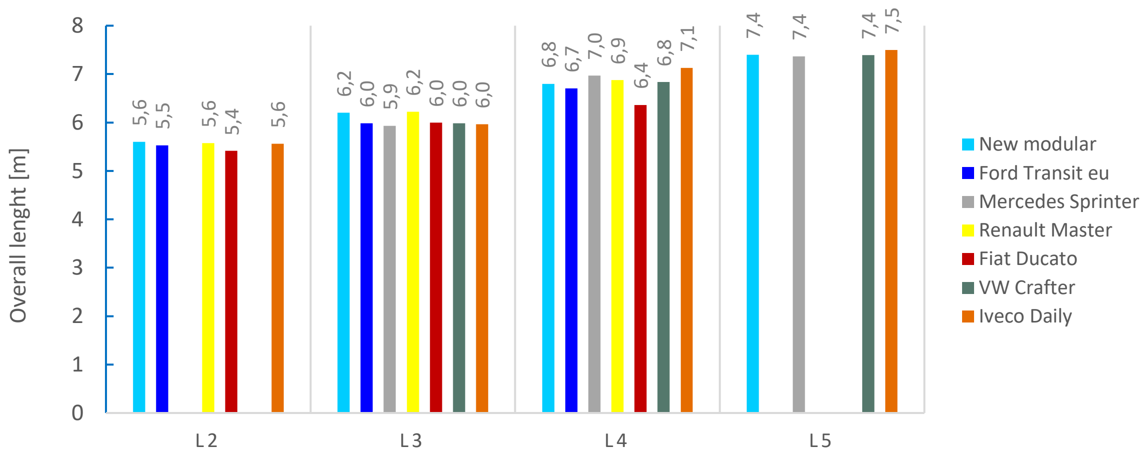

Figure 33 Comparison exterior vehicle length all legacy manufacturers

In this first graph a direct comparison with all the main van manufacturers is proposed. Not all classes are covered by every single constructor, and instead they tend to focus on the first or last three.

To make the comparison clearer, figure 34 shows the differences between the Mercedes-Benz Sprinter and the modular vehicle.

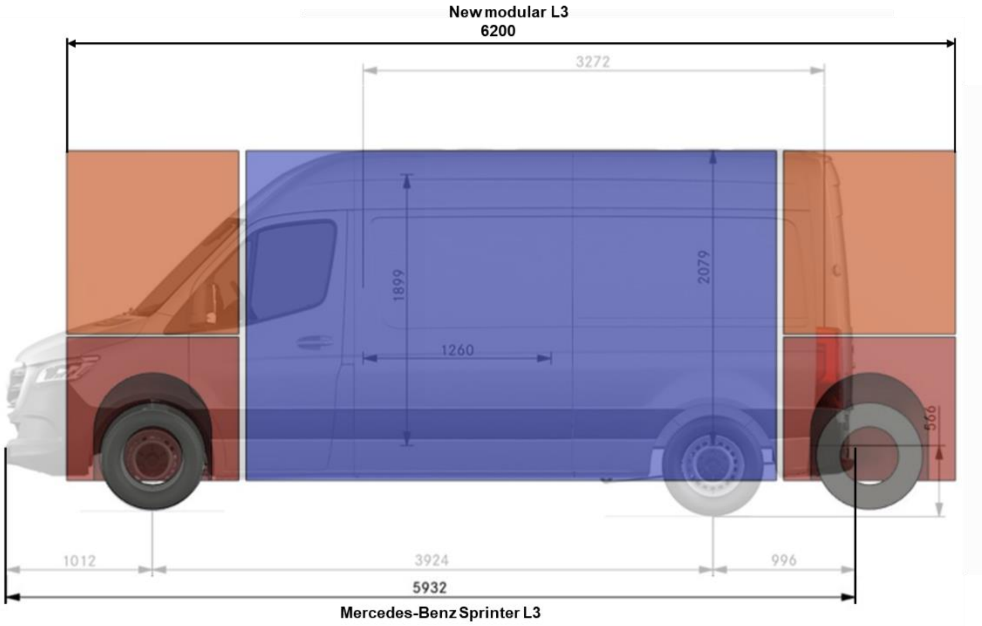

Figure 34 L3 length class comparison modular vehicle Mercedes-Benz Sprinter

For category L3, the vehicles have been aligned on the front axle in order to emphasise the difference in length of the frontend.
This difference is possible because the drive module is not suited for the transport of passengers, and this allows to compact all the mechanical part inside the wheel axle.
There is a noticeable contrast in the wheelbase between the two vehicles, and this will have its own dedicated comparison.

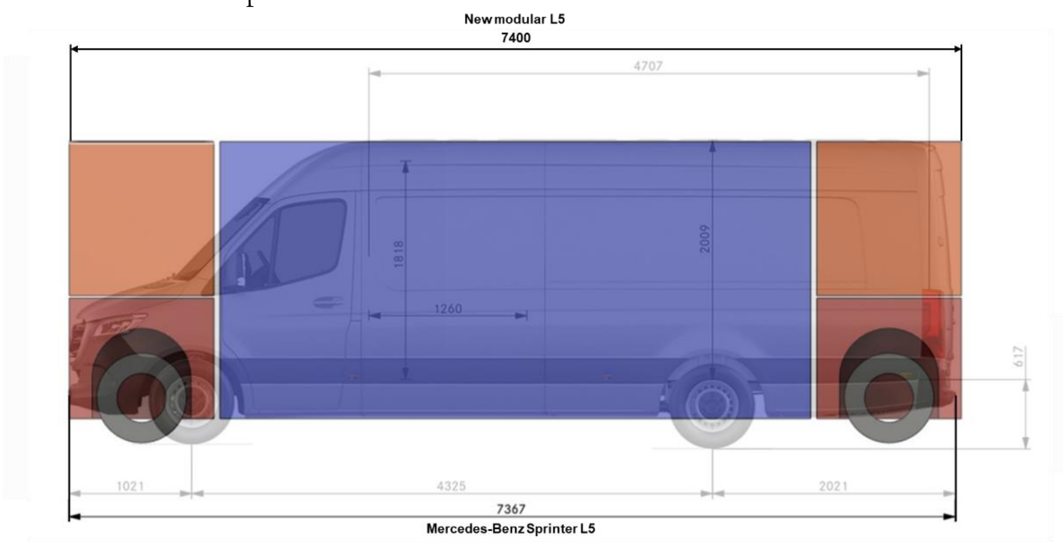

Figure 35 L5 length class comparison modular vehicle Mercedes-Benz Sprinter

In the size comparison of the category L5, the vehicles were instead aligned at the frontend, this shows that the overall length is very similar, and even the space dedicated to the powertrain is basically the same.

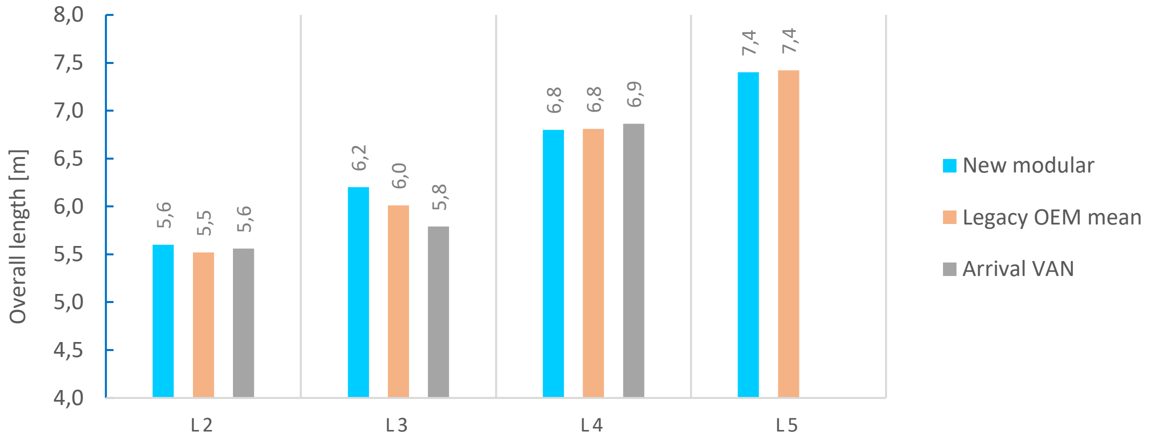

Figure 36 Comparison exterior vehicle length synthesis

To make the graph easier to read, the legacy manufacturers have been grouped into a single indicator.
The Arrival company is added as the representative of the native electric vans.
The length of the new vehicle is generally in line with that of the other manufacturers, and only for the L3 category is it at the limit allowed.

Width
In the comparison of vehicles with regard to the width, we are interested in both the external and internal dimensions of the loading floor.

As for the external dimension, the manufacturers often indicate two width measurements, one for the car body only and one that includes the maximum width with the rear-view mirrors in the open position.

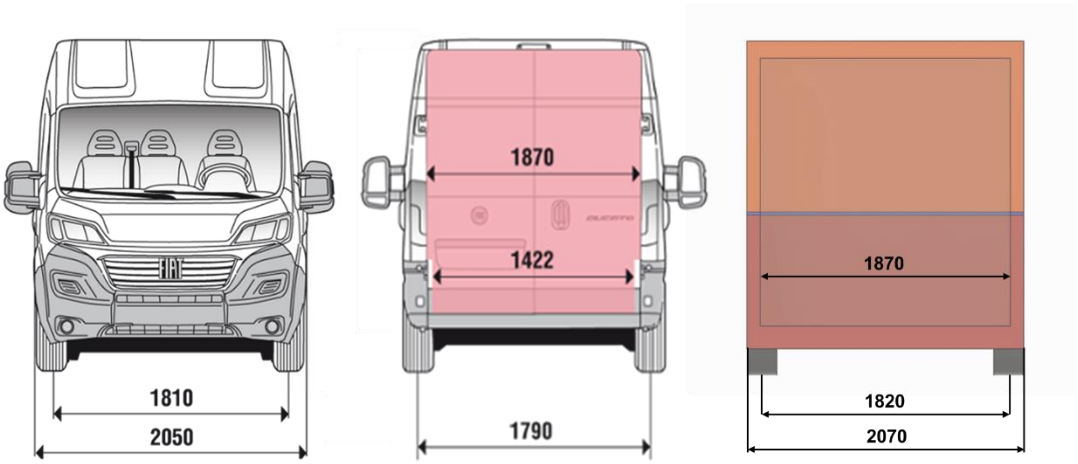

Figure 37 Exterior and interior width comparison between new modular vehicle and Fiat Ducato

For the modular vehicle, as assumed in chapter 6.1 the cargo module will have two widths available, a narrow body that will be in line with that of traditional vans and a wider body that will occupy the same space as with open mirrors.

The measurement of the internal part is difficult to obtain because the geometry of the load compartment is more complex, in particular due to the presence of the rear axle, the wheel arches lead to a local narrowing of the load floor.
Given the construction of the cargo module, its loading surface has no internal obstacles and its width remains unchanged.

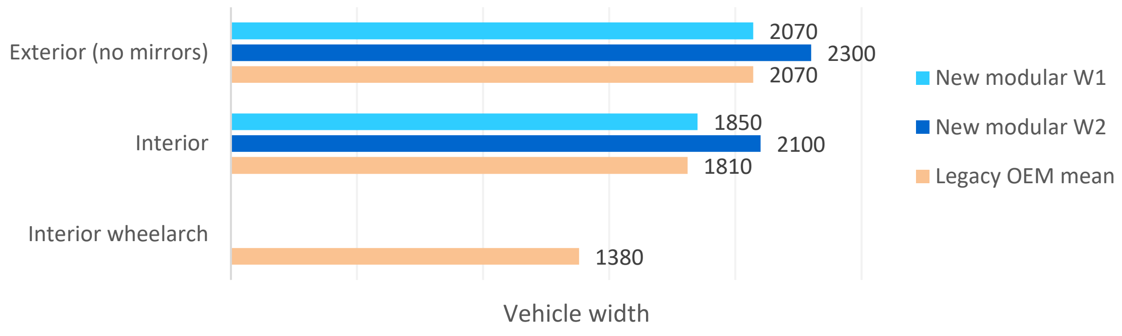

Figure 38 Comparison exterior and interior vehicle width

With the following internal measures, the advantage is to be able to load a greater number of pallets or other bulky objects.

Wheelbase

The wheelbase of the vehicle influences the dynamics of the vehicle, and in general the longer it is, the more stable the vehicle becomes and in the same way it reduces its agility, influencing for example the steering angle. Another factor that is limited by a long wheelbase is the breakover angle necessary to overcome ramps.

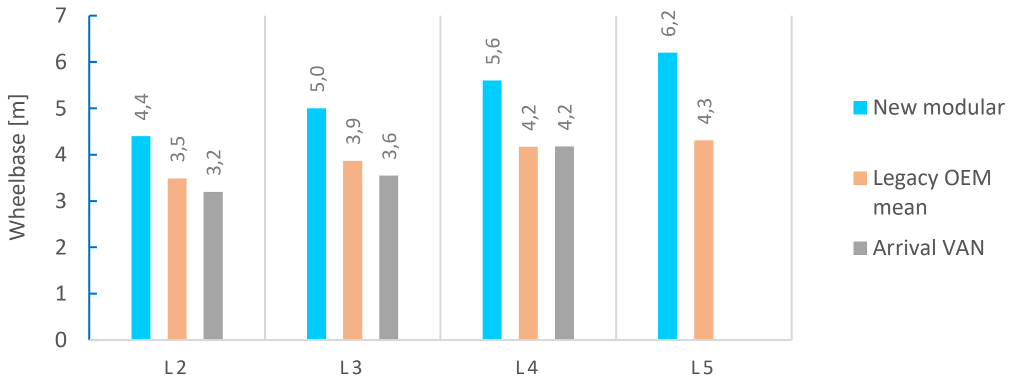

Figure 39 Comparison wheelbase as function of length class

For the proposed vehicle, the drive modules are short and placed at the ends of the vehicle, the wheel axles are therefore very far apart.
From the graph it is clear that the wheelbase is over one meter longer than a traditional van, and if the vehicle wasn't equipped with systems such as four-wheel steering and variable height, this length would be excessive and would compromise its usability.

Length of loading area

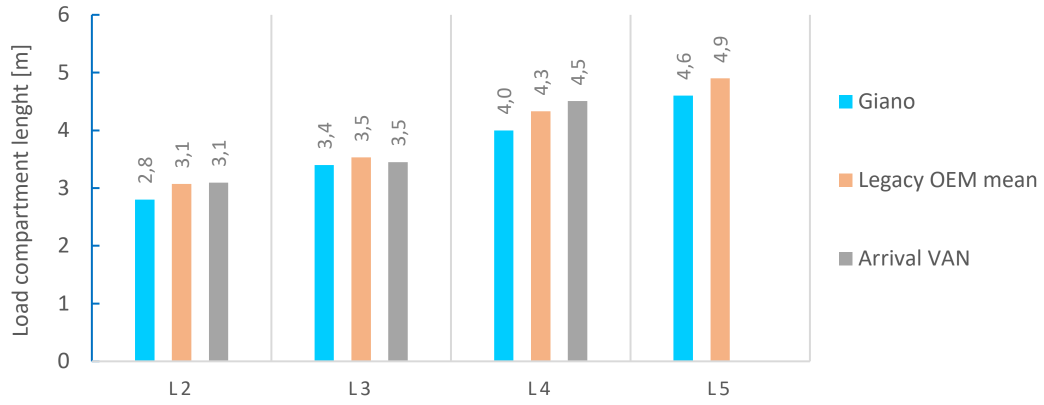

Figure 40 Comparison load compartment length as function of length class

Compared to a traditional van, a part of the space is sacrificed to make room for the rear drive module, this involves a reduction in the length of the loading surface which can be compensated by increasing the overall length of the vehicle as effectively done.

Cargo surface

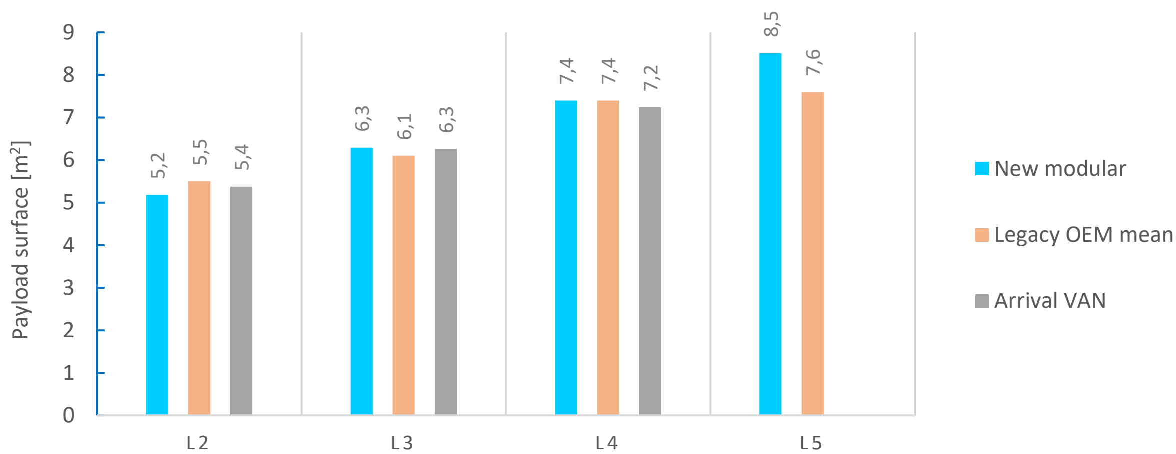

Figure 41 Comparison payload surface as function of length class

The loading area for the proposed vehicle, thanks to its rectangular shape, is simply the multiplication between the length and the internal width.
The modular vehicle returns to be competitive in the payload surface parameter thanks to the constant width of the cargo module.

Cargo volume

The cargo volume is calculated by multiplying the payload area by the internal height. This comparison is made by considering two different internal roof heights, a medium one, defined H2, that allows users to stay upright and a raised one defined H3 for higher loads.

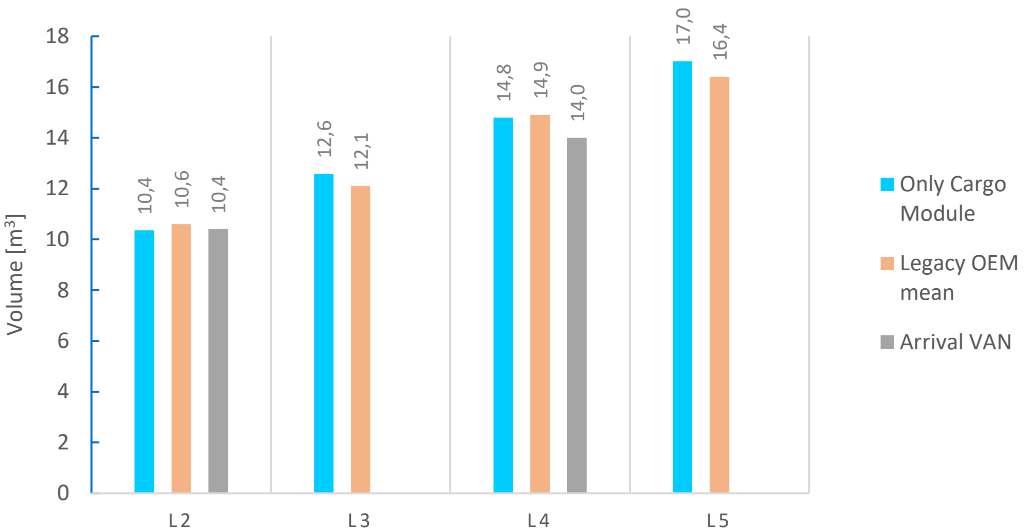

Figure 42 Comparison cargo volume as function of length class

Tor the calculation of the volume in this graph we consider the medium height H2 of the roof.
The results are in line with those obtained with the loading surface and note that Arrival does not offer a vehicle configuration with L3 length and medium roof height.

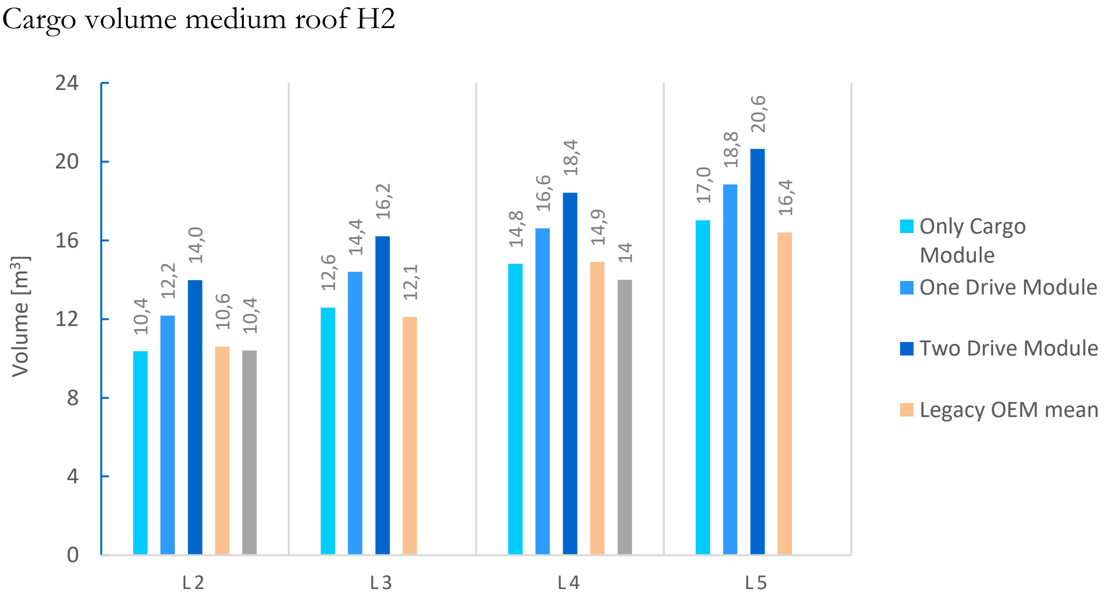

Figure 43 Modular vehicle overall cargo volume whit roof height H2 as function of length class

To show the potential of the modular vehicle, the same graph is re-proposed, but adding the load volumes also present in the drive modules.
In the graph there is the volume for the cargo module only, with the addition of one drive module and with the addition of both front and rear drive modules.
The load values that can be obtained also using all the available space are significantly higher than those of the competitors, however, it must be remembered that in this calculation the space necessary for the transport of a driver and passenger is not included in the proposed vehicle.

Cargo volume high roof H3

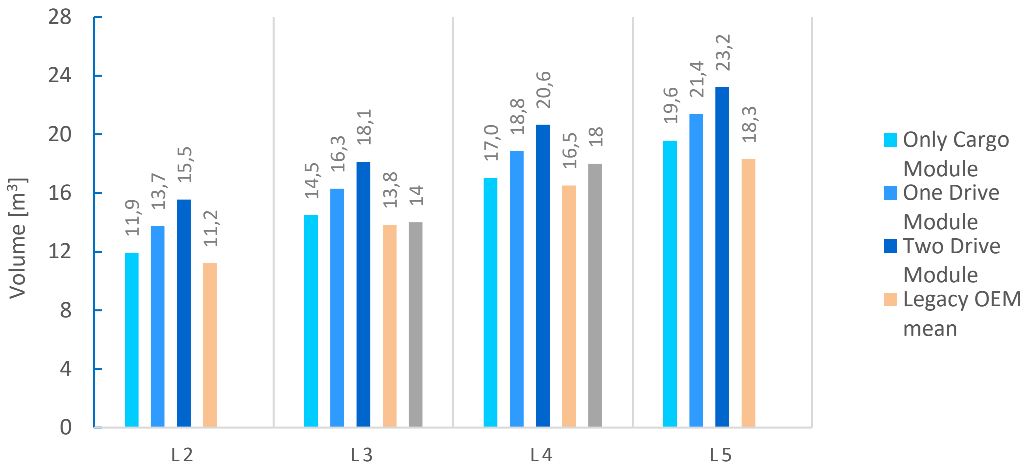

Figure 44 Modular vehicle overall cargo volume whit roof height H3 as function of length class

Also, for the configuration with high roof the same trend is repeated for the results, showing a slight advantage for the vehicle already proposed in the basic configuration.

Turning circle wall to wall

An important indicator for vehicle manoeuvrability is the minimum turning radius to perform a complete U-turn.
Generally you can find two values as shownd in figure 45, one that measures the overall radius that the vehicle needs to perform the manouvre called wall to wall and another that instead considers the dimensions at the wheel axle called curb to curb.

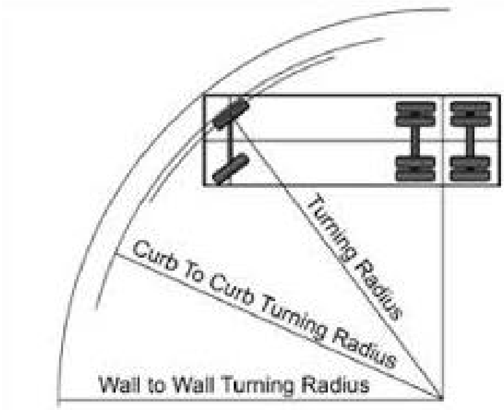

Figure 45 Turning radius definition

In the graph proposed, the value indicated refers to the diameter of the turning circle in the wall-to-wall condition.

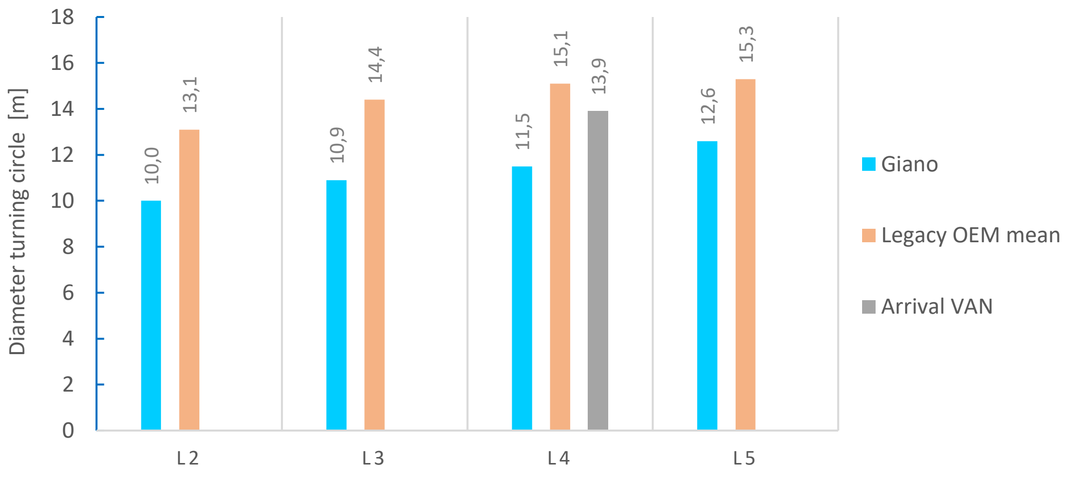

Figure 46 Comparison turning circle diameter as function of length class

Thanks to the four-wheel steering the turning circle is greatly reduced, this allows it to compensate for the long wheelbase.

Sill height

The height from the ground of the loading surface can be summarized as the sum between the height from the ground and the sill thickness.

In traditional vans this height does not vary much and depends only on the compression of the shock absorbers due to the transported load. For the modular vehicle, thanks to the variable height system, when the vehicle is parked, it is possible to place the cargo module on the ground, reducing the height to be overcome only to the thickness of the floor structure.

Considering the latter case, the next graph proposes the minimum height from the ground of the loading surface.

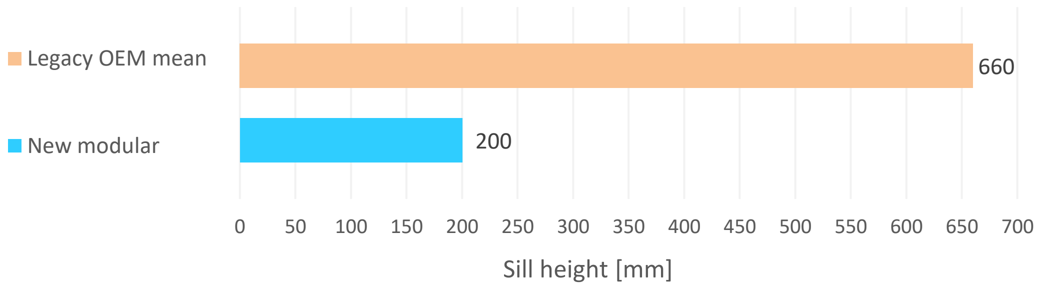

Figure 47 Comparison sill height

With a height from the ground like that of a normal step, entering the modular vehicle is much easier, plus if a ramp is included, it is also possible to get in with a pallet jack or a wheelchair as shown in the figure 26 of chapter 6.1.

7.2 Performance benchmark

Power and torque

For the legacy manufacturers the performance of electric vans is in line with the ice ones and the average is about 106 kW of power and 300 nm of torque, and for now only Ford offers a powertrain with a higher maximum output that reaches 198 kW and 430 nm.
Also, for the arrival van, the power is considerable at 150 kW.

For the proposed modular vehicle, considering that the drive modules must be able to move independently, a power between 70 and 100 kW per unit can be reasonable, bringing the total target to 140-200 kW.

Battery size

The dimensions of the batteries present greater variability between the various manufacturers and can be divided into two categories, the small ones dedicated to city use, like the 33 kWh Renault Ze-Master or the large ones such as the Ford and Fiat that are proposed with capacities of about 70 kWh.
Arrival offers four different sizes, 67-89-110-139 kWh, these battery packs have much more generous dimensions and are possible thanks to the vehicle's dedicated architecture.
Battery technology is continuously developing, and the products available on the market improve year by year, and an increase in energy efficiency leading to a weight reduction or an increase in the range.
The weight of the battery packs becomes a critical element for electric vans because if excessive, it directly affects the payload capacity.
For this reason, the modular vehicle will have a minimum battery pack for each drive module and according to the customer's needs the cargo module can be set up with different battery sizes.

8 MAIN SYSTEM DEFINITION

After having defined all the functions and dimensions that the modular vehicle must have, in this chapter, the main vehicle components will be analysed in more detail.

Since the vehicle proposed is a prototype, to reduce development time, research has been carried out to verify if the main components, that meet the performance requirements defined in the previous chapters, are already available on the market.

Carryover solutions are thus found for the powertrain, wheels and tires, and suite systems necessary for autonomous driving.

The systems geometries that will be developed are the suspension and steering system, the frame structures of both the drive module and the cargo module, and the coupling system between the modules.

CAD model development

For each component, a simplified version will be designed in a 3D CAD software to check the correct fit between the various systems.

The software used for modelling is Autodesk Fusion 360, thanks to its interface that allows the design of parts and assemblies in the same environment, it facilitates the construction of a model where components can change quickly.

8.1 Powertrain

Electric motor

The choice of the electric motor is mainly determined by the need to maintain balance of the drive module when is disconnected, and to do so an independent control between the left and right wheel is necessary.

It was therefore chosen to have two independent motors for each axis.
The advantages offered by this configuration are to increase the manoeuvrability of the vehicle both when the drive module is disconnected, allowing it to rotate 360° on its axis, and when the vehicle is coupled, allowing optimal traction control, torque vectoring, that leads to the execution of manoeuvres like the tank turn [23].

Another constraint of the drivetrain is given by geometric limits, because it must occupy the least possible space to allow the correct functioning of the suspension and steering system.

For this reason, after the research of vehicles already on the market that adopt this powertrain configuration at the front axle, two possible alternatives have been found, the first is the Rivian R1T pickup and the second is the Nevera supercar by Rimac.
Both these vehicles have a much higher power than necessary, but in this phase of the project it was preferred to focus on the size of the powertrain packages and on the arrangement of the various components that compose them.
The final choice fell on the Rimac unit, named AXL_560 [24], because the same manufacturer provides all the data of the technical specifications, and also free access to the technical drawings and 3D files.

Figure 48 Powertrain Rimac AXL_560

This e-axle includes two electric motors, the two black cylinders, two gearboxes placed on the external sides, in which the supports of the structure are also integrated, and in the upper part there is a box that contains an inverter for each motor to ensure optimal independent control.

The technical specifications of this unit are summarized in the following table [4].

AXL_560 specification	
Maximum power	2x220 kW
Maximum torque	2x280 Nm
Continuous power	2x180 kW
Continuous torque	2x190 Nm
Gear ratio	1:5.5
Weight	90kg

Table 4 Rimac Drivetrain AXL_560 technical specification

Knowing the size of the unit, it facilitated the positioning and construction of all the other components.
Considering that the Rimac motor far exceeds the target power of the modular vehicle, in the future the creation of a dedicated powertrain with the same dimensions but with less power should be possible.

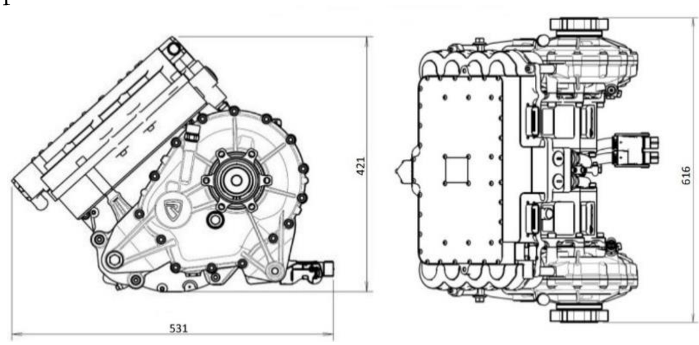

Figure 49 Technical drawing AXL_560

When designing the modular vehicle, a simplified unit of the model was used in order to reduce the overall size of the drawing file.

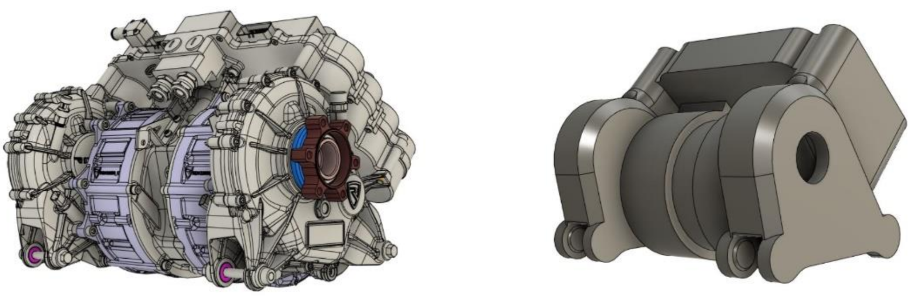

Figure 50 Simplified powertrain model

Battery pack drive module

Due to the reduced length of the drive module, the space available for the battery pack is compromised. Ideally the center of gravity should be as low as possible to improve the dynamic qualities of the vehicle, unfortunately this is not possible in the available configuration because the electric motor occupies the space between the wheels.

A possible solution would be to divide the battery pack into two parts and position it in front and behind the powertrain, managing to keep the masses in a low position. The disadvantage of this configuration is the dimensions of the battery pack, that would be considerably reduced, moreover for the modules positioned in the front, protection against an eventual accident could be difficult to manage.

For this reason, it was decided to position the battery pack directly above the powertrain and ensuring that the center of gravity of the whole drive module is exactly above the wheel axle to facilitate its control when the vehicle operates in self-balancing mode.

To determine the achievable output, research has been done to identify which battery packs currently available on the market have the best performance .
The reference taken is the battery pack of the Tesla Model Y, which has a storage capacity of 75 kWh, weighs 437 kg, and has a total volume of 335 dm^3 [25]. The energy efficiency for the entire battery pack is 172 Wh/kg, while for the single cell it reached 260 Wh/kg. As far as volumetric efficiency, it reaches 224 Wh/dm^3.

In the future, different types of innovations can be integrated to improve the performance of battery packs.
The first relates to the performance of the battery cells, which year over year is continuously increasing, and could go up to the theoretical limit of 350 Wh/kg for the lithium batteries.
Another technology that is currently under development, are the solid-state batteries, which promise an increase in battery energy density and also to improve battery safety and allow faster recharging. The challenges for mass production are still many, such as high operation temperature, high cost and chemical stability [26, 27]. The first solutions are expected to hit the market in 2023, with more coming after 2025 [27].

Another area for improvement is to work on the packaging of the battery pack. The current approach is the so-called "cell-to-module-to-pack" to integrate the cells in modules connected in parallel or series and then to locate the modules in the battery pack enclosure.
A critical aspect is the cell integration efficiency, that indicates the loss of energy efficiency when passing from the single cell to the complete pack, and this is mainly due to the whole structure that must support the cells, the cooling system, the fireproof protection shields the and various wiring and connectors. The higher this value the higher the effective density of the battery pack allowing for a lighter and more compact solution for the same capacity.
The "cell-to-module-to-pack" is currently limiting the gravimetric energy density of the battery pack. The integration approach in the future is expected to shift towards the "cell-to-pack" integration, which skips the cell grouping into modules. This allows to improve the pack energy density or reduce drastically its costs by using a cheaper and less energy-dense chemistry but exploiting it at best with better integration.
The last evolution step in cells integration is the "cell-to-vehicle" approach. In this case, the cells are directly inserted into the car underbody effectively becoming part of the structure

[27]. The structural adhesive is used to bond the cells to the underbody floor panels as a honeycomb structure, giving an integral and structural function to the cells.

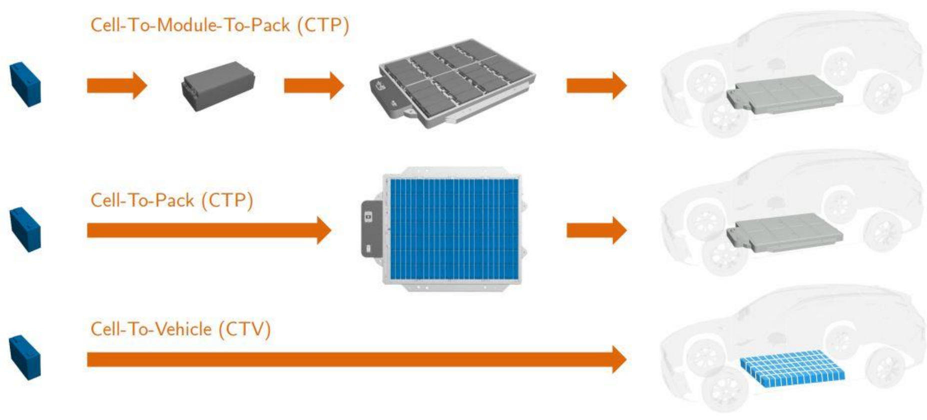

Figure 51 Comparison between different cells integration approaches [24]

These new approaches will allow cutting the cost and complexity of the battery pack while improving its energy density, thus reducing its mass and volume.

To maintain a conservative estimate, the reported results for the modular vehicle were calculated using the data of the Tesla Model Y as a reference.
Making a direct comparison with the space available in the drive module of the modular vehicle, the battery having the same resulting properties would have the following characteristics:
The space available in this configuration for the battery pack can be summarised as a parallelepiped 60 cm wide, 55 cm long and 45 cm high, leading to a final volume of 148.5 dm^3. The final storage capacity 33 kWh for a total weight of 194 kg.

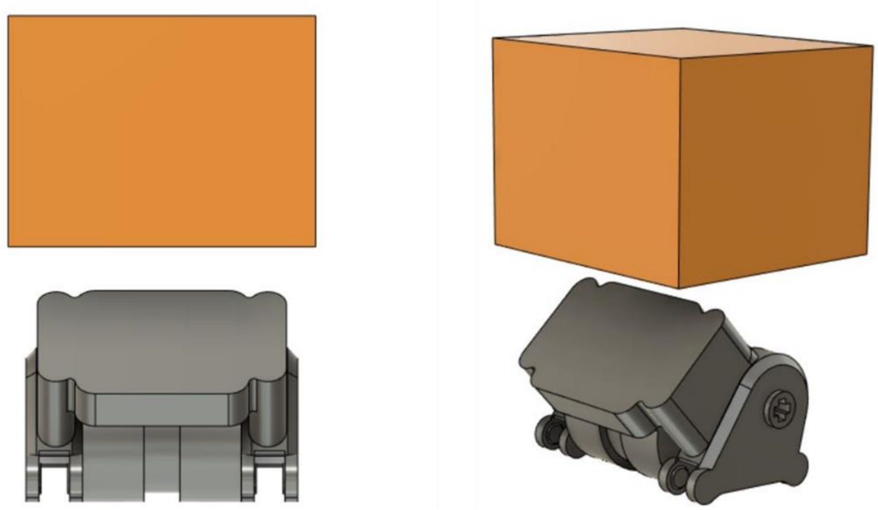

Figure 52 Battery pack available space drive module

8.2 Wheels and Tires

The choice of tires for a commercial vehicle mainly depends on the maximum weight they can handle.
On the market there are many types of suitable tires with different geometric dimensions, therefore a comparison between the various options has been made.

Data used include tires offered by legacy manufacturers vans, pick up and medium commercial vehicle. In addition, the catalogues of the main tire manufacturers were consulted.

One of the critical aspects is the size of the tire because their dimension defines the spaces available for other components such as bodywork, suspension, shock absorbers and steering. Figure 53 shows the scheme used to determine the final choice.

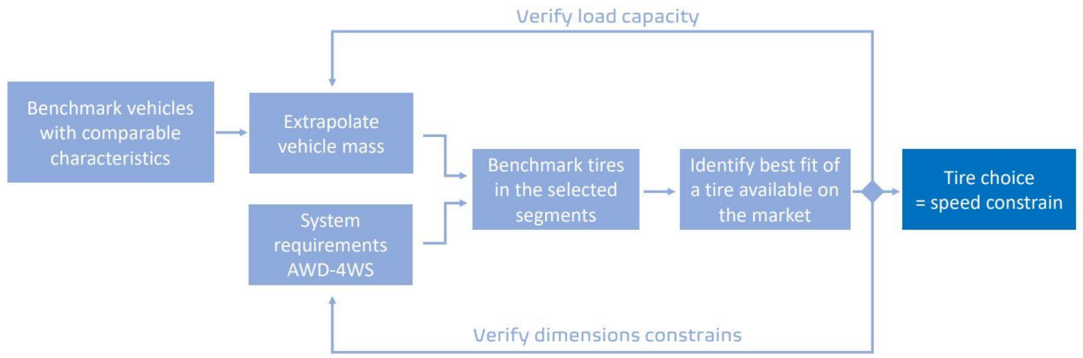

Figure 53 Logic scheme tire choice

From the analysis, the final tire choice is the Michelin Agilis 3 225/75 R16 121R which is the best compromise between its diameter of 744 mm, the width 255 mm and its weight capacity of 1450 kg [28].
Considering the four tires needed to circulate, the maximum capacity is 5800 Kg.

Figure 54 Michelin Agilis 3 Tire, photo and cad model

This Michelin tire was therefore taken as a reference for the final design of the tire. The rim, the brake caliper and the brake disc were also modelled, considering the right tolerances between the components.

8.3 Suspension ad steering design

Suspension

The suspensions are responsible for the dynamic driving characteristics of the vehicle, but for the modular vehicle they also have the fundamental function of controlling the height of the module and allowing the connection of the coupling systems.

The required objective is to have an excursion of at least 350 mm at the contact patch of the wheel, to bring the cargo module down to the ground.

To obtain this performance, it is necessary to design long suspension arms in order to reduce the variation of the camber angle during its entire excursion.
For this reason, the McPherson solution has been excluded, and only double wishbones will be considered.
A starting point is to look up to the geometries that off-road vehicles use, in particular the Baja pick-up and Ultra4. An example of this solution can be seen in figure 55 which shows an aftermarket suspension mounted on a Ford pick-up F150 Raptor.

Figure 55 Custom Ford F150 double wishbone front suspension

Taking these solutions as a reference point, a customized suspension will be developed considering the dimensions of the powertrain on the internal side and of the wheel unit on the external one.

Steering

Since the vehicle is made up of two identical drive modules, both will have a steering system. This feature makes it possible to compensate for the loss of manoeuvrability given by the long wheelbase to the vehicle.

The steering angle is limited by the maximum angle at which the CV joints of the semi shaft can operate.
Looking at the vehicles available on the market, a maximum steering angle for the inner wheel is about 45 deg, and this value has been taken as a goal.

There are several strategies that can be used to design the kinematics of the steering angle, in particular to minimize wheel slip when making low speed cornering the Ackermann geometry can be used.

The steering system chosen for the drive module is built around a rack-type pinion mechanism and a steering linkage mechanism controlled by a DC motor.
Figure [] shows a kinematic diagram of the steering mechanism: (0) chassis; (1) steering gear driven by gear motor; (2) rack; (3) left link; (4) right link; (5) left wheel; (6) right wheel

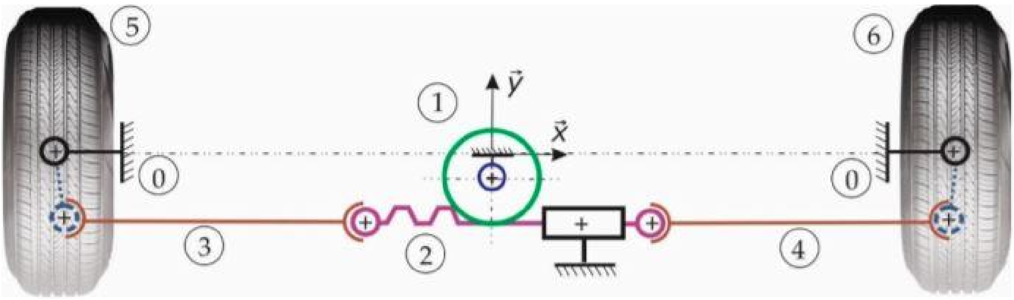

Figure 56 Steering configuration [29]

A potential development is to make independent the steering of the right and left wheel. Using two control motors and the rack and pinion mechanism, it becomes possible to independently adjust the steering angle, optimizing driving for every possible condition. This system fits well with that of the powertrain which, thanks to the independent control of torque and power on each wheel, further increases the effectiveness of manoeuvres while driving.

Suspension and steering design

The starting point for the design of the suspension is to work first with the plan views and then check the operation in the three-dimensional part.

The first work area is the front view of the suspension, where the track of the vehicle has been defined, and knowing the dimensions of the tires and the powertrain, the pivot points of the suspension arms have been defined.

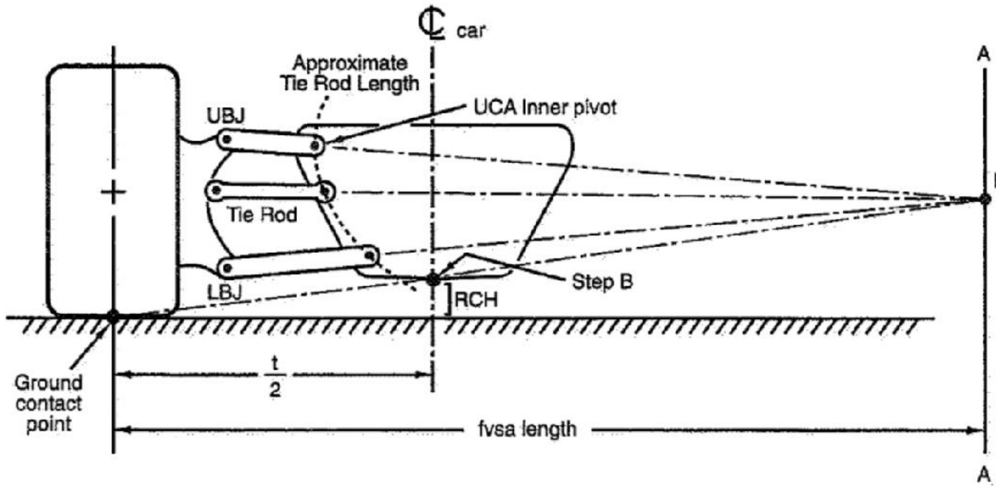

Figure 57 Fvsa suspension design [30]

In this view the front the design steps are:

a) Establish fvsa length (line A-A)
b) Establish the roll center height RCH and project from the ground contact point through roll center RC to line A-A establishing instant center IC.
c) Project lines from outer ball joints to IC (this becomes the centrelines of the upper and lower control arm planes),
d) Define inner pivot location to find control arm lengths.
e) Connect the tie rod outer pivot to IC Step
f) Establish tie rod length.

Following these steps it was possible to design a long stroke suspension suitable for the operation of the modular vehicle

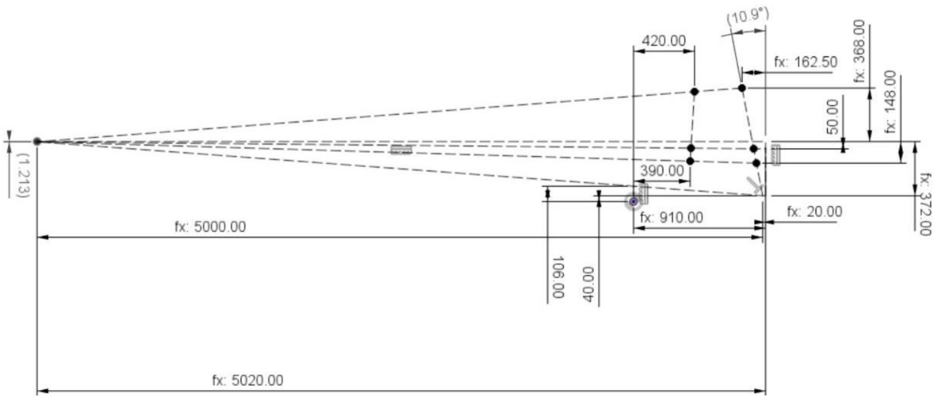

Figure 58 Modular vehicle suspension design Fvsa

Since there is only one model of drive module, it means that the suspension design must work in both directions of travel in the same way. For this reason, no anti-features were included in the design.

In this orthogonal view the attachment points of the suspension arms are identified in red and those of the steering system in yellow.

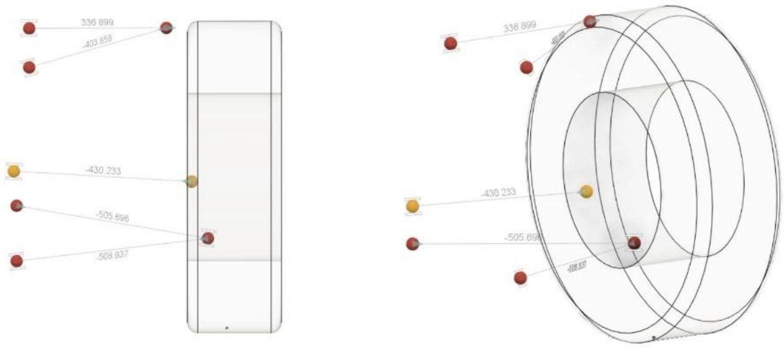

Figure 59 Suspension attachment points

To complete the geometry, the shock absorbers have also been included, the attachment points have the same conformation as the off-road vehicles, and the shock absorber length is congruent with the required stroke.

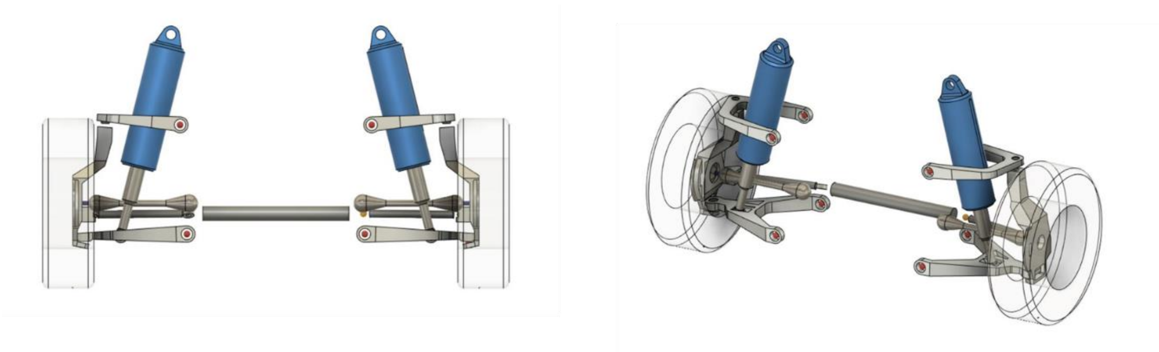

Figure 60 Full suspension drive module

All suspension components have been designed and positioned so as not to collide with eachother in any possible suspension position. In particular, when the vehicle is lowered to rest the modules on the ground, is guaranteed the necessary space to still have the maximum steering angle available.

For the suspension travel the goal was to do at least 400 mm of travel measured at the tire. As can be seen in figure 61 the effective stroke reaches this objective.

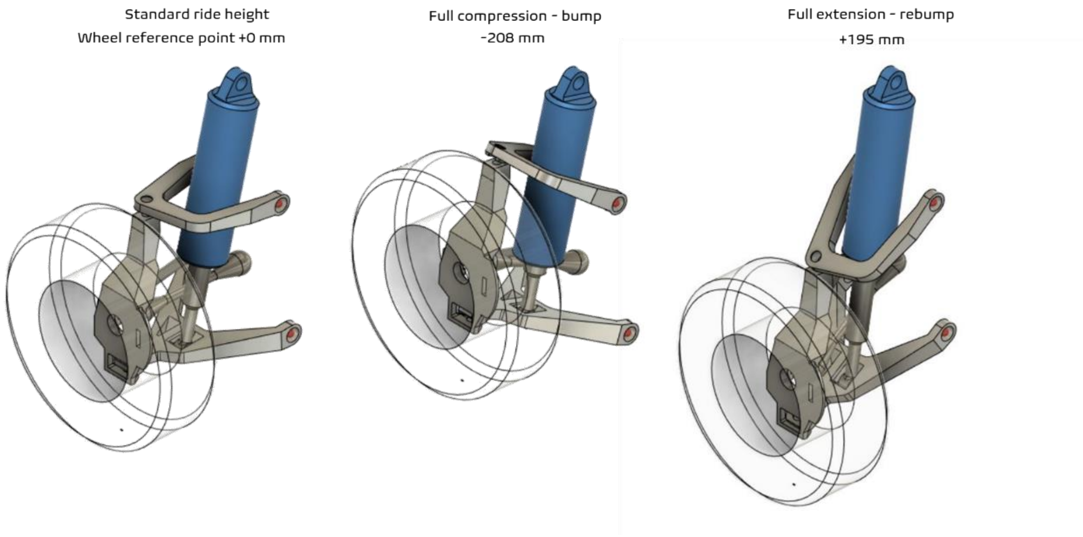

Figure 61 Extension wheel travel configurations

With long travel suspension one of the aspects that must be mitigated are the variations in the characteristic angles as function of wheel travel. An attempt was made to design a suspension with a behaviour as neutral as possible, to verify this a set of graphs are proposed where the variation of camber and track are compared as a function of the movement of the suspension.

Camber

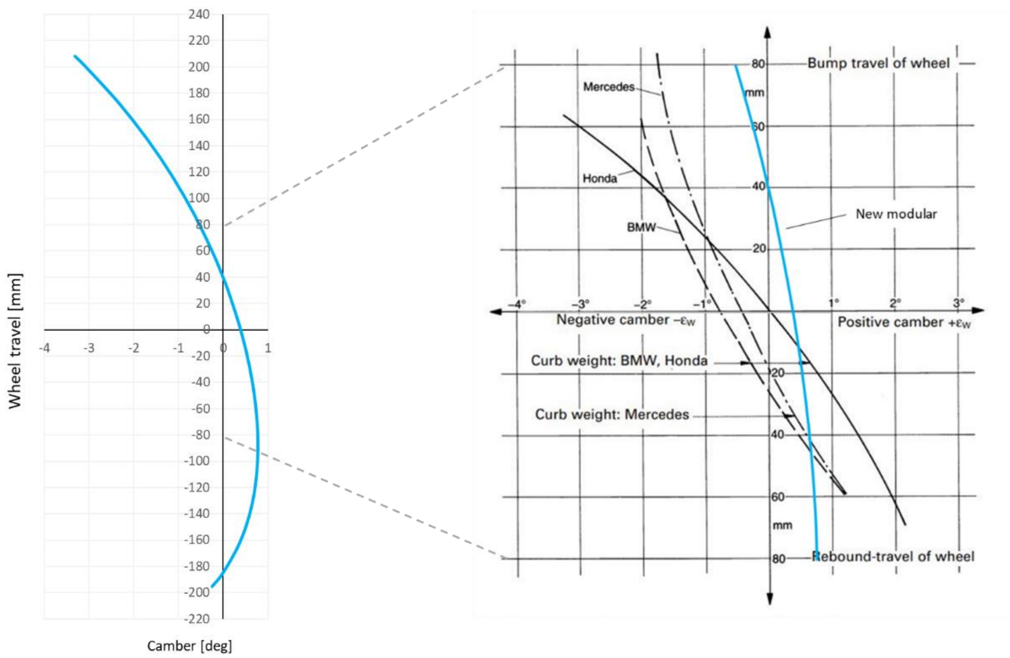

Figure 62 Camber alteration as function of wheel travel

In the graph on the left you can see the complete variation of the camper. In order to contextualize the result, a comparison with car models was made. Since cars have a much shorter stroke, an enlargement is shown on the right. this part of the stroke is however significant because it corresponds to the arc of use that is normally found on the road.

The cars compared are the Honda Accord which is equipped with front double wishbone suspensions while the Mercedes and the BMW have McPherson suspensions [31].
In any case it can be observed that the proposed design has less camber variation than the other suspensions.

Halftrack variation – scrub radius

Another aspect that comes from a suspension design with a long travel is the variation in the vehicle's track. An attempt was made to minimize this variation in the range where the vehicle is used the most, it was preferred to move the neutral point towards a compression situation to favour a lowered and more aerodynamic set up of the vehicle.

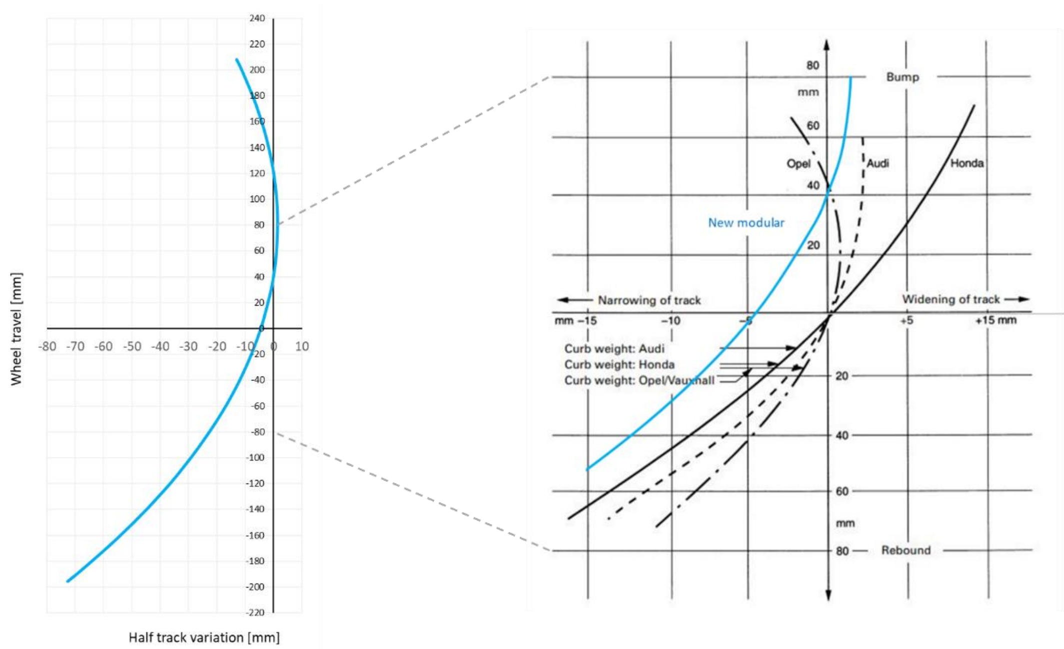

Figure 63 Halftrack variation as function of wheel travel

As before, the proposed suspension design has the least variation in track compared to other vehicles, and its range of motion its much greater.

Turning circle

The vehicle shown in the left of figure 64 has the external dimensions as the modular vehicle and the same maximum steering angle of the wheel set at 45 deg. In this way it can be seen the big difference in the turning radius between the solution with only one steering axle like traditional vehicles and the solution with four steering wheels.

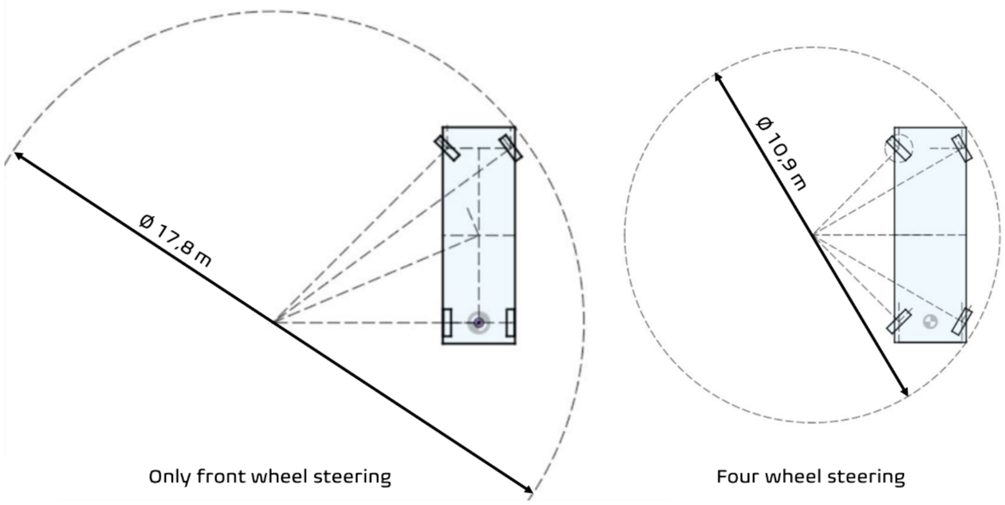

Figure 64 Turning circle reduction with four wheel steerinf

The class L3 with a wheelbase of 5 m sees a 39% reduction in the turning diameter, the final value of 10.9 m makes it competitive even with respect to much more compact vehicles such as cars.

The full geometry of the suspension and steering verifies both the maximum steering angle for the inner and outer wheel.

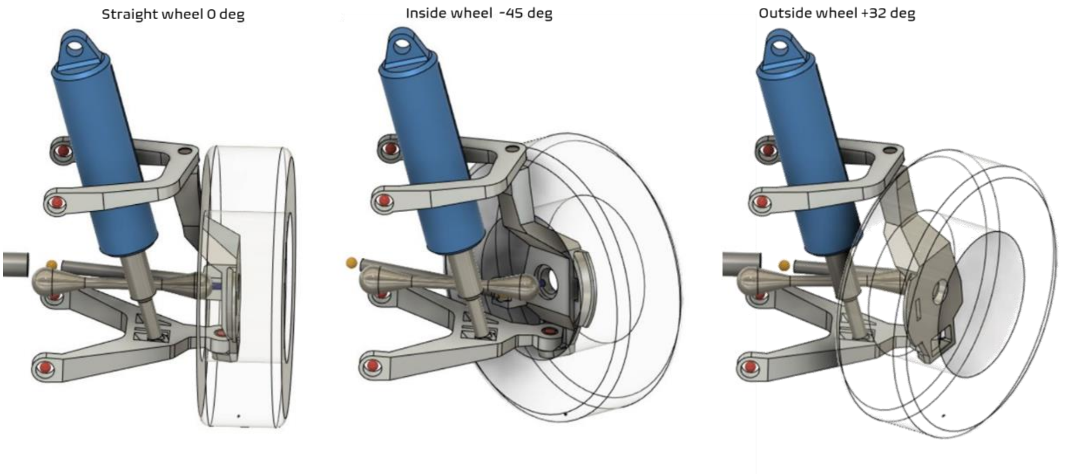

Figure 65 Maximum steering angle

8.4 Modular vehicle structure

8.4.1 Drive module structure

The chassis of a vehicle is of a very complex system given all the functions it has to perform. Among these, besides having to support all the vehicle components, it must also guarantee performance in terms of stiffness and shock absorption, as well as keeping production costs low by adopting a whole series of measures to make production easier.

Given the experimental nature of the proposed vehicle, in this phase of the design in which the dimensions and the position of all the components are still variable, it was decided to adopt a space frame tubular frame.
An example of these structures can be found in extreme offroad vehicles such as Ultra4 and Trophy trucks.

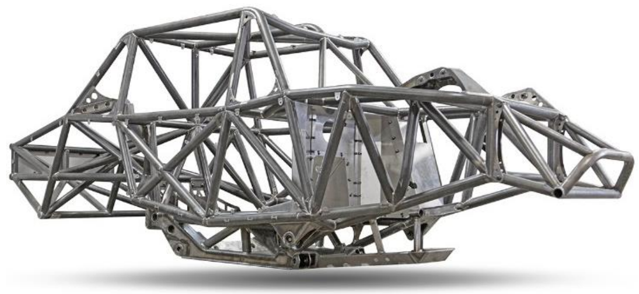

Figure 66 Ultra4 tubular chassis

The construction of this frame is simple and can be performed on a working table by welding the various tubes together. This technique has the advantage that it is very easy to make changes and additions to the structure. Furthermore, if the structure is triangulated sufficiently, its performance in terms of stiffness and weight are remarkable.
The chassis should therefore be as lightweight as possible, however, it should be justifiable in terms of cost, durability, climate impact etc.
The vehicle must be designed with regard to saving weight without substantially affecting the strength of the structure itself.
Tubular frames are not used for vehicles traveling on the road because they have significant limitations.
The labour for their construction is very intensive and this makes them suitable for the production of a few units, moreover the cost and construction time are high.
A second problem concerns the limited performance of this structure in terms of shock absorption capacity, making the pass of crash tests almost impossible.

In automotive the most used type of chassis is the body in white one, and it's an assembly of metal stampings, usually of steel but can also be of aluminium. Several material grades or alloys are used to meet the structural requirements at the formability needed to achieve the part shape. The stampings are assembled to form thin-walled structural elements.

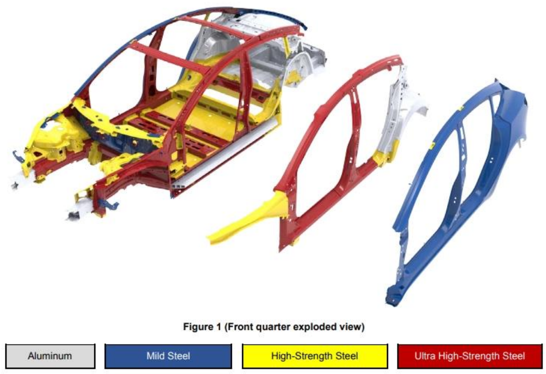

Figure 67 Tesla Model Y biw construction

A recent innovation introduced by Tesla is to use a die-casting for the production of the front and rear underbody, this drastically reduces the number of components and increases the precision of the assembly and welding of the following metal sheets.

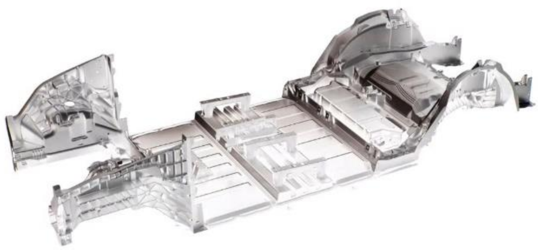

Figure 68 Megacasting Tesla Model Y

Sheet metal structures are more difficult to design so in this phase of the project they have been set aside even if they are a necessary step to bring the vehicle into production.

Drive module preliminary design

The solution chosen is to create a tubular frame for the structure of the drive module.
the starting constraints are the attachment points for the coupling system and the suspension attachment points.

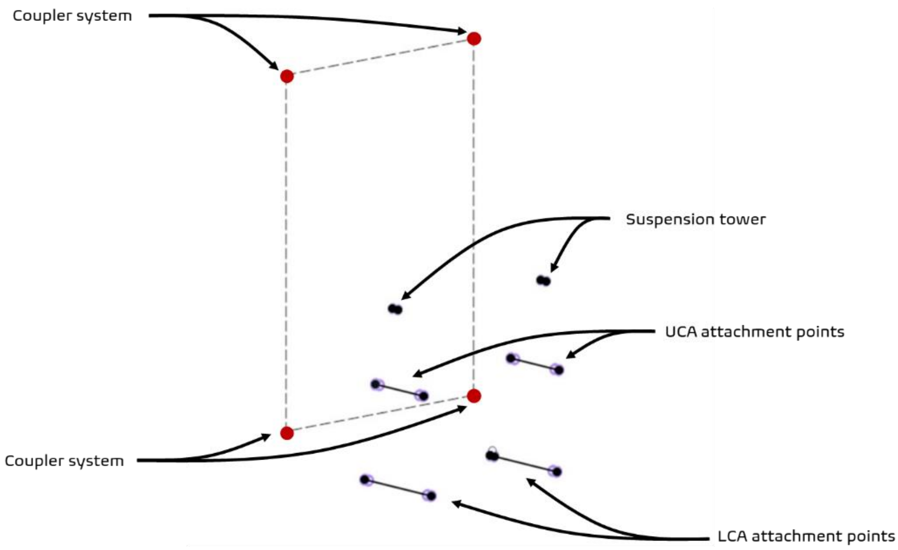

Figure 69 Chassis starting points drive module

From these initial points a structure was drawn taking in consideration the overall dimensions of all the parts of the drivetrain, suspension and steering.
The chassis should be designed in a way which makes it easy to get access to the electronics without having to disassemble the whole vehicle. This means that the powertrain, electronics, batteries and other associated equipment should have the possibility to be easily separated from the rest of the vehicle body.

The lines represent in geometric centres the sections of the tubes that will form the structure. The design is built in a parametric way so that each node of the structure can be quickly and optimally supported.

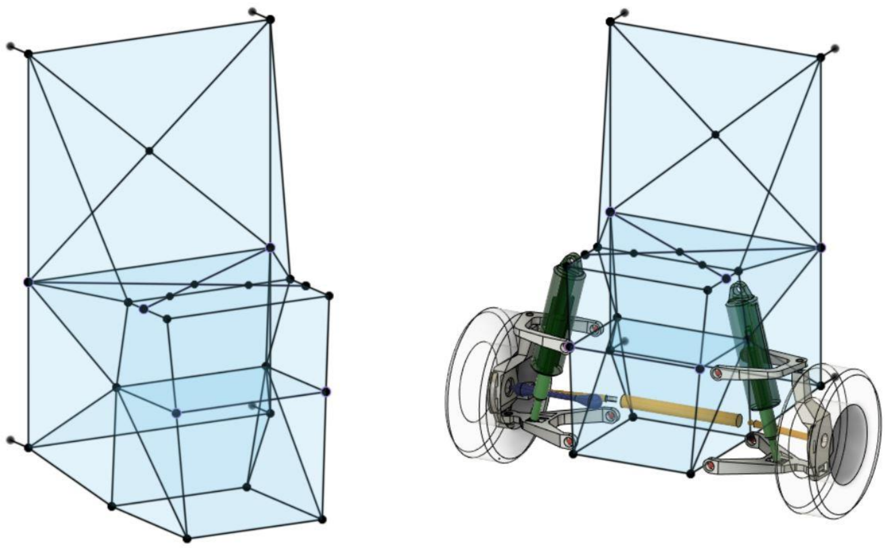

Figure 70 Drive module web structure

To verify that the overall dimensions of the poles leave enough space, a mock-up was made assuming the initial external diameters of the frame structure. The final dimensions will be determined by the fem analysis, and the drawing will be updated again, this is possible because the drawing is built in a parametric way so that each node of the structure can be quickly and optimally moved.

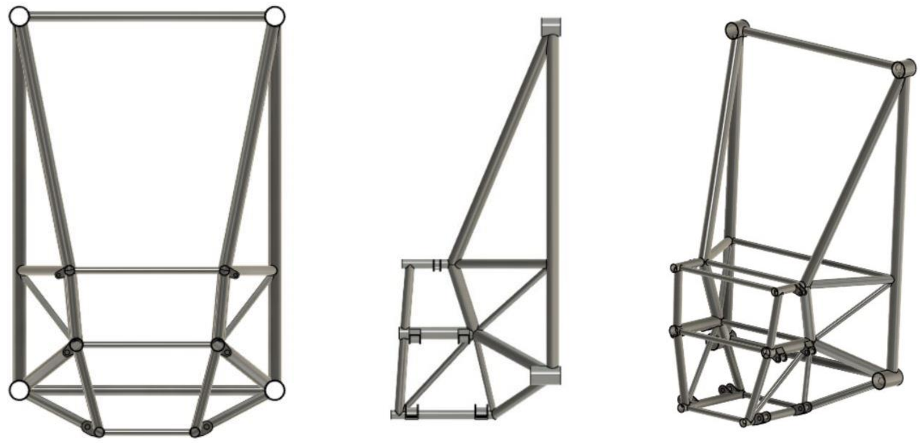

Figure 71 Initial mock-up drive module structure

8.4.2 Cargo Module structure

The structure of the cargo module must be designed in such a way as to leave as much space as possible for the transport of goods.

Many of the problems that the modular vehicle structure faces have already been solved by van manufacturers.
Belonging to the same vehicle class it is natural to see how the structures are built.
Generally they have two main rails that run for the entire length of the vehicle and all the other structures such as the cabin and the rear compartment are installed on top of these.

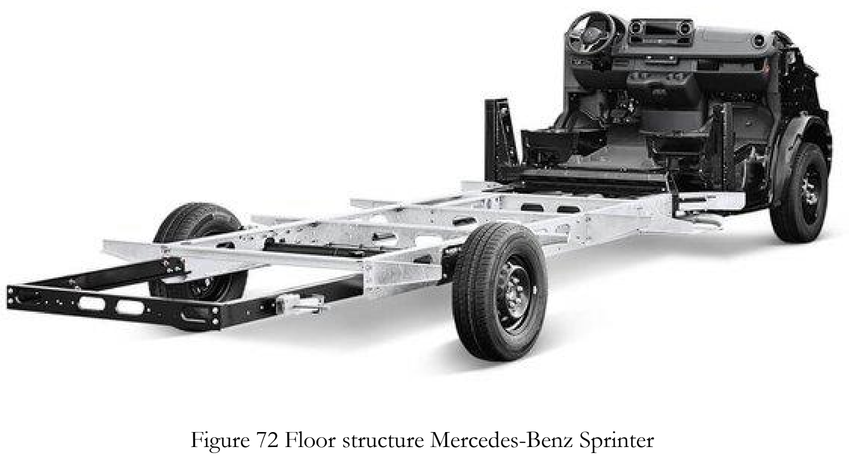

Figure 72 Floor structure Mercedes-Benz Sprinter

One of the characteristics of the vans is the variety of sizes and options with which they are offered. If we exclude the front part of the vehicle which tends to remain unchanged, the construction of the cargo part can be divided into six main parts, one for each side of the cuboid.

During the construction of a van the side structures are assembled separately and then joined by welding to the floor structure like in figure 73. Then the roof is installed on the top side and is generally both welded and glued to the sides. Finally the rear doors are positioned to close the cargo area.

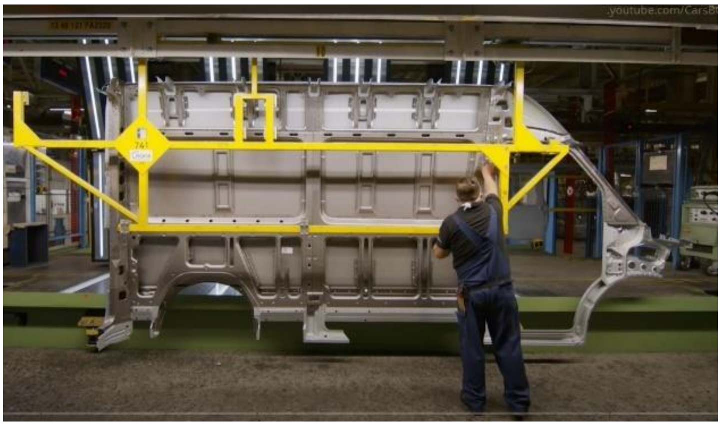

Figure 73 Side panel structure of a Mercedes-Benz Sprinter

Given the large load that the vans usually carry, in the floor structure the main rails are larger and thicker than those found on a car.

Since the cargo module has the possibility to have auxiliary batteries, the allocation of space for them is of great importance. These will be positioned on the floor starting from the center point and expanding outwards according to the selected battery pack size.

Access to the vehicle is another point of work for the structure of a van, this is because the doors leave enough space to allow large cargo to be easily loaded. This will compromise the performance of the structure.

Cargo module cad structure design

For the cargo module it is also necessary to consider its variability in the available dimensions, the structure must therefore be able to be quickly adapted with different lengths, widths, and heights.

At this stage the strategy adopted is to design the one that is thought to be the size of the best-selling module, based on the data collected on the search for vans.
In this way smaller structures will be oversized, while larger ones will need reinforcements.

The final model represents the modular vehicle in the configuration of length L3, height H2 and width W1.

Given the shape of the vehicle, the initial design points are the attachment points of the coupling system.
Looking only at the right side of the structure, since it is symmetrical, the attachment points of the coupler system are aligned vertically, so two pillars have been designed, and finally joined by a horizontal rail on the floor and one on the roof.

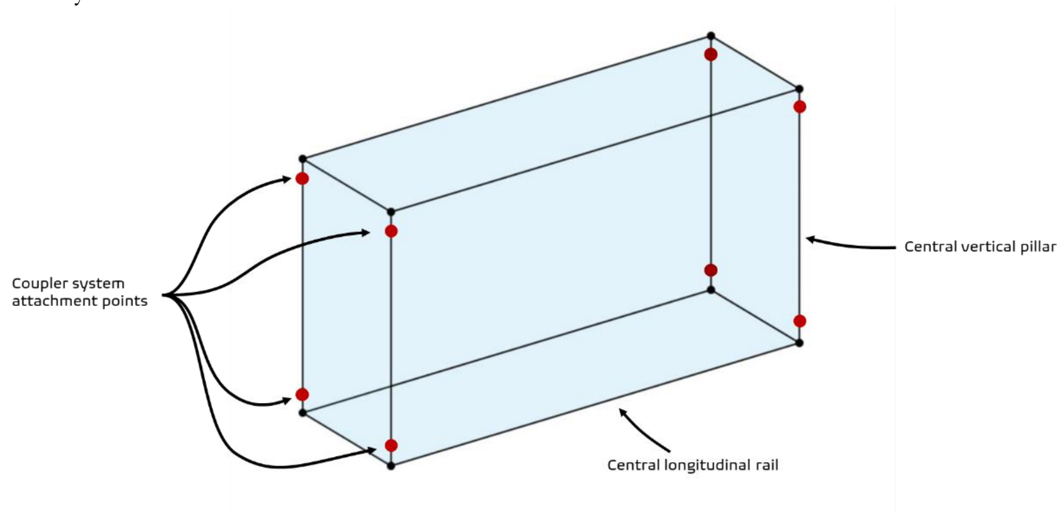

Figure 74 Cargo module initial web structure

This central part will be the heart of the structure, the lateral extensions will then be added to reach the desired width to which the side panels will then be attached.

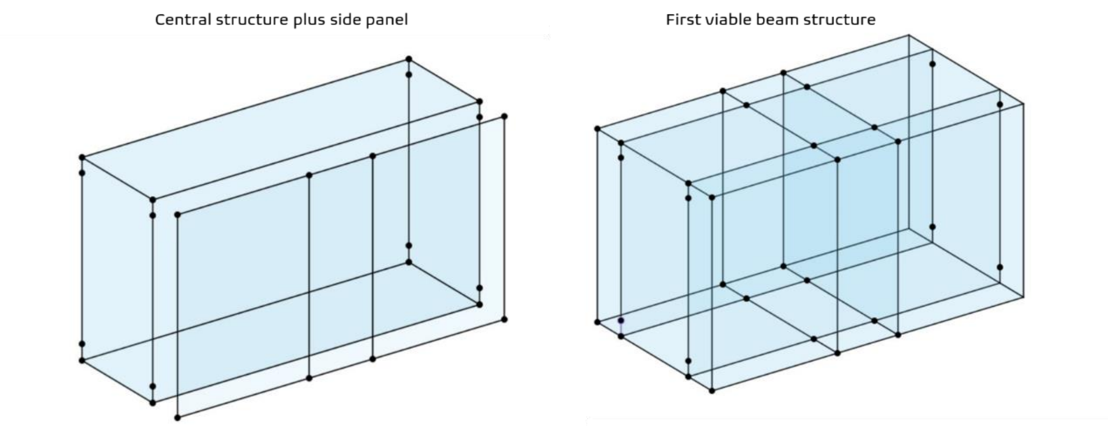

Figure 75 Cargo module intermediate design web structure

Finally, the reinforcement beam structures are drawn leaving the spaces for the doors are left open.

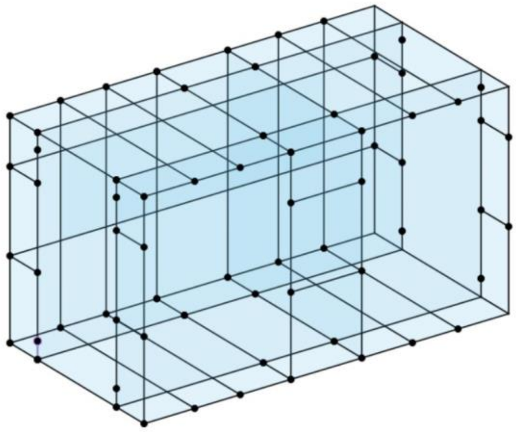

Figure 76 Cargo module final design web structure

In this structure, the sectional dimensions of the beams had to be considered to determine the position of the elements. The dimensions and thicknesses that are generally found in commercial vehicles have been taken as a reference. To verify that the structure actually works, it was decided to carry out a finite element analysis.

8.4.3 FEA modular vehicle structure

Since this is an early-stage analysis, the focus will be on the overall performance of the chassis structure, mainly in the bending stiffness performance, the torsional stiffness and modal analysis [31].

Cad setup
Having determined the global dimensions, the first step in the definition of the simplified CAD model that defines the spatial position off all the beam elements.

Since the objective is to obtain a synthesis model in the preliminary design phase the 3D sketch of the cargo and drive module are used. The construction lines identify the center of the cross sections of the various beam of the structure.
The model is then exported in Dfx format and imported in Ansys SpaceClaim.

Fem Model Development
Software used - Ansys suite
Ansys Workbench 2021 R2
    Set up the type of analysis and load cases.
Ansys SpaceClaim 2021 R2
    Used to define the main section of the imported beam structure and create necessary stitching between the surfaces and edges of each module of the vehicle.
Ansys Mechanical 2021 R2
    Analysis setting – connections between the suspension and couplers – define the forces and constrain type and position
    Simplified model - no welds and bonding connections
    Mesh setup
    the mesh continuous throughout the different structural components

Geometry Clean-up and Meshing

Each construction line of the structure of the modular vehicle was converted to a 1D element.
It's also studied the structure of the Cargo Module reinforced with surfaces 2D shell elements that represent the body exterior panels.
The set up include connections constraints between the suspension elements and for the couplers.

Mesh convergence study

The accuracy of the finite element analysis depends on the dimension considered for each single element that composes the mesh.
In this analysis was imposed that the size of the elements is constant for the whole structure. By decreasing the size of the elements, the accuracy of the final result will be greater, but it will lead to a greater calculation time. For this reason, it is necessary to do a trade-off between accuracy and computational time.

To determine the optimal size of the elements, a study is on the convergence of the results was performed. Convergence of total displacement and increase in CPU time in function of the elements size.
The used machine was a computer with an Intel ® quad core processor i5-4440 and 16 GB of RAM

The analysis was conducted using 60 mm, 50 mm, 40 mm, 30mm, 25mm, 20mm, and 18 mm elements. The latter its limited by the student licence that caps at 128k elements .

Element size	No. of elements	CPU time	Percentage discrepancy
60 mm	11631	45,3	0,32%
50 mm	14695	74,2	0,28%
40 mm	22295	156,3	0,15%
30 mm	35948	233,7	-0,04%
25 mm	49199	349,9	-0,02%
20 mm	74965	654,5	-0,01%
18 mm	91533	916,5	

Table 5 Mesh convergence study

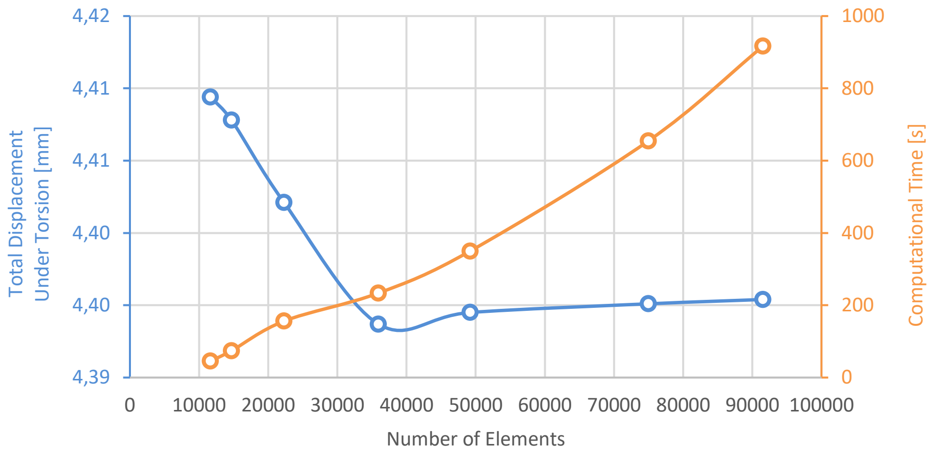

Figure 77 Mesh convergence study as function of number of elements and computational time

The final choice fell on the 30 mm elements because they represent the first point of convergence and require an acceptable calculation time. In any case, the difference between the various tests carried out is small, and this is justified by the simple geometry of the structure.

Another parameter that determines the reliability of the results is the mech quality [33]. Thanks to simple geometry almost all elements are quadrilateral ones (Quad4). Triangular ones (Tri3) less than 0.05%.
Element quality - average obtained 0.992

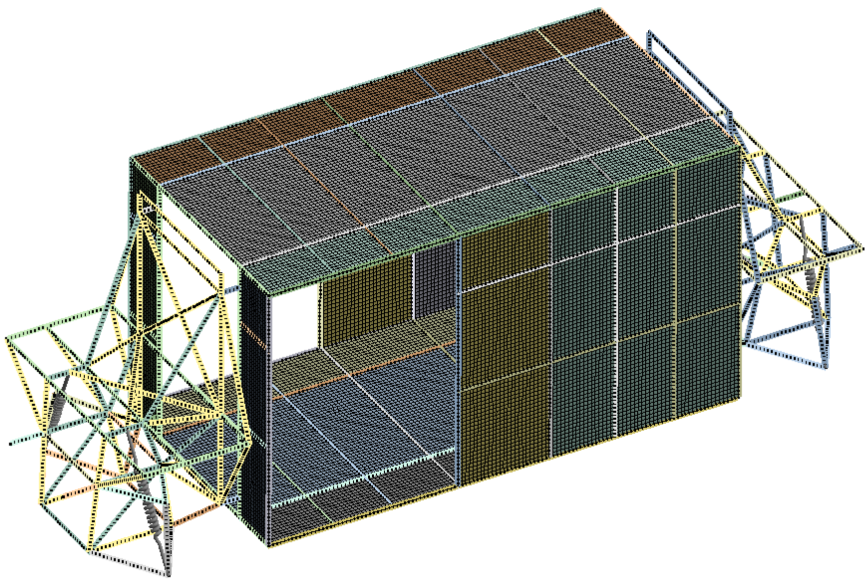

Figure 78 Modular vehicle mesh

Material Model

Being a preliminary design study, it was decided to limit the material variability.
Mild steel was selected as the base material for the structure because it is the standard for the light commercial vehicle industry.

The study it's a static linear and the material is homogeneous and isotropic and defined by: Young modulus E, Poisson's ratio ν, and material density.

Material – properties from dataset - From Ansys library

Property	Steel
Density kg/m^3	7850
E [GPA]	210
Poisson's ratio ν	0,3

Table 6 Material properties Ansys

8.4.3.1 Load Cases

Static analysis
The linear static analysis was conducted by applying bending and torsional load to assess the resulting displacements and evaluate the corresponding values of bending and torsional stiffness.

Dynamic analysis
The dynamic analysis was performed to assess the first three modal resonance frequencies of the chassis, with particular attention to the 1st.

Desired Target Outputs
Bending stiffness
Which relates the symmetrical vertical deflection of a point near the centre of the wheelbase to multiples of the total static loads on the vehicle. A simplified version of this is to relate the deflection to a single, symmetrically applied load near the centre of the wheelbase.

For a LCV that has a long wheelbase and that carries large loads the bending stiffness criteria should be more difficult to overcome that the torsional stiffness, for a passenger car usually it's the reverse.

Criteria
Customer testing in ride mules, have shown that, to achieve the feeling of solidness, a desirable range for vehicle bending frequency is from 22–25 Hz [34].
Vehicles which have higher mass loading (highly optioned luxury cars for example) or cars with long overall length (four-door sedans vs. two-seat sport coupes, for example) will require higher static bending stiffness to achieve the same frequency target.

$$\omega_n = 22.4L^{-\left(\frac{3}{2}\right)}\sqrt{\frac{Kl^3}{48M}}$$

$$\omega_n = \frac{22.4}{\sqrt{48}}\left(\frac{l}{L}\right)^{\frac{3}{2}}\sqrt{\frac{K}{M}}$$

l =Wheelbase 5m
L = Overall length 6.3 m
M = Rigidly mounted mass - 5800x0.6=3480kg
K = Required bending stiffness of the body
ωn = Desired bending resonant frequency for the vehicle (rad/sec) 23.5Hz

It's possible to compute the required bending stiffness knowing the vehicle data.
Rigidly attached masses are those which participate fully in the vibration of the body structure and do not include those masses which are isolated with bushings
For preliminary design, the rigidly attached mass is taken as 0.6 times the vehicle curb mass considering the vehicle type of electric LCV [32].

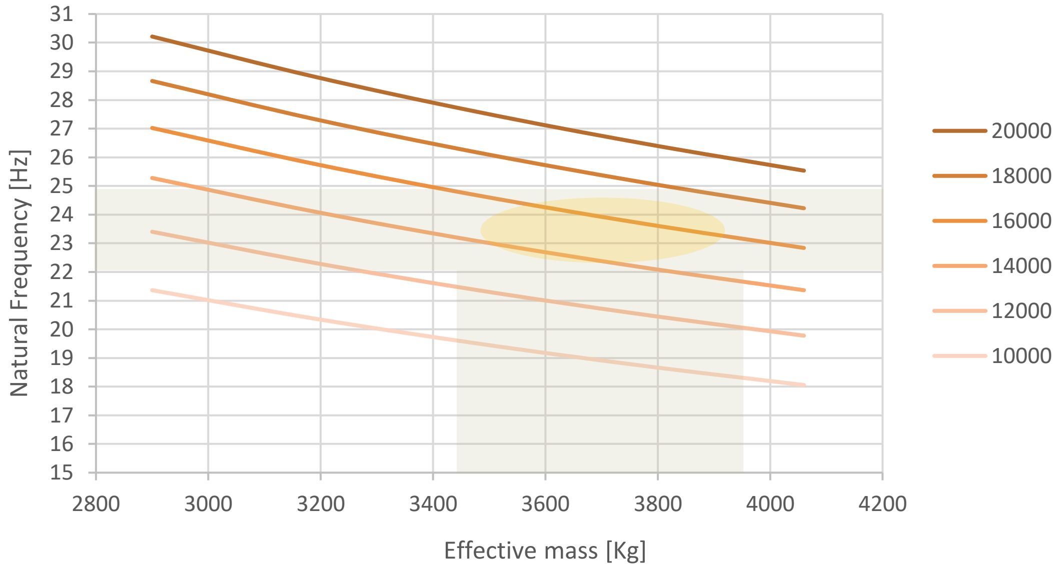

Figure 79 Bending stiffness target area

Bending stiffness target Kb > 14500 N/mm

Door opening criteria
Another criteria that can be adopter for, the bending stiffness is determined by the acceptable limits of deflection of the side frame door apertures [35]. If excessive deflections occur then the doors will not shut satisfactorily, i.e., the alignment of the door latches are such that doors cannot be opened or closed easily. Local stiffness of the floor is important for passenger acceptance.
The aim is to avoid excessive deformation that could cause noise (squeaks), leakage of the seals, and malfunctioning of the lock and hinge system [36].
Target for door frame deformation under 2.5 mm for the full loaded vehicle.

Torsional stiffness

The torsional stiffness is one of the most important properties of chassis since it significantly affects the dynamic characteristics such as handling and rollover. A high torsional stiffness is desired, otherwise it may cause resonance or vibration [37] [38].

Relates the torsional deflection θ of the structure to an applied pure torque T about the longitudinal axis of the vehicle. The vehicle is subjected to the 'pure torsion load case' where the torque is applied as equal and opposite couples acting on suspension mounting points at the front and rear, and the twist θ is measured between the front and rear suspension mountings. Twist at intermediate points along the wheelbase is sometimes also measured in order to highlight regions of the structure needing stiffening.

First resonance frequency

For the dynamic performances it is crucial to avoid the excitation of suspensions resonances, usually in the range 15-20 Hz, and cabin cavity resonances, in the ranges 50-70 Hz and 120-140 Hz. Thus, the first mode resonance frequency should be higher than 40-45 Hz and avoiding resonance of the cabin panels in the previously mentioned critical cabin ranges.

Bending load case

Remote displacements applied in the wheel contact patch with the terrain, for the rear ones all the displacements xyz are locked, but the structure is free to rotate on the wheel axis.
For the front wheels only the vertical displacement is locked, to prevent the vehicle from rotating on itself.

Vertical load applied on four beam nodes in the center of the cargo module floor, as shown in figure 80, and the total applied force is 40000 N, equally distributed between the nodes.
This value it selected considering that expected maximum load for the central cargo module is in the order of 4000 kg, and the maximum weight for the entire vehicle is set to 5800 kg.
The load of the drive modules it is excluded from the analysis because the position of its center of gravity is above the wheel hubs reducing the influence in the overall bending given the constraints position.

Vertical displacement Δz
The detection of vertical deviations was measured at various chassis positions. For the calculation of the bending stiffness the points in correspondence of the force application and the points on the door sills were considered.
Moreover, the displacement deviation on the whole door frame was measured to verify the ability to open the door even when the vehicle is fully loaded.
Knowing forces and displacements, it is possible to obtain the bending stiffness as:

$Kb = F/\Delta z$

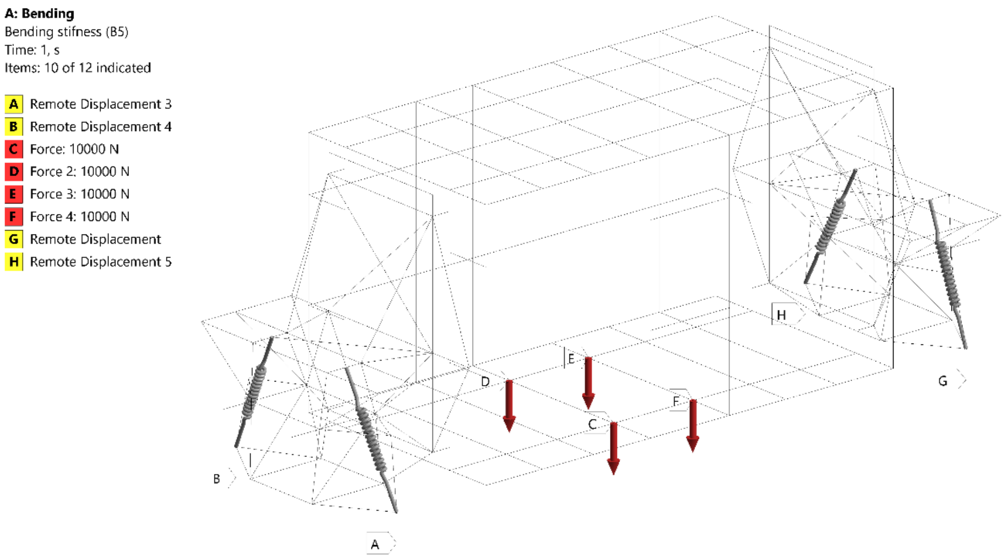

Figure 80 Forces and constrains set-up for bending test

Pure Torsion load case

To constrain the structure, the recommended method [37] was followed which involves completely locking of the rear displacements at the lower control arm.
At the front LCA, only the frontal movement is locked.

A couple of forces applied on front wheel hubs to create a bending torque on the front axle. The magnitude is not determinant for the analysis since the desired output was the stiffness, but it is chosen to be the maximum possible to observe the deformation on the door frame. The maximum torque is based on the weight and the track of the vehicle axels:

- Track 1780 mm
- Axle load 28450 N equal front rear distribution

To assess the torsional stiffness, it is necessary to evaluate the angular displacement $\Delta\theta$ by knowing the vertical displacement Δz and the horizontal distance between the force application point.
In the study the force is applied in the external points of the LCA that have a horizontal distance of 1694 mm.

$\Delta\theta = \tan{-1} (\Delta z/l)$

With the derived $\Delta\theta$ displacement, the torsional stiffness Kt as a ratio of the applied torque T and $\Delta\theta$:

$Kt = T/\Delta\theta = Fl \tan{-1} (\Delta z/l)$

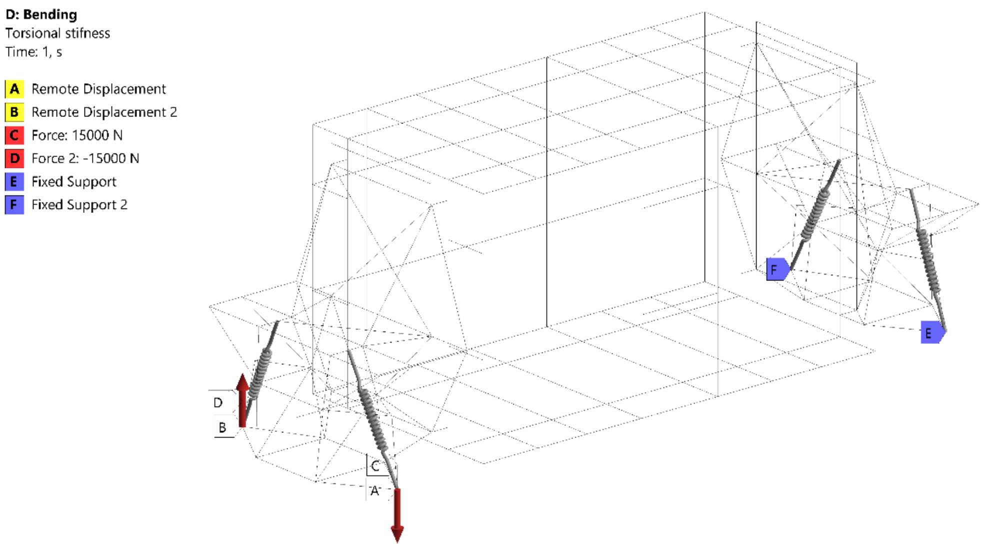

Figure 81 Forces and constrains set-up for torsion test

Modal analysis

For what concerns the modal analysis, a so-called “Free-Free analysis” was conducted, meaning with no constraints or loads being applied.
This type of analysis was selected to understand the modal behaviour of the unconstrained structure, as in the common practice of the industrial partner.
Since the structure is not constrained the first modes correspond to the six rigid body modes, usually with resonance frequencies close to 0 Hz.
Being these modes not meaningful it was necessary to exclude them from the analysis by setting the minimum frequency of the analysis at 1 Hz.
Thus, the first three modes above 1 Hz were extracted and evaluated to assess the general behaviour of the structure.

Geometry

A section and thickness have been assigned for each beam of the structure.

Drive module

Tubular construction the choice of the tube was based on the dimensions commercially available

N°	Beam Name	Shape	D1 mm	D2 mm	W1 mm	W2 mm	T1 mm
D1	Small tube	Tube	38,1	34,8			1,65
D2	Medium tube	Tube	50,8	46,6			2,11
D3	Large tube	Tube	76,2	70,1			3,05
D4	Cross beam	Rectangular			40	80	1
D5	Midrails	Rectangular			90	180	2

Table 7 Cross section dimensions drive module

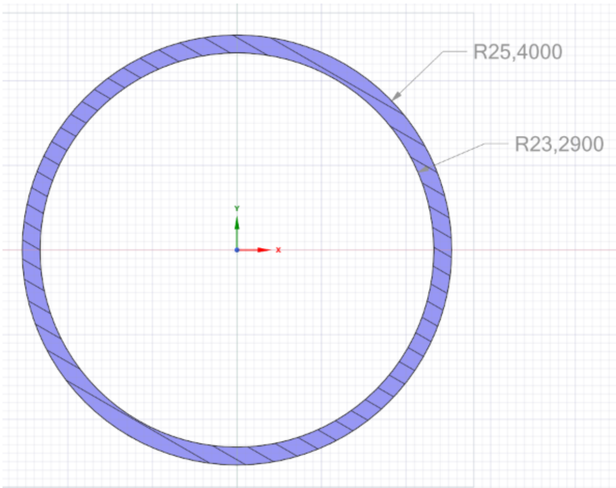

Figure 82 Example of tube section – D2 Medium tube

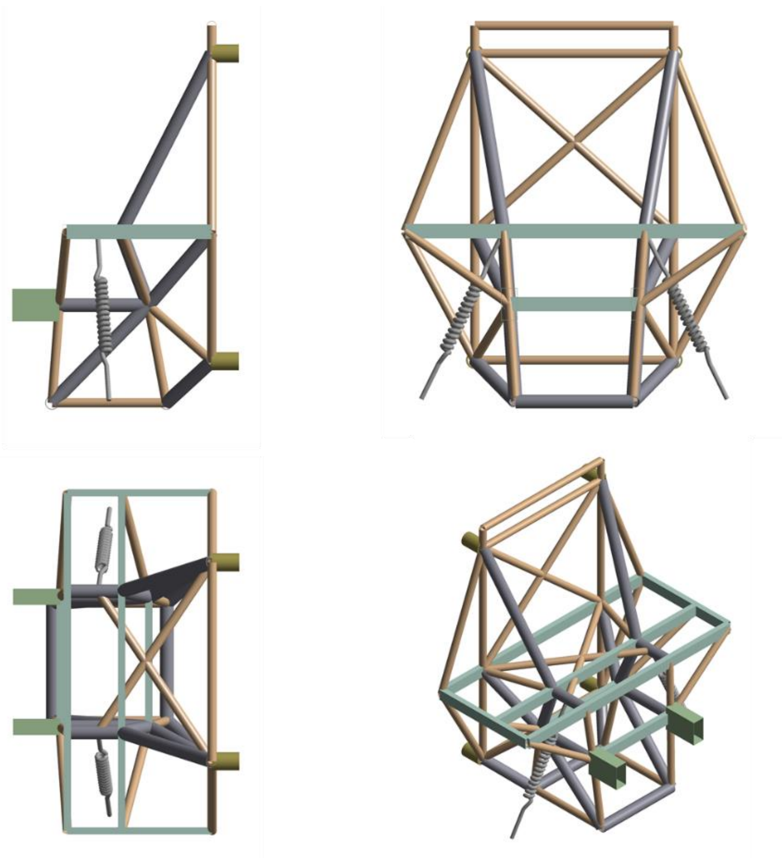

Figure 83 Drive module structure final cross section

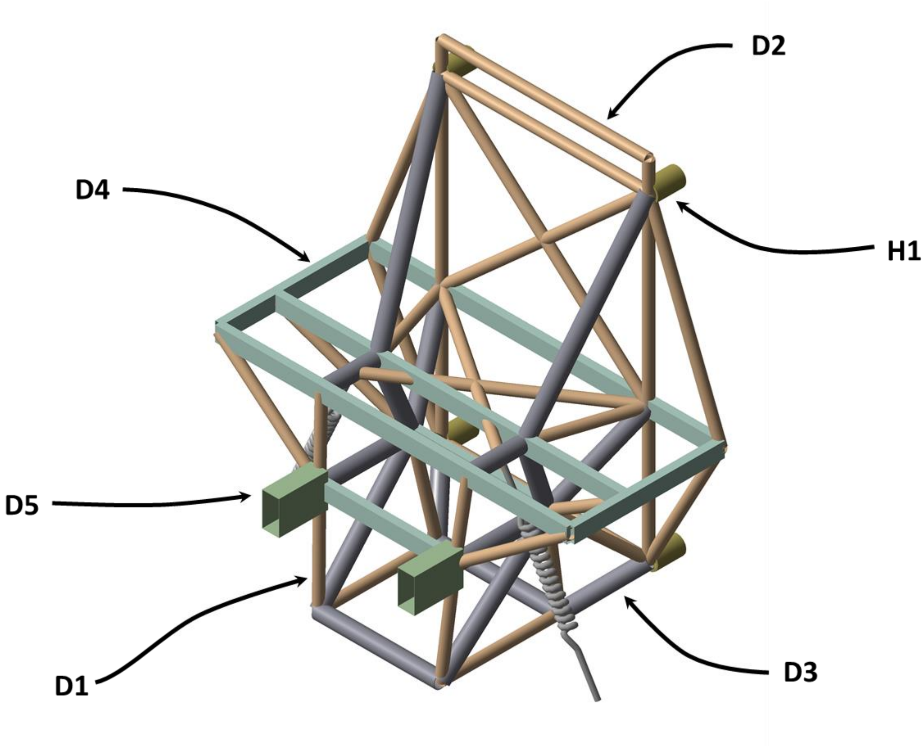

Figure 84 Drive module beam identification nomenclature

Cargo module

The starting dimensions of the beams are similar to those that can be found in a cargo area of an LCV.

In this analysis the shapes of the biw have been simplified, and in general they have a rectangular section.

N°	Beam Name	Shape	W1 mm	W2 mm	T1 mm
C1	Central Pillars	Rectangular	100	150	1,5
C2	Central Rails Roof	Rectangular	50	70	1
C3	Central Rails Floor	Channel	100	150	6
C4	External Pillars	Rectangular	170	100	1
C5	Rocker Floor	Rectangular	90	140	3
C6	Side Rail Roof	Rectangular	80	120	1,5
C7	Cross Beam Floor	Rectangular	90	130	1,5
C8	Cross Beam Roof	Rectangular	80	70	1
C9	Intermediate Pillars	Rectangular	100	60	1
C10	Longitudinal Side	Rectangular	50	90	1

Table 8 Cross section dimensions cargo module

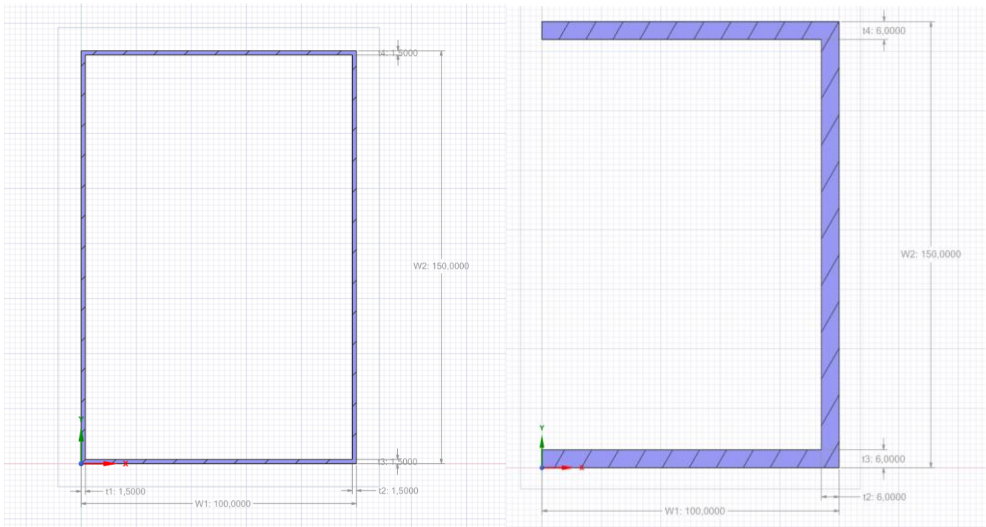

Figure 85 C1 and C3 beams cross sections

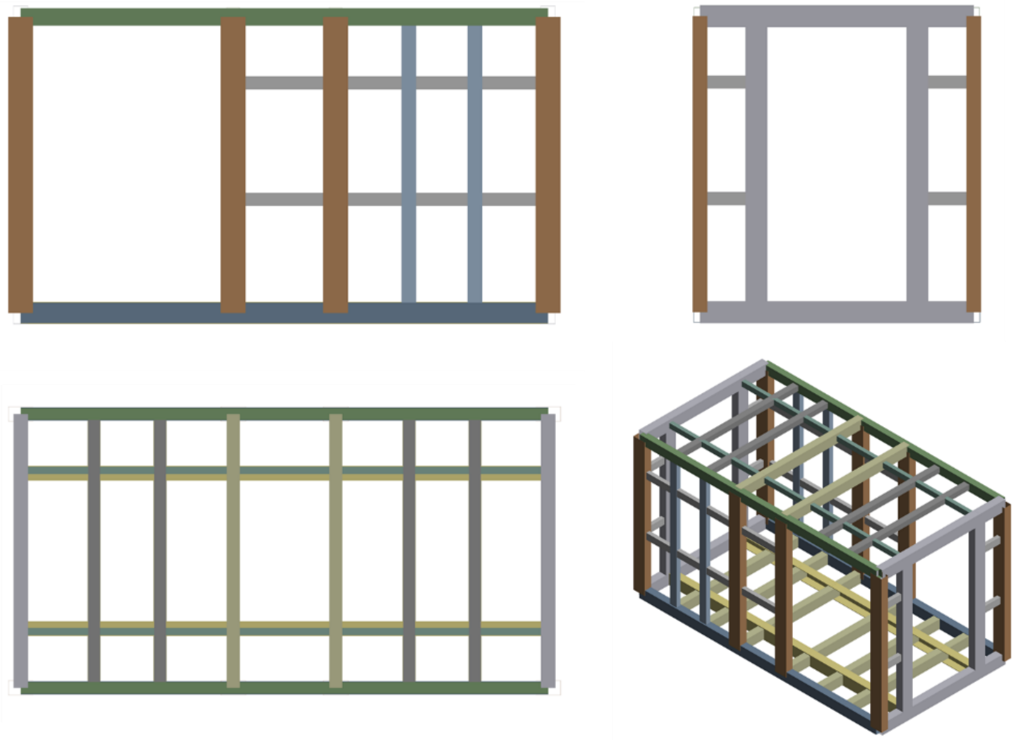

Figure 86 Cargo module beam geometry

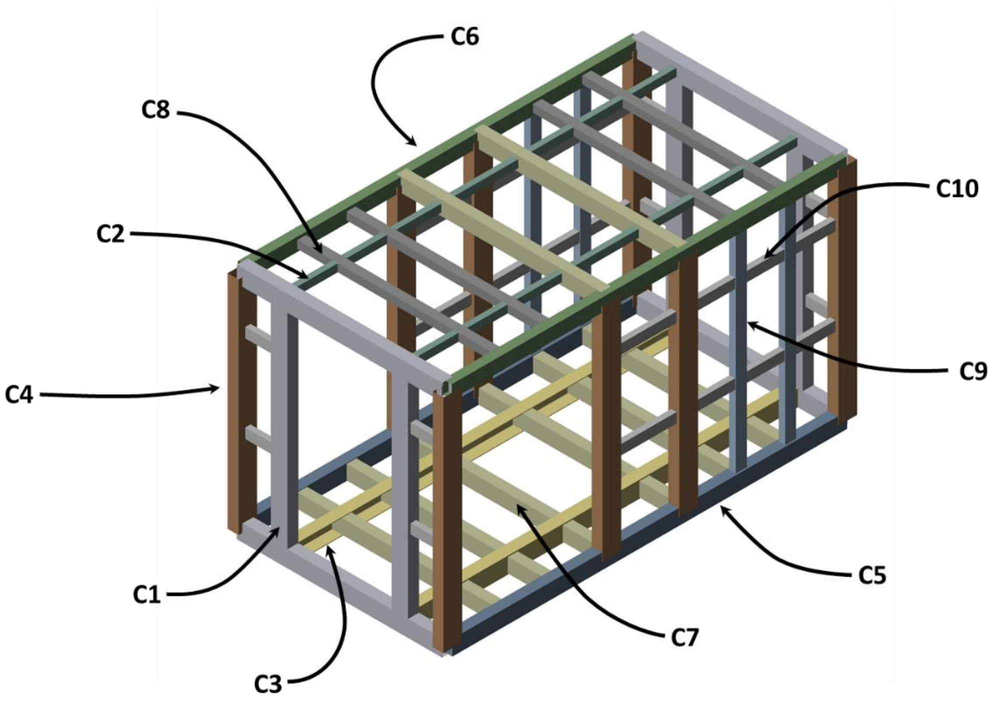

Figure 87 Cargo module beam identification nomenclature

Layout Variations

The variability of the vehicle was reduced to the cargo module only, leaving the drive module unchanged.

Door position

> To give a good customer choice flexibility but at the same time not compromise too much the performance of the structure, it was decided to limit the number of side doors that can be had as an option to two.

Body panel presence

> Note the increase in performance between the structure of the naked space frame and that with the entire bodywork.
> That's because the closed one could give an optimistic result in overall performance, given the nature of the simplified model which does not provide all the details of the union between the various elements.

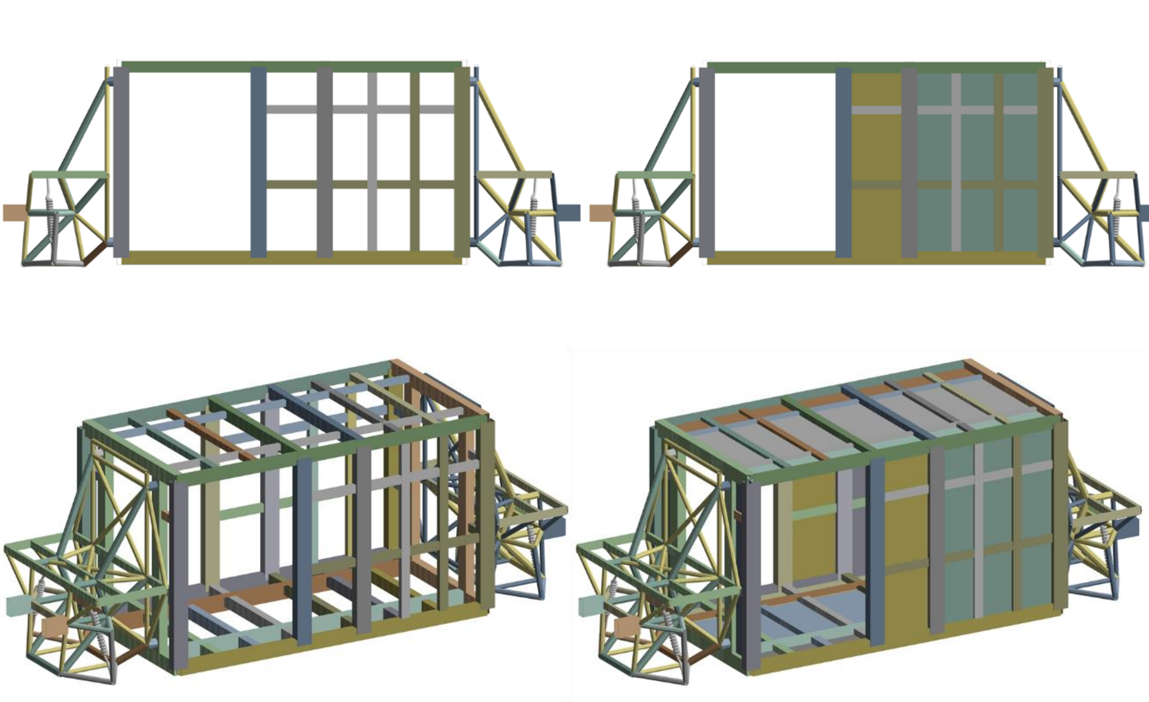

Figure 88 Double forward door configuration

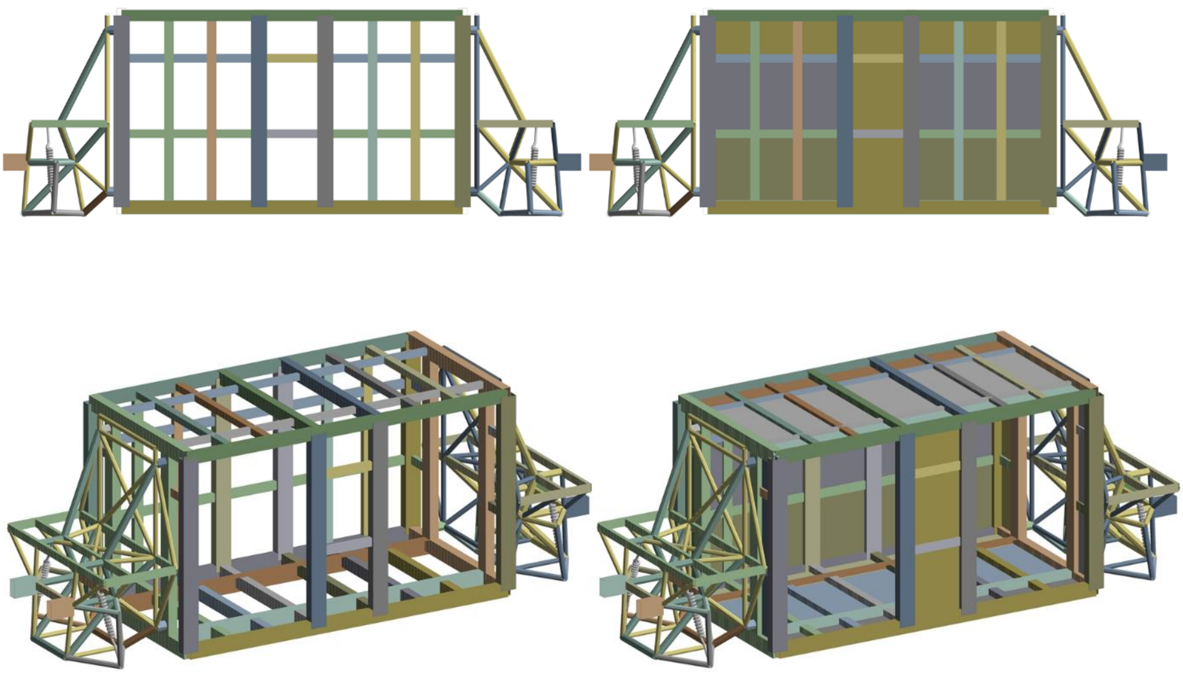

Figure 89 Double side door configuration

Complete model analysis

Mass

The first output of the analysis was the mass of the chassis structure in kg.

	Cargo Module	Drive module single
Double forward door with bodywork	694	149
Double side door with bodywork	694	149
Double forward door	535	149
Double side door	535	149

Table 9 Mass modular vehicle as fucntion of body congiguration

The results for the cargo module are in the expected range but on the heavy side, it must be remembered that the structure is very simplified, and the weight can be reduced with the same technique current LCV employ, which involves the use of lightening holes and stiffeners on all the beams of the structure.
For the drive module the weight its optimistic simply because it lacks the component needed to sustain the bodywork that in this analysis are not present.

Bending stiffness

In figure an example of the deformed structure under bending is shown. It was necessary to amplify it by 50 times to make it more appreciable.

Double forward door

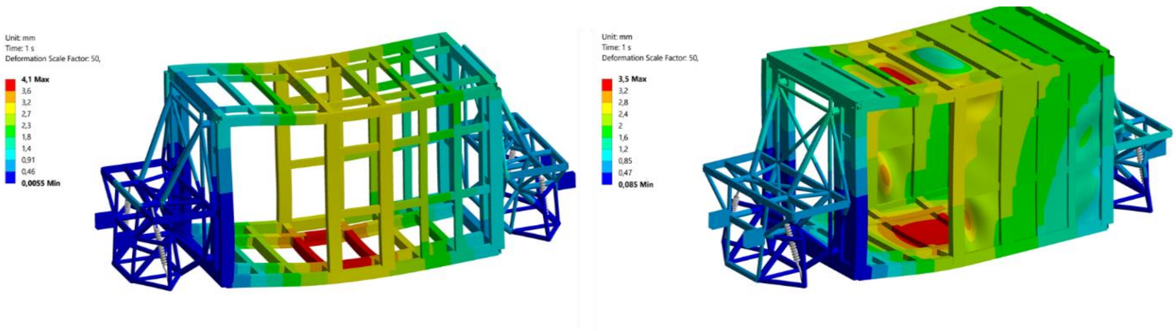

Figure 90 Bending stiffness results double forward door

Double side door

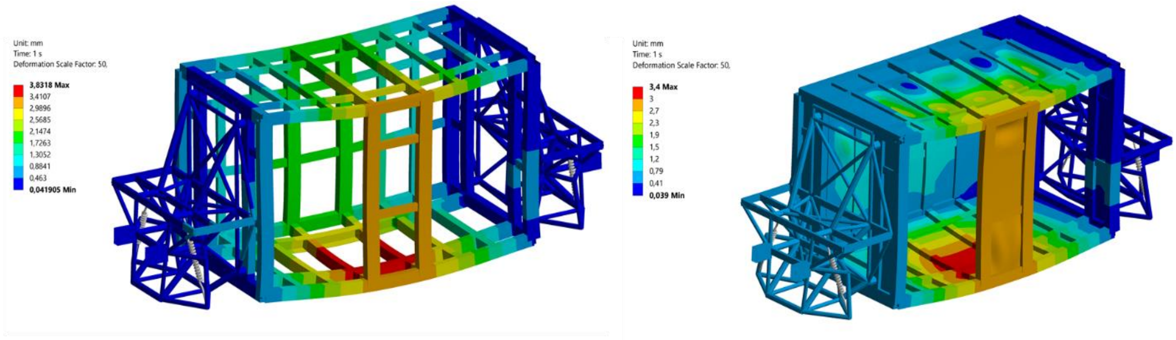

Figure 91 Bending stiffness results double side door

	Central rail	Rocker	Stiffness central	Stiffness rocker
	mm	mm	N/mm	N/mm
Double side door	3,2	2,4	12369	16349
Double side door + body	2,5	1,6	16207	25183
Double forward door	3,5	2,8	11396	14291
Double forward door + body	2,9	2,2	13769	18051

Table 10 Bending stiffness results as fucntion of body configuration

The obtained results for the bending stiffness measured on the rockers that is the standard for the automotive industry are in the expected range and even the worst result is close to the identified target Cap 8.4.3.1 of 14500 N/mm.

Furthermore, the second criterion chosen is that of the ability to open the door even when fully loaded, and it's identified by having the structure deforming less than 2.5 mm in the hinge locations. This test was not passed only by the naked double side door variant, which on the central pillar shows a maximum vertical displacement of 2.7 mm.

For the variant of the double side doors the structure bends in a non-symmetrical way with an increased deflection on the side near the door, the recorded values are the mean between the two central points on the cross beam near the door where the forces are applied. For the rocker points the total deflection is measured on the same cross beam.

As expected, the models with the additional panels show a significant increase in stiffness. Since this is a preliminary study, these results should be taken as a point of reference since structure is simplified at its maximum.
The lacks the detail in the connection (like welding, etc..) between the various panels of the biw lead to an overestimation of the overall performance, but this effect could be balanced by local reinforcing plates.

Torsional stiffness

Double forward door

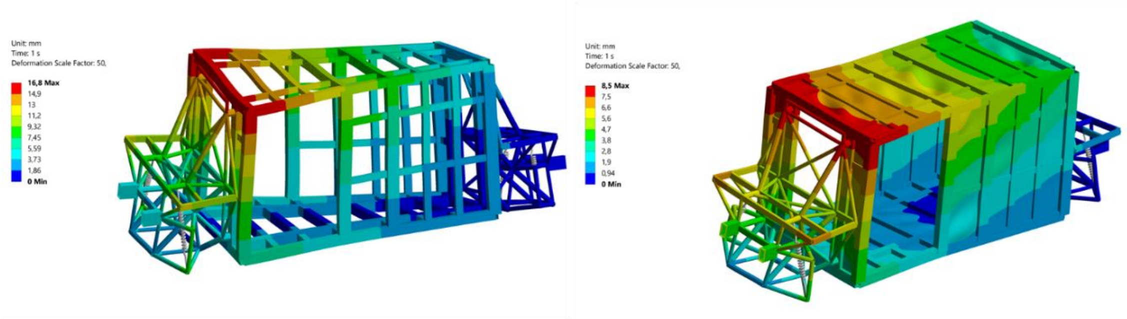

Figure 92 Torsion stiffness results double forward door

Double side door

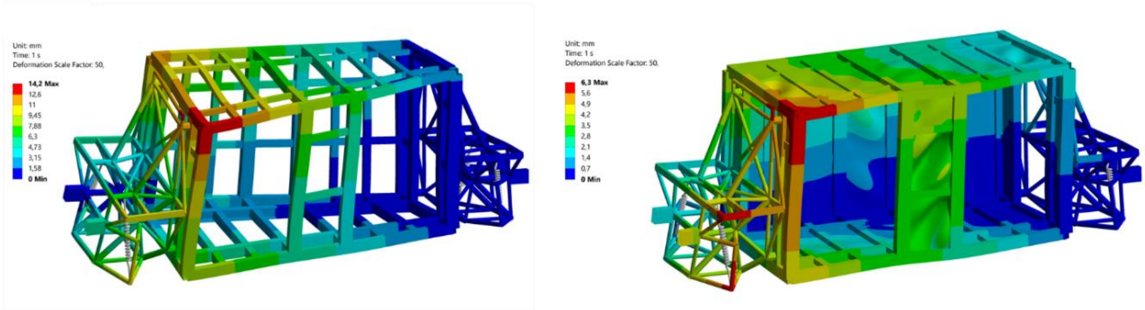

Figure 93 Torsion stiffness results double side door

	Torsion angle deg	Torsional stiffness Nm/deg	Torsional stiffness kNm/rad
Double side door	0,5	52948	3034
Double side door + body	0,2	121272	6948
Double forward door	0,6	44861	2570
Double forward door + body	0,3	91604	5249

Table 11 Torsion stiffness results as fucntion of body configuration

The results for the torsional rigidity of the structure with the body panels exceed the expected performance. This can be justified by the fact that these panels are perfectly flat and have no compound curvature which if introduced reduces their performance.

First modal frequency

Since to keep the design of the structure simple, flat panels have been used instead of curved ones, these will tend to resonate before any other part of the structure, thus leading to non-significant results.
Therefore, only the variants that do not include them were analysed.
The first three modes were calculated starting from frequencies higher than 1 Hz to exclude the first six rigid body modes.

	Double forward door Hz	Double side door Hz
First mode	25,6	25,0
Second mode	38,2	40,1
Third mode	40,4	43,0

Table 12 Modal frequancy as function of bosy configuration

These figures show the amplified deformations for the first three modes and have been ordered by the final shape that the deformed structure assumes to have a better visual comparison between the two different door configurations.

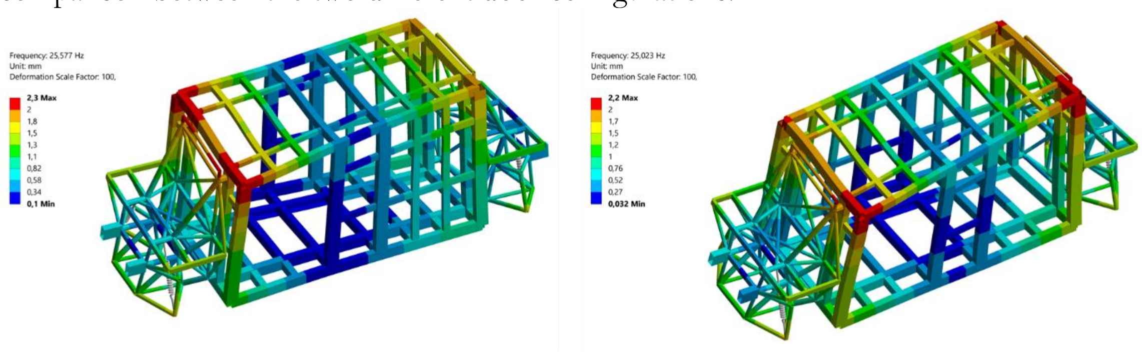

Figure 94 First modal frequancy

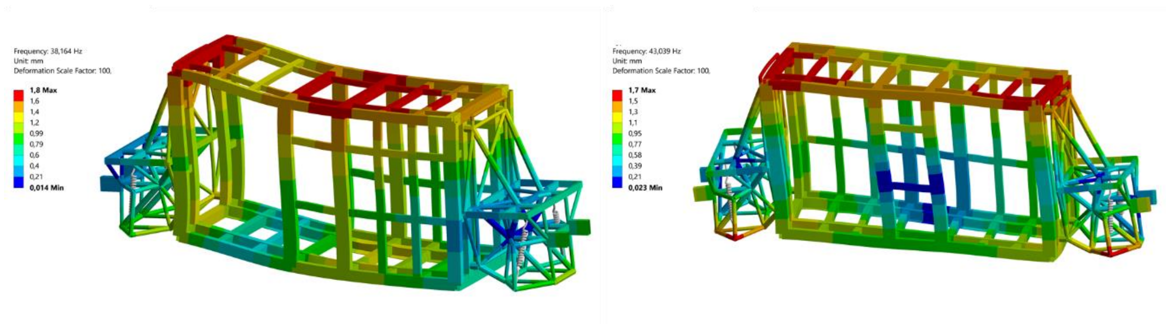

Figure 95 Second modal frequancy

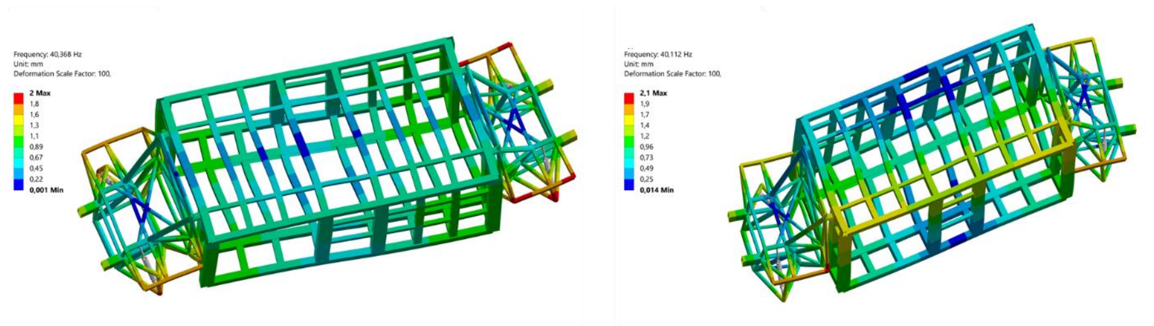

Figure 96 Third modal frequency

The results obtained show that the behaviour of the two structures is very similar and therefore the door position doesn't affect the too much the resonance.

8.5 Battery Cargo module

To better adapt to all the various needs of customers who will use the modular vehicle, the cargo module can have several battery packs installed in its floor as an option.
Remembering that the drive modules already have a 60 kWh battery, if the autonomy of the vehicle is not sufficient, different sizes of additional modules can be chosen.
An important aspect that the customer will have to consider is the extra weight generated by these modules which will attack the payload directly.
The choice of how many additional modules it is possible to install is determined in part by the length of the cargo module itself that we remember can vary from L2 of 3.2 m to L5 of 5 m.
The maximum width of the additional battery is limited to 98 cm in the current cargo module structure, the height is set at 10.5 cm, equal to that of Tesla Model Y, and the length is variable.

A table of the maximum installable dimensions of the battery modules for each cargo module length is shown.

Cargo module class	Cargo battery module			
	Length cm	Volume dm^3	Capacity kWh	Weight kg
L2	280	294	66	384
L3	340	357	80	466
L4	400	420	94	548
L5	460	483	108	630

Table 13 Battery pack characteristic as function of cargo module lenght

With the addition of these units, even for the smallest model, the maximum distance that can be travelled can be doubled.
Furthermore, given the powers involved, a cargo module can keep many accessories operational that can be used by the customer during his work.

8.6 Coupler system

To be able to connect the drive modules to the cargo module, it is necessary to identify a suited coupler joint.
In this chapter we will introduce a selection of already existing coupler types, explaining the principle of operation and the needed adaptation to perfectly fit the modular vehicle requirement.

Environment
The operation of coupling should be performed in various types of situations that can be found in the typical use of the vehicle. The easiest condition for engaging starts from a parked position in a flat terrain, but the locks should be able to operate also on a steep road or unstable terrain.
Looking at the drive module general position with the balancing arm deployed, the drive module is tilted in a way that the bottom coupler engages before the top one.

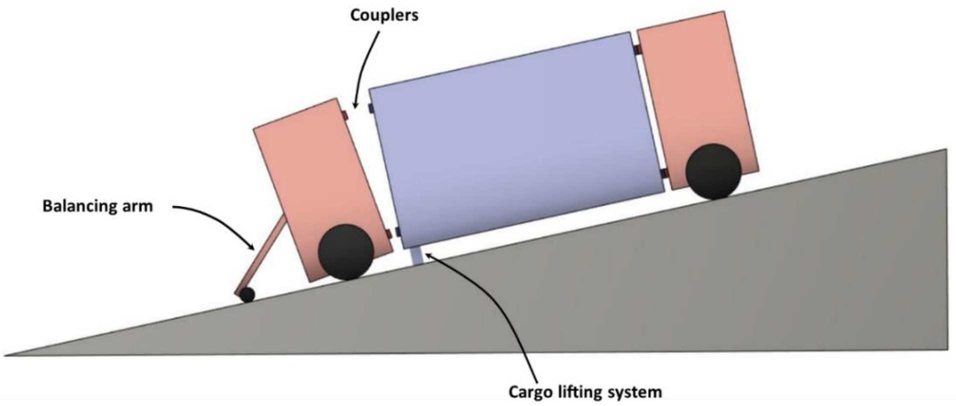

Figure 97 Working condition during coupler operation

Another key feature is that the coupling system must be compatible not only between the drive module and the cargo but also between the two drive modules. This becomes a strict constrain considering that there is only one type of drive module, and this means that the coupler design should be able to connect to itself, as shown in figure 98.

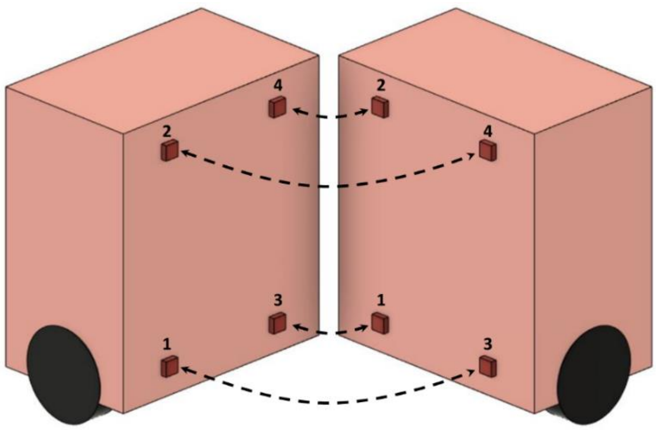

Figure 98 Coupler system compatibility

8.6.1 Functional request – mission requirement coupler

- Lock drive module to cargo module
  Lock drive module to drive module
  Couplers together lock all degrees of freedom

- Safe operation
  All the phases of the operation should prevent any harm to passengers and people around the vehicle. This could be done actively by using control systems but also selecting safer designs.

- Able to transmit all the loads passing through the chassis
  Axial Torsion Bending
  Preferable to have a system that doesn't actively stress the hydraulic or mechanical components that move when the coupler its fully locked

- Automatic operation
  The locking operation between modules should be performed autonomously by the modules of the vehicle without any human intervention.

- Easy coupling phase
  Be able to lock even if the modules are not perfectly aligned or parallel

- Able perform the coupling operation in:
  Frontal streets slope up to 16%
  Lateral streets slope up to 5%

- Able to perform the coupling operation also in non-ideal road condition
  b road – dirt road – gravel

- The mechanism that controls the coupler operation should stay on the drive module because reduces to the minimum the maintenance needed to the cargo module.

Other active system engagement operation

These systems help to align the faces of the modules to permit an easier matching phase thanks to the ability to control the position of the modules. This allows to reduce the complexity of the design single coupler.

Autonomous drive

Necessary to control the vehicle position and determines the accuracy parching manoeuvre, especially its responsible of the lateral misalignment between modules.

Independent control of each driven wheel

Since there is a motor for each wheel and the drive motor has only one axle the paths available are far greater that the ones of a normal vehicle, and this includes diagonal motion and turning around 360 degrees on its main axis.

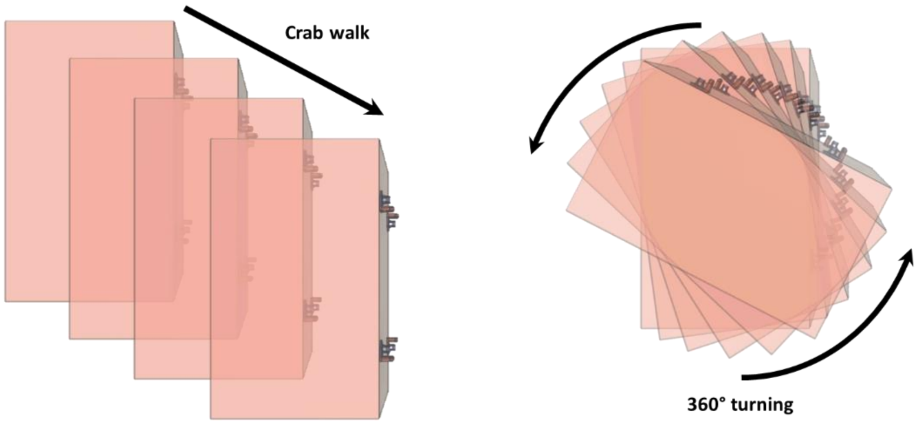

Figure 99 Drive module possible motion to simplify coupler operation

Active suspension - Height control cargo module

They control the height and the frontal and lateral inclination of the modules.

Balancing arm drive module system

This functions as an extra foothold for the drive module. This prevents the fall of the module in non-flat roads and improves the range and stability of the coupling operation.

8.6.2Types of locking mechanisms for the modules

Showcase of heavy-duty couplers already tested in their specific field, we are interested in the principle of operation and geometry to see if they can be adapted to the use of the modular vehicle

8.6.2.1 Railway couplers

The analysis of railway couplers its focused only on the head since is where the locking mechanism are situated.

Figure 100 High-speed train with exposed coupler system

Tightlock coupling

TypeH Tightlock couplers are a variety of Janney coupler (the oldest semi-automatic coupler). They are designed with mechanical features which reduce slack in normal operation and prevent telescoping in derailments [38].
Like all Janney couplers, the Tightlock is "semi-automatic" with the couplers on cars or locomotives automatically locking when cars are pushed together.
To separate cars, a worker needs to use a lever to move the locking pin that keeps the coupler closed.

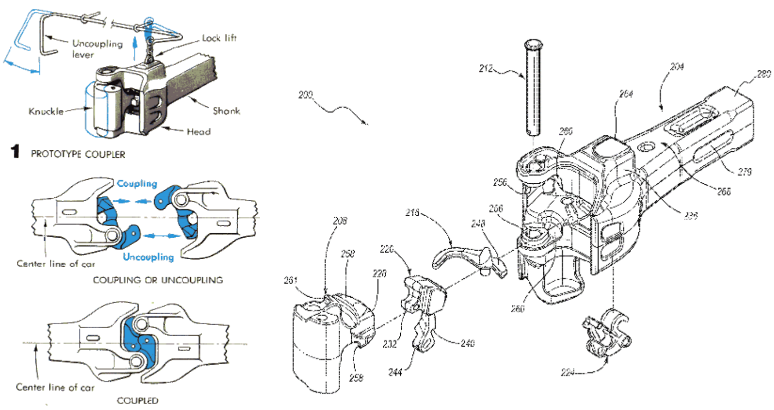

Figure 101 Technical drawing Tightlock coupler

The use of this coupler its limited for the modular vehicle requirements without substantial adaptation for the task because it lacks an automatic disengagement and the ability to transmit forces in the vertical direction and torque moments. Also, its symmetrical design means that we have movable components in both sides of the connector.

Considering the transmission of forces problem that could be overcome if a Tightlock couples is inserted as head of a conical body and its function is be reduced to transmit only axial loads and leave the remaining forces to be dealt by the surrounding body. Also using at least three locks solves the problem of the transmissible torque.

Scharfenberg coupler

The head of the Scharfenberg coupler has a protruding cone and a matching cup.
Inside the cone there is a rigid metal hoop connected to a revolving, spring-loaded metal disk with a notch on the opposite side, as shown in figure 102. When ready to couple, the spring turns the disk, so the hoop is extended from the cone. As the cars meet, the hoop enters the cup on the other coupler, stopping against the disk. The hoops are then pressed back into their own coupler, causing the disks to rotate until the notches align with the hoops.
After the hoops have entered, the notches on the disks spring back into the hoop extended position, locking the coupling. In the coupled position, forces on the hoops and disk will balance out, which means that the Scharfenberg, unlike many other couplers, is not dependent on heavy latches to stay locked [39].
Small air cylinders, acting on the rotating heads of the coupler, ensure the engagement of the components, making it unnecessary to use force to get a good coupling.
One problem with the coupler is that it is often hard to connect it in a curve. Planned coupling is normally done on a straight flat track, while there has been trouble coupling a broken down train at an unplanned place.

Figure 102 Scharfenberg coupler open and closed position

Jr Shibata
In the inside the coupler, there is a rotary lock shaped like a half-cylinder cut in the vertical direction, a release lever is integrated with to form the heart of the coupler mechanism.
At the time of coupling, the half cylinders are forced to rotate by the main body shape.
After the couplers are completely connected the half cylinders return in the initial position ensuring locking state.
At the time of disconnection, the lock is released by operating one of the release levers, and the disconnection becomes possible.

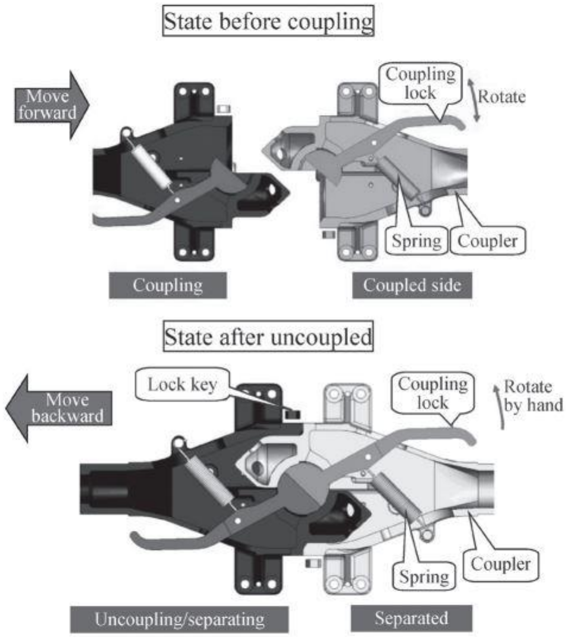

Figure 103 Jr Shibata coupler

Looking at degrees of freedom only one Shibata coupler is needed. This solution leads to a heavy central coupler that could be problematic for the weight of the modular vehicle. Another option is to use multiple Shibata couplers, but considering its geometry, the small lateral tolerances could make the engagement phase difficult.

8.6.2.2 Construction machines quick couplers

There are many variations in the design of quick couplers. An initial difference between those that can pick up any of a range of buckets and attachments by clamping onto the mounting pins for the attachment (known as "pin grabbers" or "pin couplers") and those that work only with buckets and attachments designed to suit that quick coupler (known as "dedicated"). The claimed advantage of pin-grabbers is flexibility in use in that a machine owner can use a variety of buckets and attachments without changing the quick coupler or buying an adaptor.
The claimed advantages of dedicated couplers depend on their individual design, and often include better performance and smaller size.

Caterpillar S Type Couplers

Figure 104 Caterpillar S Type Couplers

Used principally to connect to the excavator utility tools like jackhammers and grabbers. The function of this type of coupler relies on the ability to rotate the head and first engage the passive side with a standard hook, then in the front part it's equipped with a simple linear pin that slide out and locks to the horizontal rod. The hydraulic and electric connectors are integrated in the same body of the pins that slide out [41].

For the vehicle two major solutions can be adopted, one where we use multiple copies of this head type, each one independent, with all the related complexity, or we can imagine spreading the coupler component in the edges of the connecting face of the vehicle modules.

This type of solution is preferable because it reduces the number of components required even if it makes the movement phase of the engagement more complex. If we imagine positioning the sliding pins in the upper part, in the lower part there will be fixed hooks, these to be positioned require an upward translation movement and a rotation of the hook that can be performed with some difficulty by the system of suspension of the drive module.

Liebherr Hydraulic quick coupler

Figure 105 Liebherr Hydraulic quick coupler [42]

Figure 106 Liebherr Hydraulic quick coupler open and closed position

Like for the one before the coupler has different types of lock in the front and rear part, one it's a passive simple hook and the front one has a mechanism that allows to the pins to slide out. The difference with S coupler is that the fit tolerance between the pins and the hole its much tighter, becoming an advantage when the coupler its lock but requiring a precise control in the engagement operation.

The proposed use its equal that for the s type coupler and has the same problems/solutions. A remarkable point is that this type of coupler has already been used in the heavy-duty trailer mover Gavarini GAPO [43] which presents many of the same challenges that must be faced for the modular vehicle.

Figure 107 Gavarini GAPO coupler system

JCB Surelock Quickhitch

Figure 108 JCB Surelock Quickhitch [44]

The feature of this coupler is that it has a grabber in the front and in the rear part and presents a trade-off between an easier connection phase and complexity of the design.

Four grabbers positioned in each corner of the connecting face of the modules, easy frontal connection only downside is that it's necessary to maintain pressure in the system to maintain closed the claws.

8.6.2.3 Fifth-wheel coupling

The fifth wheel is one of the two parts relating to the mechanical fifth wheel/pivot coupling between a road tractor and a semi-trailer to form an articulated vehicle. The fifth wheel is located on the tractor, while the pin is located on the semi-trailer [45].

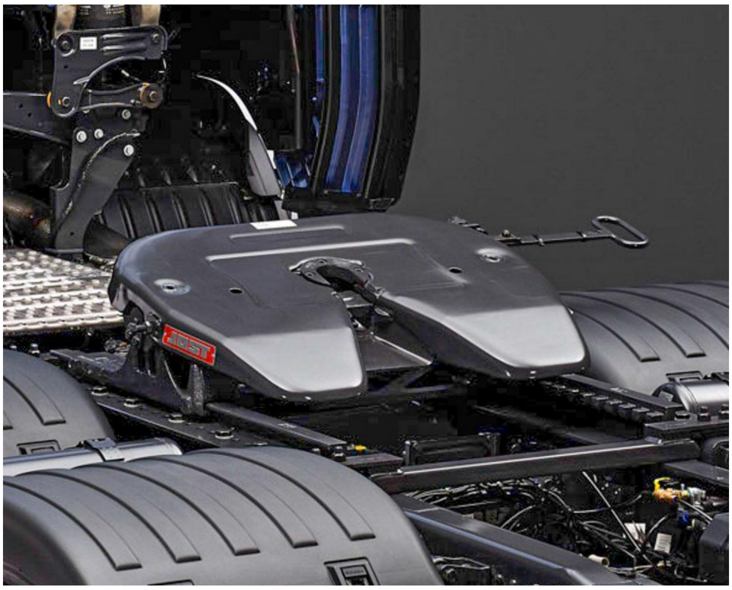

Figure 109 Heavy truck fifth wheel coupler

It consists of a steel plate with a central hole and a V-shaped guide ramps for the kingpin; in this way the coupling is possible even if the tractor and semitrailer are not perfectly aligned with each other.
The steel plate also supports a good portion of the trailer load as well as constraining the front and side movements of the pivot when the coupler is fully closed [46].
There are different types of solutions for the kinematics of the central coupler, and these depend on the manufacturer. For this product the main players are Fontaine, Holland and Jost.

After an analysis of the various solutions, the Holland TwinLock [47] mechanism was chosen because it is the one with the most compact dimensions.

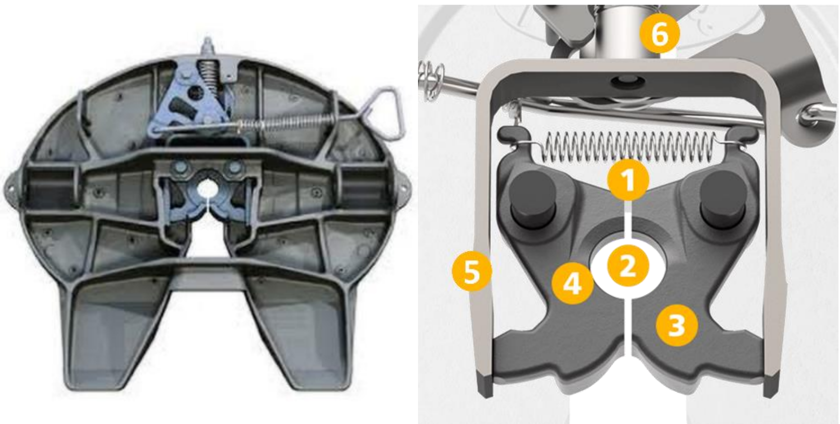

Figure 110 Fifth wheel coupler Holland TwinLock mechanism

1 Spring that tends to keep the jaws open
2 King pin position
3-4 Grabbing jaws
5 movable yoke
6 Spring that tends to keep the yoke closed

This type of attachment can be used in various configuration in the proposed vehicle.
The minimum number of fifth-wheel connectors is three for each drive module since we want to lock all the translations and rotations between the modules.
The coupler can be oriented in all the principal axis – with the kingpin parallel to the direction of motion or perpendicular to it in the vertical and horizontal axis.

Parallel direction of motion king pin
For the engagement of the king pin in this solution is necessary to guide the drive module in a top-down or bottom-up motion depending on the orientation of the opening of the fifth wheel coupler. All the axial forces are absorbed by the king pin head and could be necessary an auxiliary system to reduce the slack in the frontal direction.
This solution can easily recover a misalignment in the lateral direction that is the harder to control for us.

King pin horizontal axis – pin grabber style
Double lock ring in series to fully close the gap - conical design

Advantages and disadvantages

	Railway coupling			Construction machine			Fifth-wheel coupling	
	Tightlock	Scharfenberg	JR Shibata	Caterpillar S Type	Liebherr LIKUFIX	JCB Surelock Quickhitch	Frontal	Vertical
Locks on contact	√	√	√				√	√
One side mechanism				√	√	√	√	√
Only frontal motion to lock	√	√	√					√
Easy to adapt to for drive module to drive module connection			√	√	√			√
Good catching when misaligned	√					√	√	√

Table 14 Comparison Coupler characteristics

The summary table contains each desired characteristics for all the different types of locks considered.
The hook that satisfies the most features is the one based on fifth wheel coupler in the vertical position. For this reason the design of this coupler will be further developed in the next chapter.

8.6.3 Development selected coupler system

The engagement phase is preferred to be executed by directly driving the drive module in the cargo module, so without the necessity of complex motions paths.

The bottom couplers are usually the ones that engage first, so it should be preferred a type of lock that automatically closes when in contact.

Considering also that the coupler design should allow for the drive module to drive module coupling the final choice is to have four grabber coupler with claws derived from the Holland fifth-wheel and optimized to work in vertical position.

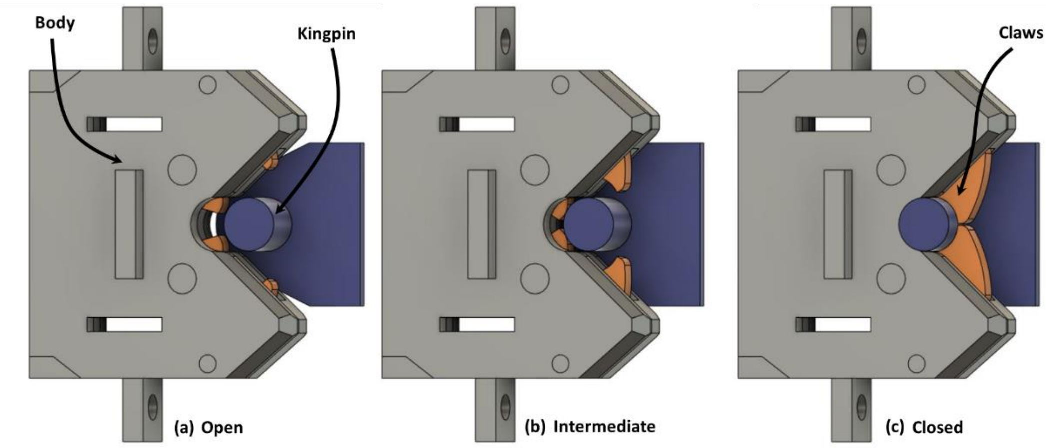

Figure 111 New coupler exterior - Closing phase

The ramps of the main body help to guide the kingpin in the central locking position. The claws only lock the kingpin in the frontal direction, all the other movements are limited by the body of the coupler.

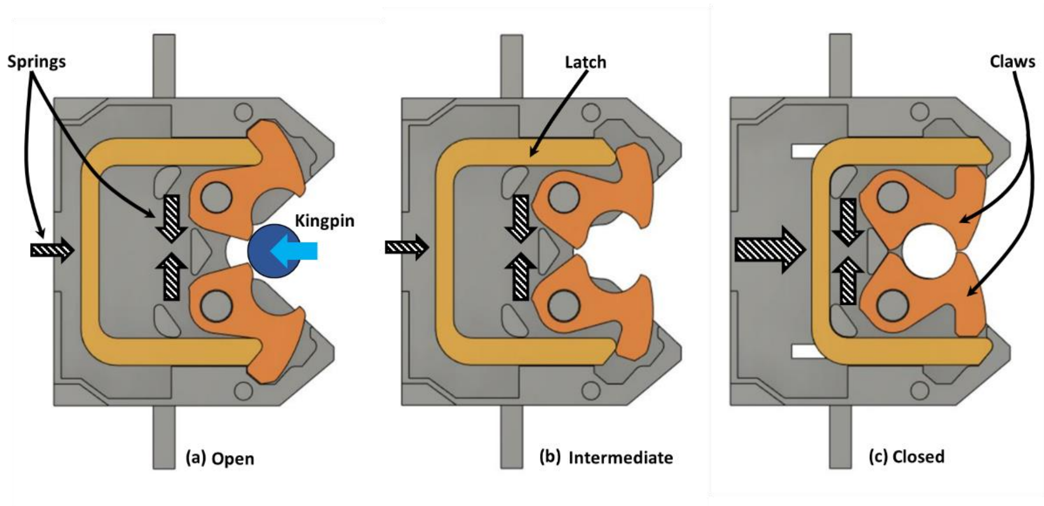

Figure 112 Interior mechanism during closing phase

In the position (a) the claws are held open by a spring between them.
In this position the latch that also has a spring that pushes it trying to close the claws, but thanks to the geometry of the interface of these two bodies this movement is prevented.

If the kingpin starts to push the inside of the claws, they begin to close, and their movement frees the latch.
At this point the latch slides into the final position (c) where it locks any movement of the claws.
In order to open the hook it is necessary to retract the latch with a suitable actuator.

A coupler prototype was built to test actual operation. The prototype was made of PLA plastic using a 3d printer.

The chosen scale is 1/3 which is a compromise between the minimum size to have a functional coupler and a suitable dimension to test the whole system with the faces of the modules and the four hooks.

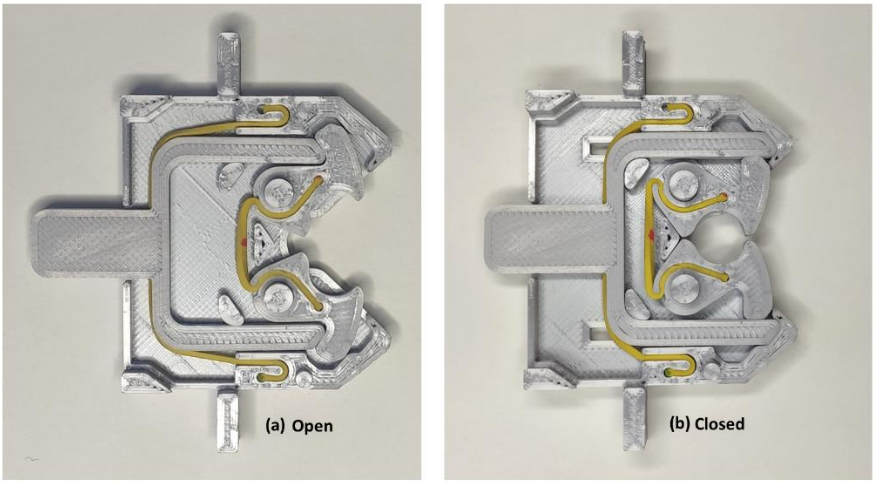

Figure 113 Single new coupler 3d printed prototype

The force required to close the claws can be adjusted by changing the stiffness of the spring, for the scale model this is done by changing the length of the elastic elements.

After some fine tuning of the elastic elements, a satisfactory actuation force was achieved. To have a simple numerical evaluation of the effective force the following experiment was performed using a kitchen scale.

Figure 114 Experiment closing force coupler claws

By subtracting the weight of the components, the force required to activate the coupler was recorded. Over a series of twenty tests, the average recorded force was 67 grams with a standard deviation of 27 grams.

The results can only be considered in a qualitative way, because it is not guaranteed that the full size hooks have the same properties, but the experiment indicates that the system can be easily adjusted to different activation settings

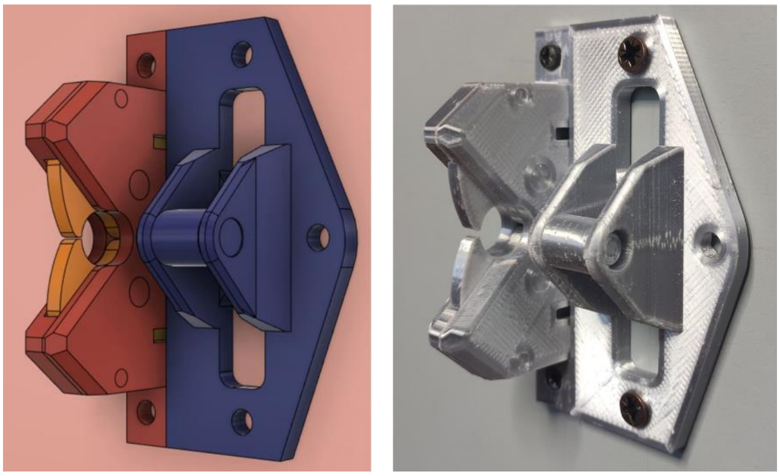

Figure 115 Complete coupler design

The following image shows the complete coupler already installed on the face of a module. Since the coupler must have the ability to mate with itself, it is composed of both components, the active one with the claws and the passive one with the kingpin.

Engagement drive module - cargo module

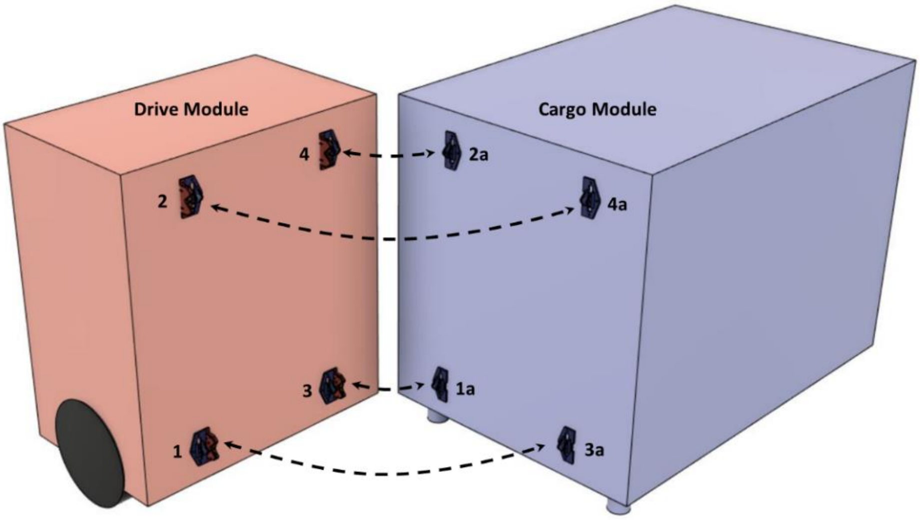

Figure 116 Couplers position on drive and cargo module

On the cargo module there is only the passive part of the coupler, and it's necessary to reduce the need for maintenance on the module that the customer uses the most.

The configuration of the couplers gives a great freedom for the engagement operation because allows an acceptable error on the alignment of the modules and this results on multiple available strategies for the path of the drive module.

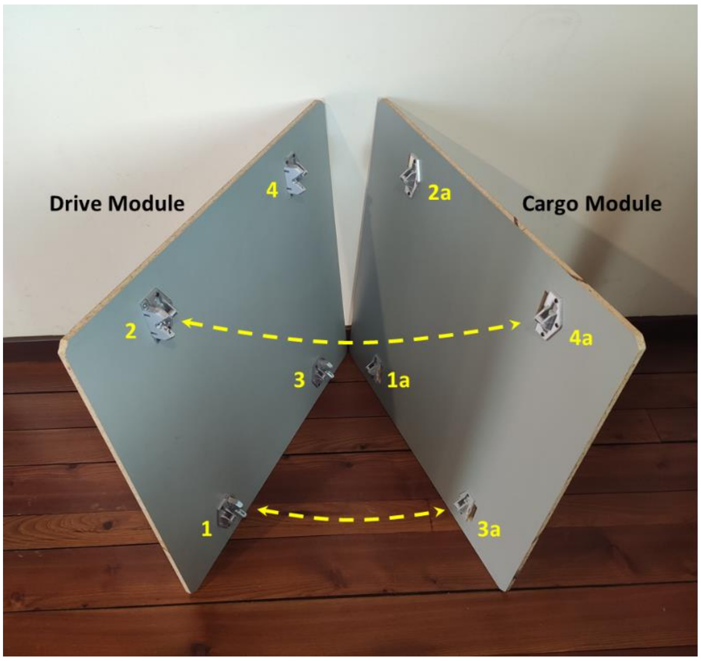

Figure 117 Coupler test 1:3 scale module – position couplers

Figure 118 Coupler test 1:3 scale module - engaging phase

The faces of the modules are also in the same scale of the couplers, and this is import because we can observe what happens in various approach position and for which cases the edges collide.

Also, for the complete model a functional tests was carried out for the closing mechanism, it behaved as expected, snapping with the contact of the kingpin and ensuring its effective locking.

The approach between the modules can be done from one side first or from the bottom couplers first.

Figure 119 Coupler test 1:3 scale module – maximun misalignment angle

The maximum angle between the modules where at least one coupler engages it's been measured in build prototype the following test:

Side first

Max angle 10 degrees

Bottom first

Max angle 14 degrees

This result is satisfactory in this phase of the conceptualization, also considering that we can increase the range of engagement controlling the other systems of the vehicle like independent wheel control and the active height adjustment.

Engagement drive module - drive module

The main difference between the coupling of the drive modules alone with the one with the cargo module is that the couplers are complete on both sides, this means that there are twice as many couplings to connect, resulting in an increase in the precision of the movements that have to be made.

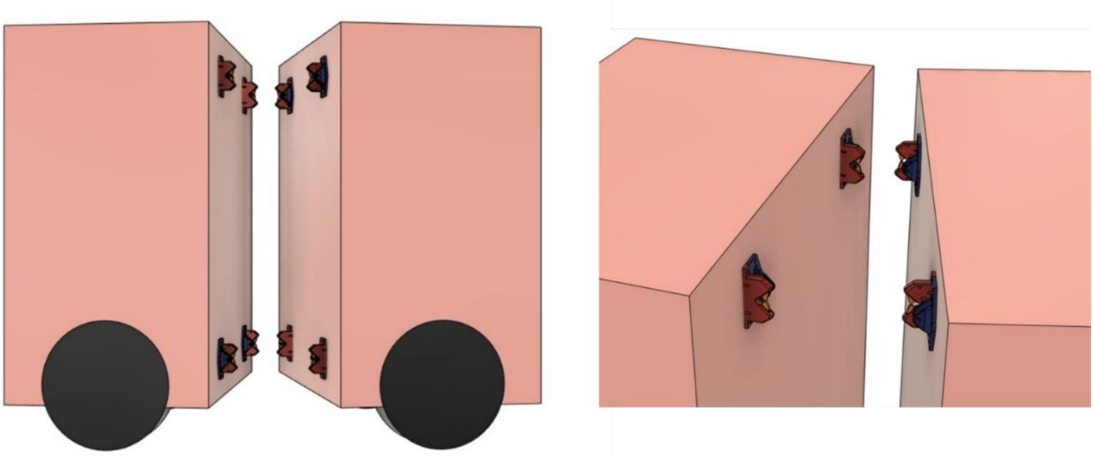

Figure 120 Double drive module coupler engagement

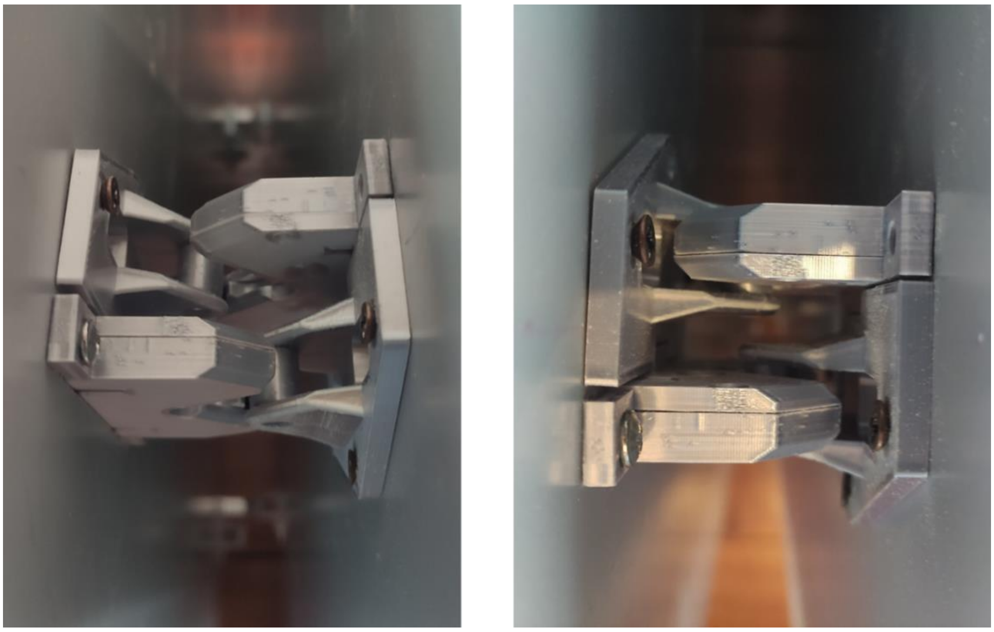

Figure 121 Coupler test 1:3 scale module – double drive module coupler engagement

No major drawbacks were found in this configuration because the overall angles of attack remained unchanged and only the force required to close the system slightly increased, which is not a problem considering that the drive modules can both push against each. Even in case of difficulties in the engaging operation, the modules can still move to a more suitable terrain to complete the task.

8.7 Autonomous drive sensors

As regards autonomous driving, in this project we are mainly interested in the dimensions of the components necessary for its operation.
The sensors are a critical aspect for the autonomous vehicles, they allow to see and sense everything on the road, as well as to collect the information needed in order to drive safely. Furthermore, this information is processed and analysed in order to establish a path from point A to point B and send the appropriate instructions to the controls of the car, such as steering, acceleration, and braking.
The majority of today's automotive manufacturers most commonly use the following three types of sensors in autonomous vehicles: cameras, radars, and lidars.

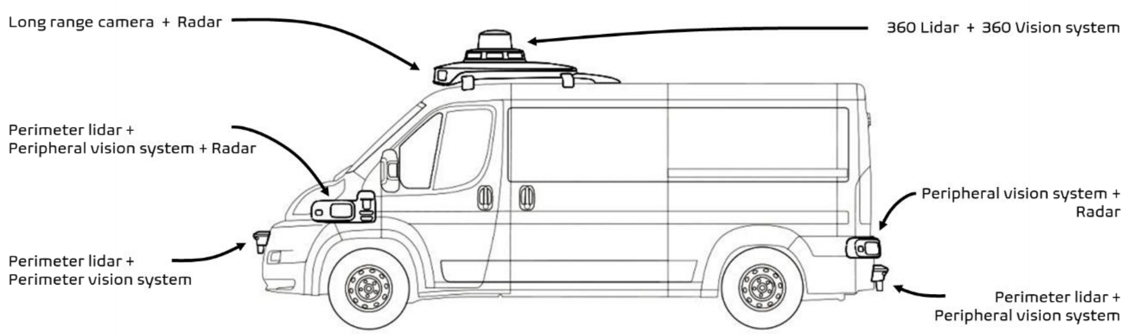

Figure 122 Waymo autonomous drive sensor position

The configuration and location of these sensors depend on each company and for each type of vehicle.
Waymo recently introduced a sensor configuration dedicated to trucks, because given their size it was necessary to split the central lidar into two components, one on each side [48].
Another possible configuration is the one used by Zoox and the GM Cruise Origin prototype where the cameras and lidar are placed at four corners of the vehicle.

Figure 123 Cruise Origin autonomous drive sensor position

The positioning criterion of the various sensors is to give for each one the maximum field of vision, for this reason in the drive module there will be two lidar systems at the top as in the truck proposed by Waymo Via, integrated in the same unit there will also be the cameras, while the radars will be mounted lower in the car body.

When the modular vehicle will travel in the coupled configuration, the sensors of the two drive modules will guarantee a 360 degree field of vision.

8.8 Balancing arm

A mechanical support system was added to the drive module, this is necessary for carrying the weight of the module itself in conditions in which it is difficult to operate in self-balancing.

The tractor used to move construction machinery Gapo developed by Gavarini [43] is a vehicle with an operating concept similar to that of the drive unit of the modular vehicle.
To prevent the Gapo from overturning, they added a jack with a wheel in the front left.

Figure 124 Gapo balancing wheel

This solution works if the vehicle does not have considerable possible variations in its inclination.
For the drive module it is preferable to have a support point that extends more than the car body to guarantee a condition of superior stability.

Another possibility is to derive inspiration from the kinematics of the retractable landing gear of aircrafts or rockets like for example the SpaceX Falcon 9 leg. This solution will be developed in detail when during the next component design phase.

A possible evolution of the balancing system is to integrate it with a system that facilitates access to the load compartment of the drive module. It was decided to develop these balance arms so when fully deployed, they form an access ramp to the top of the drivetrain.

Balancing arm design

The design of the balancing arm started considering the initial position of the arms when fully retracted and in the final position when fully open. The attachment points of the arms have been set so that they connect to the frame of the drive module.

With a two-dimensional sketch the characteristic angles were then set, in particular, the ramp angle in the open position has been set at 45 degrees.

By drawing these two positions in parallel, it allowed, through dimensional constraints, to determine the exact lengths of the various components of the system.

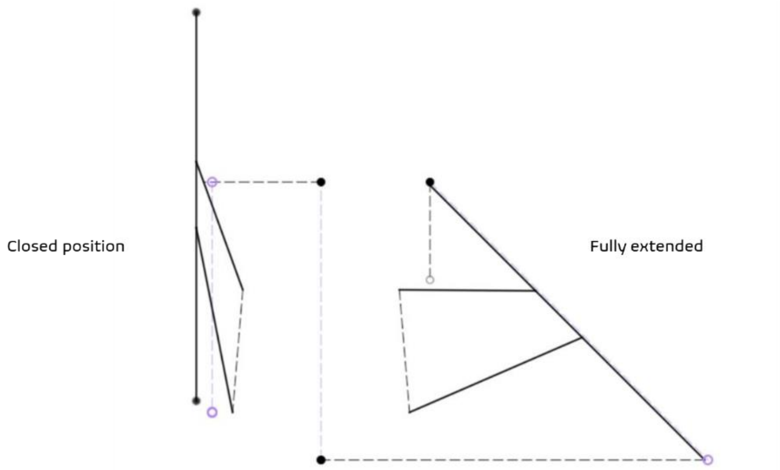

Figure 125 Initial design balancing arm

To better understand how this geometry works, the outline of the drive module has also been included.

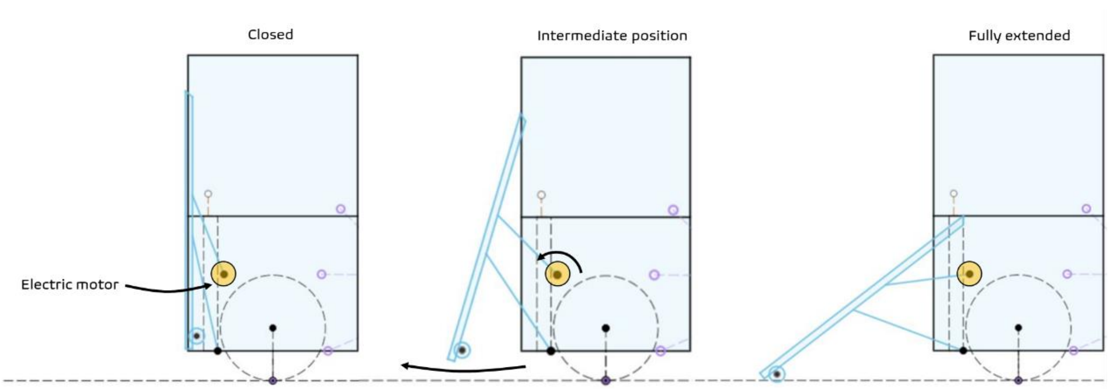

Figure 126 balancing arm operation

8.9 Cargo lifting system

The cargo module needs a height control to facilitate the coupling phase and level the cargo floor independently from the road surface.

Different solutions can be adopted, but the simplest is to equip the cargo module with a lifting leg at each corner.
it is possible to adopt a solution of a hydraulic jack like the one shown in the figure 127 capable of lifting heavy loads such as containers.

Figure 127 Hydraulic jack lifting cargo system [49]

Another possibility is to use a mechanical screw system controlled by a motor, this choice is preferable given the possibility of using the electrical energy stored in the batteries of the cargo module.
A further development is to equip the jack feet with motorized wheels, for example of the omni wheel type. These can allow short trips to and facilitate the parking phases of the cargo module.

9 FINAL DESIGN

The modelling of the frame of the various structures was completed with the updating of sections of the various components based on the results obtained from the structural in the fem model, the centres of mass of the sections always matched on a common vertex, instead in the updated model the various poles have been moved to align them on the vehicle faces, in this way the vehicle floor rests on a single flat surface, the same treatment applies to the other external walls of the vehicle.

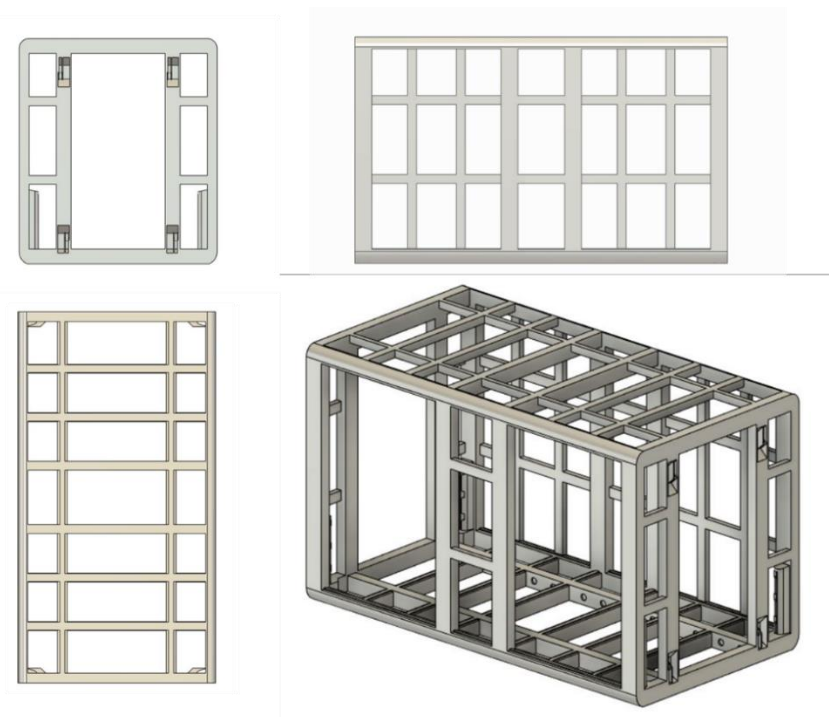

Figure 128 Structure Cargo module

Figure 129 Complete cargo module

In addition to the cargo module frame, the battery modules and the lifting system were also included.

The drive module has had some changes on some elements of the external structure in order to better conform to support the bodywork.

Figure 130 Structure Drive module

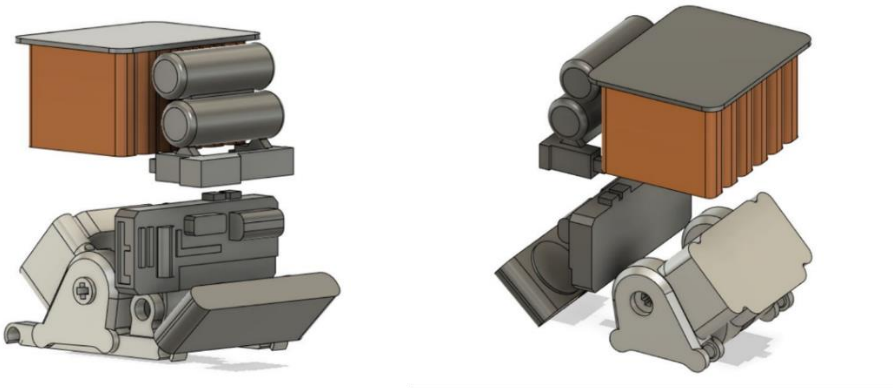

Figure 131 Image battery box

All the systems necessary for the operation of the engine module have been modelled in a simplified way to indicate their presence.
These systems are integrated in the lower part of the drive module.

In image 132 the drive module is complete with all its systems and the balancing system is also presented, with the integration of an automatic mobile lifting system for the drive module cargo upper space.

Figure 132 Drive module cargo plane

Sequence of phases of deployment of the balancing system, starting from the closed position to the final stabilized one.

Figure 133 Final design balancing arm operation

Having completed the modelling of the frame, the complete model with all the components is presented.

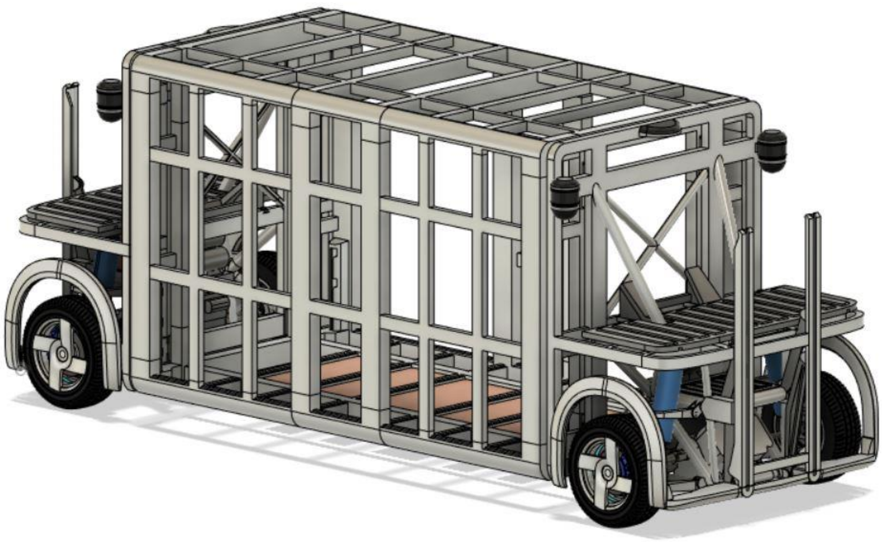

Figure 134 Complete model - modular vehicle

Figure 135 Render complete modular vehicle

9.1 Scale model 1:10

In order to create the vehicle model while maintaining its main functions, such as the ability to disconnect the modules and suspensions that respect the intended movements, the technique chosen is 3D printing.
The scale chosen is 1:10 because it allows to appreciate small details and also allows the creation of components such as coupling systems.
With this scale, the model reaches the final dimensions of more than 60 cm in length, making it difficult to create the structure in a few pieces, this because the dimensions of the printing surface of the available 3D printer is limited to 23x23 cm.

It was necessary to divide the model into parts with suitable dimensions.
These parts must be able to be connected with each other, so the joints as in the figure 135 have been created.

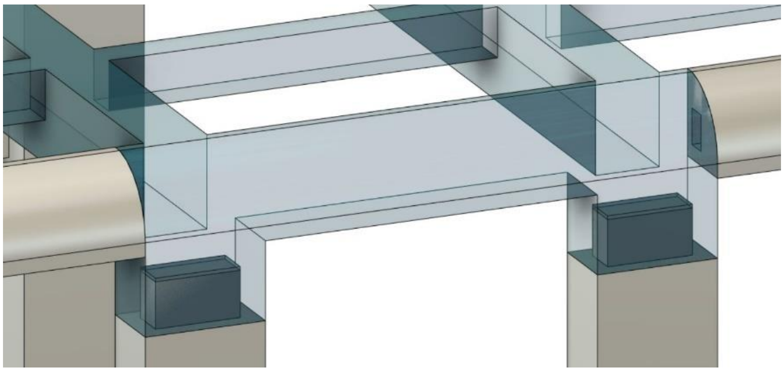

Figure 136 Model subdivision for 3d printing – joint creation

To allow the operation of all the various systems, given the reduced size of the components, some small redesigns of details were necessary.
In the suspension system, one example is the lower control arm that includes in a single part also the ball joint and the connection for the shock absorber.

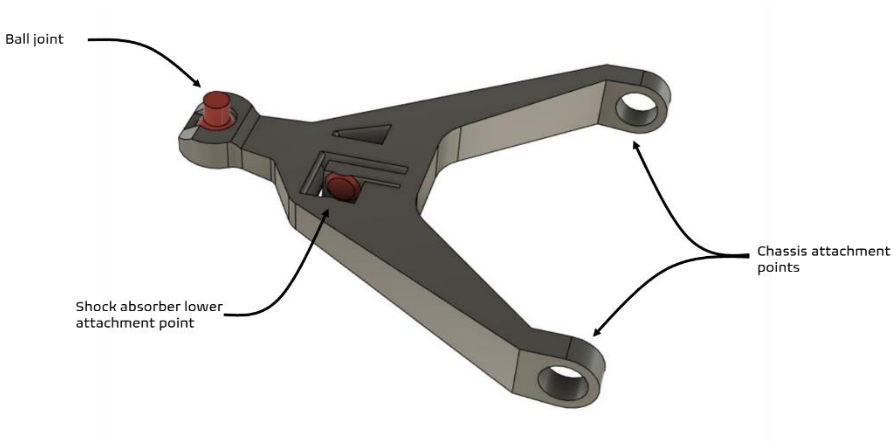

Figure 137 Part design for 3D printing

In total the final model is made up of 284 pieces, divided into 54 for the cargo module of which 26 for the structure and 115 pieces for each single drive module of which 52 for the frame only.

Material
Due to its simplicity of printing, the material used is PLA, the only exception are the vehicle tires which, in order to have a more realistic behaviour, are made of flexible TPU plastic.

Slicer
After saving a file for each component it is necessary to generate the machine path for the 3d printer.
The software used is PrusaSlicer with custom settings adapted to the Artillery Genius printer.

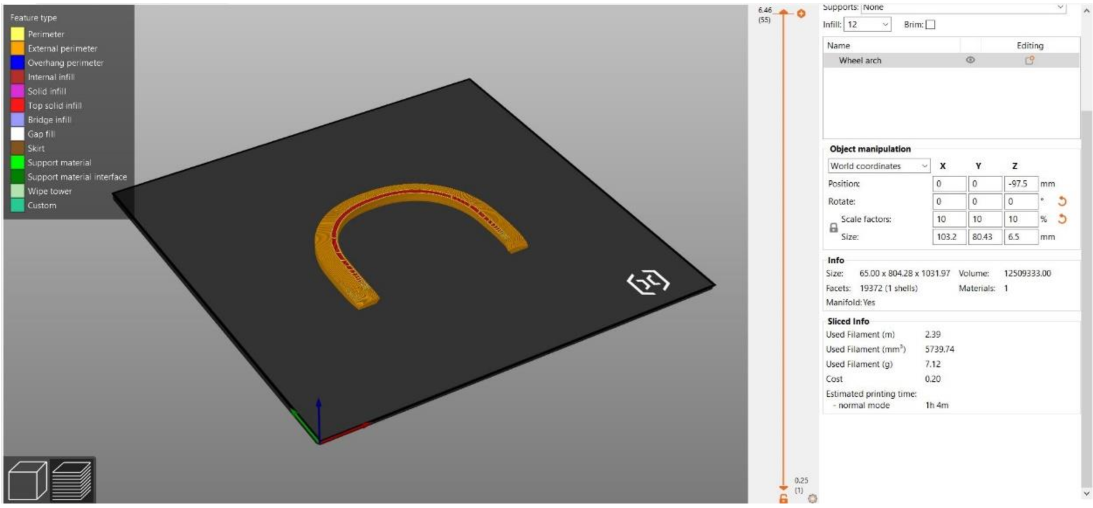

Figure 138 Slicer for g-code creation

To obtain a superior result, the various pieces of the model have been oriented in an optimal way in order to reduce any critical situations such as undercuts.

Overall, the model required 220 hours of printing, of which 76 for the cargo module and 72 for a single drive module.

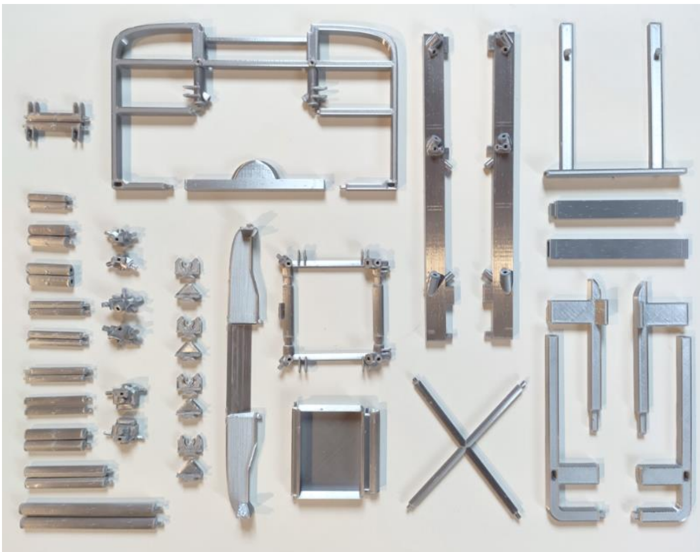

Figure 139 Drive module chassis disassembled

The last phase involves cleaning and assembling of the various parts to obtain the finished model.

Showcase final model

Figure 140 1:10 Complete model modular vehicle

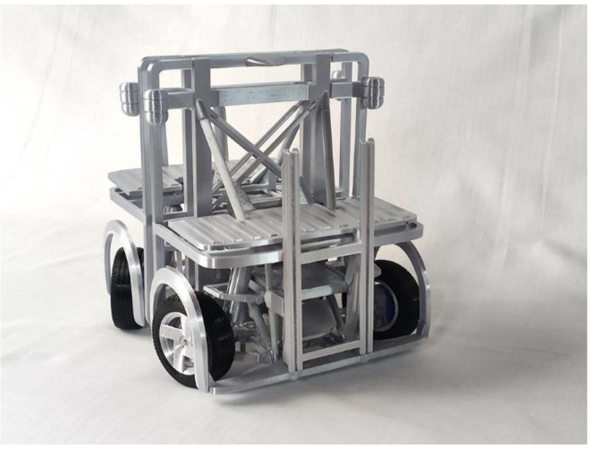

Figure 141 1:10 Two drive modules connected and balancing arm extension

10 CONCLUSION AND FUTURE WORK

The purpose of this project was to design a modular vehicle concept for the future mobility using new emerging technologies.
The extended global automotive industry is undergoing an unprecedented transformation to a new mobility ecosystem, as technological innovations in the form of electrification, connectivity, and autonomy advance, the way people and products move around is set to change dramatically.

The scope of the study was to investigate what type of vehicle can take the most advantage of the technologies like autonomous driving, electric traction and sharing solutions.
From these premises, it was deduced that a modular vehicle can combine these technical solutions in a package that improves the user experience and offers greater flexibility for the infrastructure of tomorrow's smart city.

The three-piece design deviates from the current existing prototypes of modular vehicles, bringing numerous advantages, such as complete autonomy of the driving module, greater customization of the passenger compartment, both in terms of dimensions and fittings, ease of access, volumetric efficiency of the load compartment.

To place the modular vehicle in a defined context, the large van segment was identified as the best fit for the introduction of this new vehicle.

From the market research on vans, the needs and demands of customers have been identified, and from these results it has been possible to find the technical characteristics of the modular vehicle that meet these requirements.

The ability of the vehicle to operate both in the configuration with the modules connected and with the modules disconnected, generates a cascade effect on how the user can and the vehicle interacts. Therefore, having explained how the vehicle performs the coupling operation and the management strategies of maintenance and charging.

Defined the requests for the vehicle and its way of functioning, all that remained was to design the vehicle and its proportions. In this phase, all the internal and external measures were defined. To comprehend how the proposed vehicle is positioned on the market, for each parameter analysed a comparison was made with the current vans of the main legacy manufacturers but also with new start-ups that offer dedicated electric van platforms.

To pursue the development of the prototype, it was necessary to first define all the carryover components, to focus on the most critical systems for the modular vehicle.
These parts are the chassis structure divided between the drive module and the cargo module and the coupling system which connects these two units.

The drive module structure was designed as a tubular construction space frame. This solution presents several problems for a possible industrialization but in order to rapidly develop the prototype in which the position of the subsystems can change quickly, this compromise was considered acceptable.

For the cargo module, on the other hand, was taken as reference the rear structure of the vans and this type of construction should not present any problems.
To validate the strength of the frame, a finite element analysis was performed to verify the torsional stiffness, bending stiffness and the first resonance of the structure.
The type of analysis carried out considers an extremely simplified beam structure, therefore the results give only the general performance of the chassis, while for the computation of local stresses a more detailed model that also include the local joints is necessary.

One of the characteristics that distinguish the proposed modular vehicle from the others is its coupling system.
To see if existing products could offer a valid solution, the couplings already used by heavy industry, such as railways and construction machinery, were considered.
From the comparison of these, it emerged that the coupling system between heavy trucks and trailers offered an excellent starting point. It has therefore been adapted for the modular vehicle of operation, redesigning it and also creating a functional scale prototype of the proposed solution.
The produced prototype has exceeded the required expectations, resulting more robust and with a wider field of use.

Having therefore defined the entirety of the components, to collect all the solutions and all the required functions, a definitive design was made.

To demonstrate the actual validity of the project, a scale model of the vehicle was built with the aid of 3D printing. All the main systems have maintained their function even if, given the reduced size of the components, simplifications were necessary.
One of the objectives of the scale model was to confirm the effective function of the suspension geometry, both for its entire range of wheel travel and for the achievable steering angle.

Future work

Since the project started from a clean sheet with no starting positions or guidelines, only the initial part of the vehicle conceptualization has been done.

To continue development, the largest work areas are the frame structure and its coupling system.

For the chassis, now that the position of the macrosystems are known, a re-engineering is necessary to make the structure capable of passing all the destructive crash tests. Furthermore, a more accurate study on the construction methods and any cost analysis must be carried out.
For the coupling system, the following phases concern its size, defining exactly the loads it has to support. Once this phase is over, full-scale prototypes should be built and tested to verify the correct functioning of the mechanism over is entire lifecycle.

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