Karlsruher Institut für Technologie

Deutsches Zentrum
DLR für Luft- und Raumfahrt

Powertrain Development for Advanced Self-propelled Fully Integrated Bogie (ASINO)

Master Thesis

By

Aatharv Keskar

University Supervisors

Prof. Dr. -Ing. Martin Doppelbauer
Dr. Ing. Matthias Brodatzki

DLR Supervisors

Mathilde Laporte
David Krüger B.Eng. (McGill University)

Submitted to
Karlsruhe Institute of Technology,
Institute of Vehicle Concepts - DLR Stuttgart
2025

KIT Karlsruher Institut für Technologie

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Declaration

I, Aatharv Keskar hereby certify that this thesis represents my original work, carried out under the supervision and guidance of the **Electrical and Information Technology Institute, KIT** and **Institute of Vehicle concepts, DLR Stuttgart**. The sources used for literature research are fully cited and referenced.

Karlsruhe, 29.08.2025

Acknowledgement

First and foremost, I would like to express my sincere gratitude to my academic supervisor, Prof. Dr. Martin Doppelbauer for his acceptance to supervise my thesis work and constant support. I am especially grateful to Dr. Matthias Brodatzki, my second academic supervisor, for his continuous technical guidance and constructive feedback throughout the thesis.

I am thankful to my supervisors, David Krüger and Mathilde Laporte, at the DLR- Institute of Vehicle Concepts, for giving me the opportunity to undertake this thesis. I would like to thank them for their consistent support, facilitation of key technical discussions with the experts at the institute, and for providing the required resources, all of which were instrumental in shaping the outcome of this thesis.

I would also like to sincerely thank all the component suppliers who generously assisted through calls and email exchanges by providing essential technical information about their products.

Last but certainly not least, I would like to thank my family and friends for their constant support and motivation throughout this period.

Abstract

The movement of goods through freight system is essential to the functioning of global economies and is an invisible force behind the global progress. In railway freight operations, the "last mile" shunting phase, responsible for delivering cargo to its final destination remains a challenge due to its reliance on conventional process. To address the limitations and align with environmental sustainability goals, the electrification of last mile shunting operations presents a promising solution.

This thesis focuses on the design and development of an electric powertrain system for an advanced self-propelled bogie and also on the preliminary evaluation of the thermal management of the overall drive system. The work involves a comprehensive analysis of the technical integration among powertrain components, focusing on the selection of optimal component types based on performance characteristics and ensuring their seamless integration while effectively managing cost and spatial constraints of the application.

For each component type, multiple options were considered and technically integrated with other components to ensure that performance requirements were met. Various powertrain system configurations were then developed and evaluated based on efficiency, cost, and spatial constraints. The result is a well-integrated powertrain architecture optimized to deliver reliable and efficient operation within the targeted application domain.

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List of Abbreviations

ASINO	**A**dvanced **s**elf-propelled fully **in**tegrated b**o**gie
AC	Alternate current
Ah	Ampere hour
BMS	Battery management system
CSI	Current source inverter
DTC	Direct torque control
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DC	Direct current
EV's	Electric vehicles
EMI	Electromagnetic interference
EMF	Electromotive force
FOC	Field oriented control
GHG's	Greenhouse gases
IM	Induction motor
LA	Lead acid
Li-ion	Lithium ion
Li-metal	Lithium metal
LFP	Lithium iron phosphate
LTO	Lithium titanate oxide
LMO	Lithium manganese oxide
LCO	Lithium cobalt oxide
Mt	Mega tonne
MOSFET	Metal–oxide–semiconductor field-effect transistor
NMC	Nickel manganese cobalt
NCA	Nickel cobalt aluminium oxide
NiCd	Nickel cadmium
NiMh	Nickel metal hydride
PM10	Particulate matter
PMSM	Permanent magnet synchronous motor
PMDC	Permanent magnet brushed direct current
PMBLDC	Permanent magnet brushless direct current
PWM	Pulse width modulation
rms	Root mean square
RPM	Revolutions per minute
SoC	State of charge
SiC	Silicon carbide
Si IGBT	Silicon insulated gate bi-polar transistor
SM	Synchronous motor
SRM	Switched reluctance motor
VVVF	Variable voltage variable frequency
VSI	Voltage source inverter

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1 Introduction

1.1 Motivation

Freight transport serves as a foundational component of global trade and economic activity. The constant flow of goods through various logistical processes including packaging, transport, reloading, and distribution is essential for supply chain continuity. The COVID-19 crisis between 2020 and 2022 also showed how important freight logistics are for the economic stability. However, after the impact of COVID-19, both logistics and freight transport have experienced a boom and as a result it is also essential for freight transport to reduce its emissions. Freight transport produces Greenhouse gases (GHG's), air pollutants and also creates noise pollution, hence it is a burden on environment and climate.[1]

As per the data, freight transport in Germany accounted for 55 megatonnes (Mt) carbon dioxide equivalents (CO_2e), which constituted more than 7% of the nation's total GHG emissions. Taking into account the emissions from indirect sources such as electricity, warehouse operation and infrastructure construction the sectors emission could increase up to 160 Mt. However, only national part of freight transport is covered under the German Climate Protection Act (Klimaschutzgesetz -KSG).[1]

Road freight transport contributed 98% to the total GHG emissions, making it up a majority of the contribution. Also, in the year 2022 it generated 107 000 t of nitrogen oxides and 25 000 t of particulate matter (PM10). In comparison, rail freight transport generated lower emissions, releasing less than 8 000 t and 9 000 t of nitrogen oxides and PM10 respectively. The contribution of nitrogen oxide in the rail freight transport is mainly due to combustion of diesel, e.g. in shunting operations. [1]

Germany aims to achieve greenhouse gas neutrality by 2045. Realising this vision will demand coordinated efforts in technological innovation and the scaling of low-carbon infrastructure. This transformation involves replacing diesel engines with electric drives, transitioning to post-fossil energy sources and a modal shift from road to rail integrating digital technologies across logistics networks. [1]

The existing conventional freight transport is divided between unit trains, which travels as a fixed arrangement of freight cars, and wagonload freight, in which the individual wagons have to be manually coupled and decoupled at the shunting yards before travelling to their final destination. This process of train formation, which also includes lengthy brake checks before departure, is time consuming and also not cost effective. This, in part, has driven the modal shift to road transport.

To address environmental concerns and make rail freight competitive with road freight, the potential solution would be to replace conventional freight wagons with modular and flexible self-propelled freight wagons. This can be realised by integrating the bogies under the wagon with a battery-electric drive system. These bogies are individually powered and operate independently. Based on this concept of self-propelled bogie, last mile shunting operations could become more effective and also GHG emissions would be reduced as compared to conventional freight operations.

1.2 About ASINO

To address the challenges of decarbonising rail freight transport, logistical complexities and modernising rail freight technological infrastructure, the Institute of Vehicle Concepts at Deutsches Zentrum für Luft- und Raumfahrt (DLR), Stuttgart under the ProCo project launched the sub-project "TP 4000: Self-propelled freight wagon bogie (ASINO-DG)" , a compact and advanced fully integrated freight wagon bogie.[2] The concept promotes modular propulsion, enabling wagons to operate independently in shunting yards and non-electrified segments.

The advantages of the self-propelled bogie include:

- Improved efficiency in last-mile and terminal operations
- Reduced environmental impact due to lower energy consumption and emissions
- Cost-effective logistics by minimising the reliance on conventional locomotives.

1.3 Use cases of self-propelled freight wagons

This section highlights the use cases of self-propelled freight wagons:[3]

1. It addresses the challenge of tractive power, by acting as a power booster and peak power shaver:

    - The "Power Booster" scenario enhances uphill traction by using self-propelled wagons to supplement locomotive power, maintaining constant speed and maximising line capacity. This distributed force reduces strain on the locomotive, preventing slowdowns and enabling longer or heavier trains for efficient freight transport on hilly terrain

    - The "Power Peak Shaving" scenario addresses electrical grid strain during peak loads by leveraging battery-powered bogies. Upon detecting grid peaks through communication, the system dynamically shifts traction demand from the locomotive to the battery bogies. This ensures consistent train power requirements are met, thereby preventing grid overload and enhancing network stability and efficiency

2. In combination with an automatic coupler, the wagon can be coupled and uncoupled. This greatly reduces the need for manual labour and increases the efficiency of freight operations through automated goods handling.

3. With these self-propelled wagons multiple wagons can be parallelly driven to different locations and shunted, significantly reducing the shunting time by 40-60% compared to the sequential shunting with the traditional wagons.

1.4 Scope of thesis

In the previous theses the mechanical design along with the functional requirements of the bogie – ASINO were conceptualised. [4, 5] The present work focuses on the electromechanical design of a compact and lightweight **electric powertrain** for the bogie, encompassing the selection and integration of key powertrain components that can be well fitted within the limited design space of the bogie, along with a preliminary thermal management analysis of the powertrain system. The final objective is to achieve a fully integrated drive system that meets the functional requirements described in details in the upcoming sections.

1.5 Solution approach

This section highlights the approach for the development of the powertrain for the self-propelled bogie, ASINO. The development for a powertrain system followed a structured and iterative design cycle ensuring the system-level integration of electrical and mechanical subsystems. A significant challenge throughout this process was accommodating the powertrain within the existing mechanical bogie's limited available design space while fulfilling all functional requirements.

The initial phase of concept development involved comprehensive literature research into powertrain systems. This included identifying major subcomponents and understanding their interdependencies. Following this, a systematic study of existing railway drive concepts was conducted. This analysis focused on how components are spatially arranged in current designs and evaluated the advantages and disadvantages of each drivetrain layout to understand their suitability.

The next step involved the detailed analysis and selection of system components. This encompassed determining the optimal battery system type, inverter topology, traction motor type, and gearbox type. Component selection was then performed based on defined system technical requirements.

This proved to be an iterative process, as the inherent interdependencies between components had to be carefully managed, particularly in the absence of exact technical specifications for readily available parts. This phase involved extensive research into various suppliers, analysis of technical datasheets, and direct communication with suppliers to gather detailed product information beyond what was publicly available. For each component, available options from different suppliers were compared and shortlisted.

The final phase of system development focused on the selection and integration of the selected components from the suppliers. Packaging concepts were then developed and optimized using CAD design, ensuring all elements could be accommodated within the constrained space while meeting performance objectives.

2 State of the Art

2.1 Types of Drives in Rail Freight Transport

2.1.1 Diesel Electric

In these drives, the combustion of fuel generates the mechanical energy to drive the generator or alternator. Alternators are usually preferred in modern-day locomotives. The alternating current generated by the alternator is then sent to the motors, which convert the electrical energy into mechanical energy to drive the wheels. Figure 1 represents the main components of a diesel electric locomotive [6]

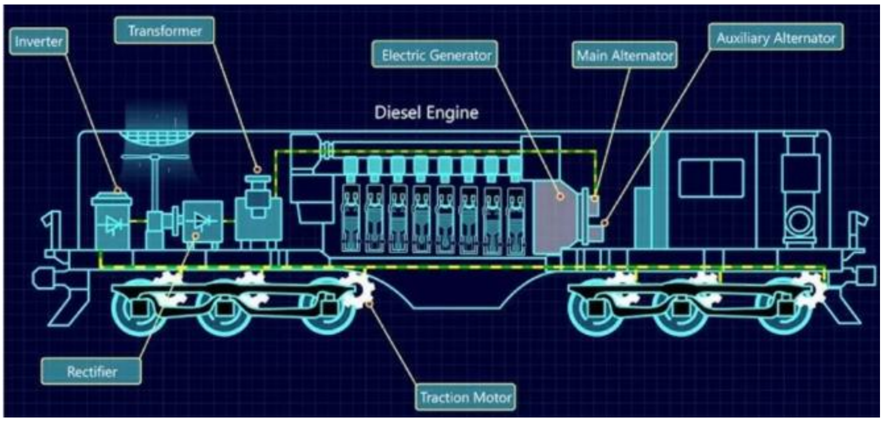

Figure 1 Diesel-electric locomotive [7]

2.1.2 Electric

An electric locomotive is a rail vehicle built to propel a train. It achieves this by drawing electrical energy from an external source, usually overhead cables or a third rail, and then conditioning that power to supply the traction motors that drive its wheels.[8]

Electric traction systems are typically divided into three groups: direct current (DC), alternating current (AC), and composite systems that integrate features from both. AC traction systems have become increasingly prominent, largely due to their practical and operational efficiencies.[9]

The process begins with the pantograph collecting single-phase AC, which a transformer steps down before it is rectified to DC by a rectifier. This DC is then smoothened and known as DC-Link, after which an inverter converts it into the necessary three-phase AC for the driving motors. Throughout this conversion, the current and voltage output to the motors is controlled by varying the output voltage and current across all the components by the microprocessors in the locomotive driving cabin. This integrated system, known as a Variable Voltage Variable Frequency (VVVF) drive ensures seamless and efficient operation. Figure 2 depicts the main components of an electric locomotive. [8]

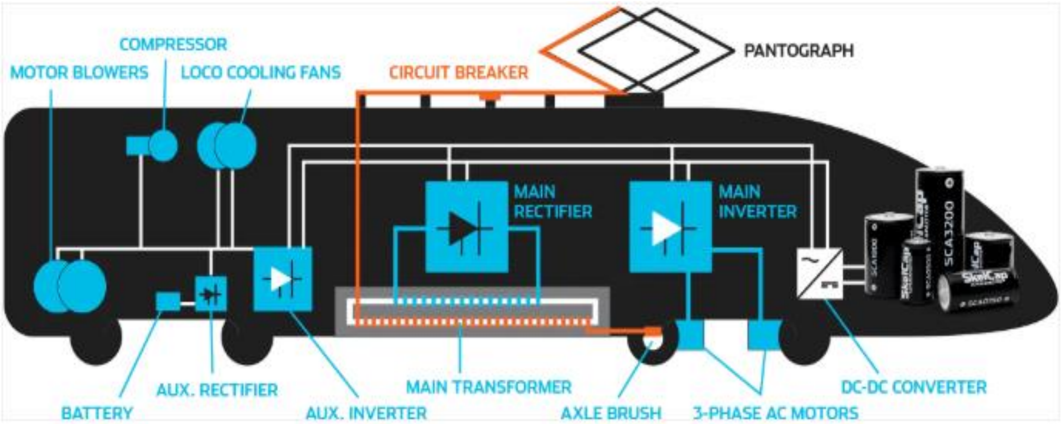

Figure 2 Electric locomotive [10]

2.1.3 Hybrid Drive

Hybrid locomotives are equipped with both, a diesel engine and a battery power system. Typically, an electric motor powered by battery, directly converts electrical energy into the mechanical force needed to propel the train. The internal combustion engine (diesel or gas) functions as a supplementary mechanical power source, activating to provide additional power during peak demand situations.[11]

2.1.4 Battery Electric Drive

Battery electric locomotives use a battery pack to power the electric motor, which converts electrical energy into mechanical energy to drive the wheels. These locomotives are not dependent on the supply from catenaries. Battery chemistry to be used in these locomotives depends on the application of the locomotive. These have less moving parts leading to the reduced maintenance requirements.[12] Figure 3 shows the main components of battery electric drive.

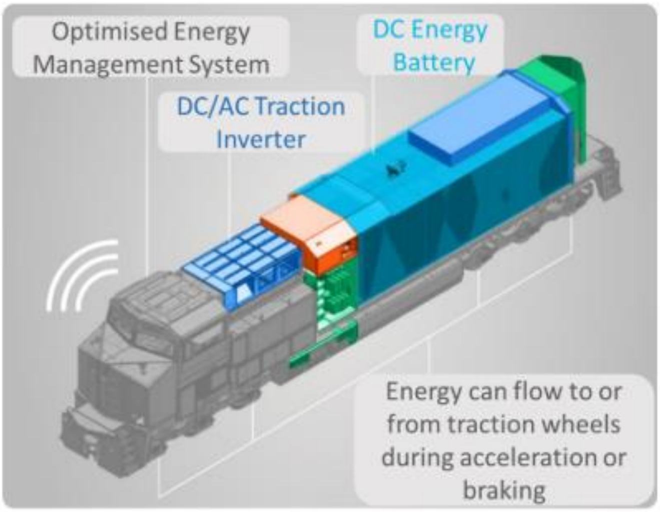

Figure 3 Battery electric drive [13]

2.2 Drive concepts for standard vehicles

Drive systems in railways are used to transmit the torque from the traction motor or the combustion engine, usually operating with higher speeds, to the wheelset via a gearbox. The overall trend from the early beginning of the drive design development was to apply increasing speeds of motors and engines to achieve a lower mass and to save space. This results in a higher gear ratio at a given train speed.

In addition, drive designs have to be capable to accommodate relative movements between the bogie/vehicle frame and the wheelset. Mass classification is an important aspect to be considered for the selection of drive system design. The mass is classified as:

1. **Sprung mass**: It refers to the weight of the components suspended by the springs including the body, transmission and the propulsion system.[14]
2. **Unsprung mass:** It refers to the weight not supported by the spring. This includes the weight of the wheel, tyres, brakes and other components and also the weight integrated with the wheels.[15]

Drive systems need to be suspended to reduce the unsprung mass for several reasons, some of them includes:[15]

1. It induces less shock and vibrations from the track irregularities which results in less stress on the cargo
2. Suspended components are easier for access and maintenance

3. Drive components which include sensitive electronics are protected from impacts of track irregularities.

Drive system design also has some requirements, such as it should be cost-optimised to balance budget constraints. Additionally, it should be compact and lightweight, ensuring efficient use of available space, and it must have bi-directional operability to ensure a reliable performance.

The sub-sections below describe the types of drive systems used in railway application.

2.2.1 Fully suspended drive system

In a fully suspended system, the traction motor and gearbox form a rigid unit that is fully sprung, meaning they are mounted to the bogie frame above the primary suspension. The connection between the suspended motor-gearbox unit and the unsprung wheelset is made via cardanic coupling. This coupling accommodates the relative movements between the sprung bogie and the unsprung wheelset as the train navigates track irregularities. Figure 4 shows a how different components are mounted in fully suspended type drive systems. [16]

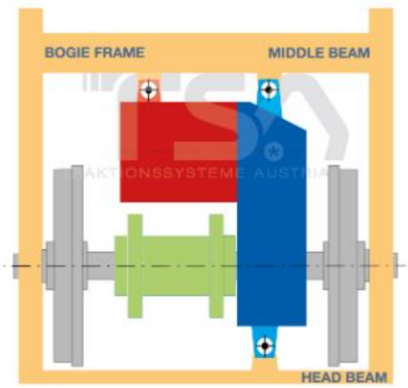

Figure 4 Fully suspended drive [16]

2.2.2 Semi suspended drive system

A semi-suspended drive systems is designed to distribute the weight of the traction motor and gearbox between the bogie frame and the wheelset. In this configuration motor and gearbox are rigidly bolted together forming a single unit suspended on the bogie frame with the help of two suspension elements. This also has third point of support which is the output coupling, connecting the gearbox's output shaft to the wheelset shaft. This coupling is important for accommodating the angular movements of the wheelset relative to the drive unit, while also providing minor damping to the system. Figure 5 depicts a semi suspended drive system. [16]

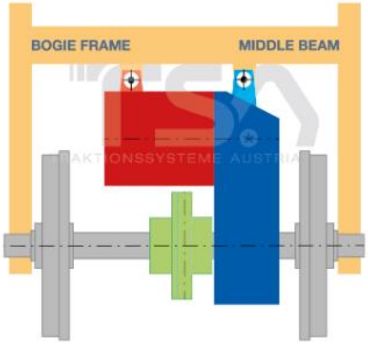

Figure 5 Semi-suspended drive [16]

2.2.3 Partly-Suspended Drive systems

In this drive system configuration, the traction motor is suspended most predominantly on the bogie frame, while the gearbox is supported both by the wheelset shaft and a dedicated mounting bracket affixed to the bogie's central cross-member. The main gear of the gearbox is directly mounted on the wheelset shaft. This is most commonly found in freight locomotives and medium speed passenger trains where robust and reliable solution is required. The advantage of this drive system is that it has no speed limit and both motor and gearbox can be handled individually. Figure 6 shows the arrangement of components in partly suspended drive system with their mounting points. [16]

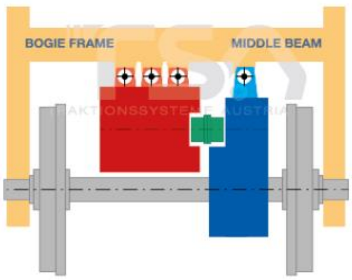

Figure 6 Partly suspended drive system [16]

There are also other types of drive concepts for standard vehicles like: [16]

- Partly suspended drive system: Wagon Wheel
- Partly suspended drive system: Head Beam
- Nose suspended drive systems

For the freight bogie application under consideration, a partly suspended drive system was selected. This choice is primarily due to the absence of a head beam in the current bogie design, which renders fully suspended and partly suspended head beam-type drive systems unsuitable for implementation. When compared to nose-suspended drive configurations, the partly suspended system offers a significant advantage in terms of lower unsprung mass, as the traction motor is predominantly supported by the central beam of the bogie. The reduction in unsprung mass leads to decreased dynamic forces acting on both the rails and the wheels, thereby contributing to extended service life and reduced wear.

Moreover, in a partly suspended drive setup, the motor and gearbox do not form a rigidly coupled drive assembly. This allows each component to be maintained or replaced independently, and the drive system is not constrained by specific speed limitations. This is in contrast to nose-suspended systems, which typically lack such operational and maintenance flexibility.

Overall, the partly suspended drive system presents a well-balanced trade-off between performance and cost, making it a highly suitable choice for various railway applications, especially in freight and conventional passenger transport. This configuration enhances dynamic behaviour, improves ride comfort, and extends the operational life of key components. Importantly, these benefits are achieved without incurring the higher capital expenditure and complex maintenance demands typically associated with more advanced drive systems.

2.3 Existing self-propelled freight cars

The driverless self-propelled freight wagon is an interesting concept to win market share for rail-bound freight transport. The advancement in technology with respect to sensors, artificial intelligence, and energy storage systems has accelerated the development in the field of self-propelled freight wagons in recent years.[3]

Some of the best examples of self-propelled freight wagons are:[3]

- SELF PROP RAIL: Eams-z wagon by RŽV Čakovec
- Intramotev ReVOLT: Self-propelled battery -electric rail car
- Self-Powered wheel units by Parallel Systems

2.3.1 Eams-z - Self Prop Rail

The self-propelled Eams-z wagon is intended for bulk material transportation and enhancement in railway infrastructure construction and maintenance. The wagon is integrated with two standard Y25L bogies and can operate at a maximum speed of 100 km/h with a train formation. It has a tare weight of 37.34 t and a maximum payload capacity of 52.5 t. The payload is distributed in two cargo bodies with each having the possibility of lateral and frontal lifting. The cargo crate kinematics is achieved using the power pack consisting of a 55 kW diesel engine and built-in hydraulic cylinders.[17] [18] The self-propelled wagon can be visualised from the Figure 7.

The wagon operates in 2 modes:[18]

1. **Transport Mode**: When it is operating as a standard freight wagon coupled with a regular train.
2. **Working Mode**: When it is moving independently along the tracks without needing to be coupled with an external power source

In the self-propelled mode, two small-diameter friction wheels connected to the hydraulics can also be lowered to the track and provide the tractive force required for wagon movement. The hydraulic mechanism for friction wheels is shown in the Figure 8

Figure 7 Eams Z wagon [17]

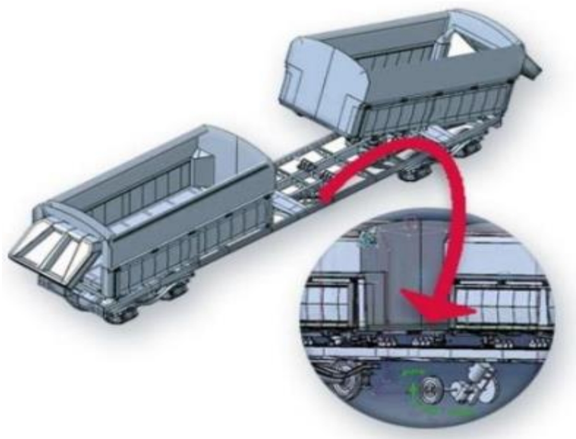

Figure 8 Self-propelled mode [18]

2.3.2 Intramotev ReVOLT

The next in the category to discuss is the ReVOLT – a self-propelled battery -electric rail car from Intramotev, an American technology company developing autonomous and zero emission rail solutions. It is powered using an on-board battery pack and also uses regenerative braking to recycle waste energy and use it to charge the battery pack.

Figure 9 represents the self-propelled ReVOLT rail car. The technology application of Intramotev is evident from its use as a freight train to transport coal from a coal mine of Iron Senergy to its storage facility. It covers the 27.3 km distance during this transport making it the world's first battery -electric railcar in regular commercial use. [19]

Figure 9 Intramotev ReVOLT- self-propelled battery car [20]

In addition to this, their product portfolio also has a proprietary kit that can retrofit existing railcars to become battery-electric named TugVolt. Carmeuse Cedarville mines have partnered with Intramotev to provide them with three TugVolt trains to transport materials. With the use of this, the company has estimated the reduction of diesel as a power source by 11 356 l/year. One of the TugVolt has been operational since November 2024 and the remaining were planned to be delivered by the spring of 2025. [21]

2.3.3 Parallel Systems

Another concept that aligns with the similar goal of this thesis is from Parallel systems, working towards a mission to deliver a safer, efficient and a sustainable alternative to short-haul trucking. They have developed self-powered traction units with each consisting of a battery pack, electric motor, wheelsets and sensor package which can carry the shipping containers placed on them autonomously. Figure 10 shows the traction units from Parallel systems. [22] Theoretically, each container supported by two traction units could be moved individually but will likely end up travelling in platoons. As long trains take time to load and block traffic while passing the Parallel Systems can break into smaller parts, reducing traffic jams with smart coordination. [23].Figure 11 depicts the platooning operation possible with the self-propelled traction units.

Figure 10 Parallel systems - Self-propelled traction units [23]

Figure 11 Platooning operation [24]

It is equipped with low maintenance and high efficiency electric powertrain which makes it possible to travel 800 km in a single charge. These rail vehicles are equipped with hydraulic braking system and braking electronics that prevents wheel slippage and maximizes the stopping force.

Each rail vehicle is equipped with software using predictive models to monitor onboard vehicle systems and also allowing seamless integration with the existing train control systems. [24]

On 4th June 2025 has launched its first commercial pilot for the first phase of testing on heart of Georgia railroad, a short-line rail-road operating in Georgia and Albama. Figure *12* shows the testing undergoing. [25]

Figure 12 First phase testing undergoing on heart of Georgia rail road [25]

3 Requirements of ASINO

The following sections details the specific requirements and specifications for the powertrain to be developed.

The bogie is supposed to be used individually for the last mile shunting operations and even has to be coupled with the locomotive for long distance travelling. The maximum speed of the bogie travelling alone is considered as 25 km/h based on freight stakeholders survey and previous theses. This is also based on the fact that the bogie has to travel shorter distance during the last mile shunting. As per the International union of railways (UIC) guidelines for a freight wagon with 22.5 t of axle load, maximum permissible speed is 120 km/h, hence it is considered as the maximum speed for the bogie. [4]

Similarly, there are other specifications which are provided by DLR and also from the results of the previous theses which are listed in the Table *1* of the section. [26]

The table lists the functional requirements of the bogie categorised as per the MoSCoW technique of prioritisation: [27]

- **M**ust-have – Critical and absolute necessary
- **S**hould-have – Important but not critical
- **C**ould-have – Desirable
- **W**on't-have – Not necessary

Specifications	Requirement Values	Unit	M = Must C = Can S = Should
Mass of the bogie	5 200	kg	M
Nominal static axle load	22.5	t/axle	M
Track Gauge	1 435	mm	M
New wheel Diameter	920	mm	M
Worn wheel diameter	840	mm	M
Drive Parameters			
Driving speed (When driving alone)	25	km/h	M
Max speed (When in convoy)	120	km/h	M
Minimum Power	75	kW	M
Maximum Power	100-120	kW	C
Acceleration at standstill, fully loaded (at a 12.5% gradient in a 100m curve)	0.05	m/s^2	M
Maximum Wheel Torque (15-30sec)	12 350	Nm	M
Continuous torque at wheel	6 350	Nm	M
Drive Type			
Partly Suspended			
Battery Parameters			
Battery Capacity	25	kWh	M
Battery Type	LFP or LTO cell type		
Cooling requirements	Liquid cooling - preferred		
Environmental Conditions			
Operating Temperatures	-30 bis +45	°C	M

Table 1 Requirements of ASINO

4 Components of Electric Powertrain

A powertrain is the most crucial component of the battery electric driven systems. It is a set of components assembled and integrated with each other and is responsible for the conversion of electrical energy stored in the battery pack to mechanical energy required to drive the wheels.

Electromechanical components of powertrain include:

1. Battery pack
2. Inverter
3. Electric motor
4. Gearbox

A comprehensive understanding of the electric powertrain components, and their intricate interdependency, is important to understand the overall system operation.

The following section describes the technical overview of each powertrain component.

4.1 Battery Pack

A battery pack is the main source of power in the electric traction application. It is made up of cells or modules, including the battery management system and the enclosure. Individual cells can be directly integrated to form a pack, which is known as cell-to-pack architecture, or cells may group to form modules, which can further be integrated to form a pack, known as module-to-pack architecture. Within each module, cells can be connected in series to increase the total voltage, or in parallel to enhance the battery capacity, or in combination to achieve the required capacity and voltage. Figure 13 shows the formation of module -to-pack architecture.

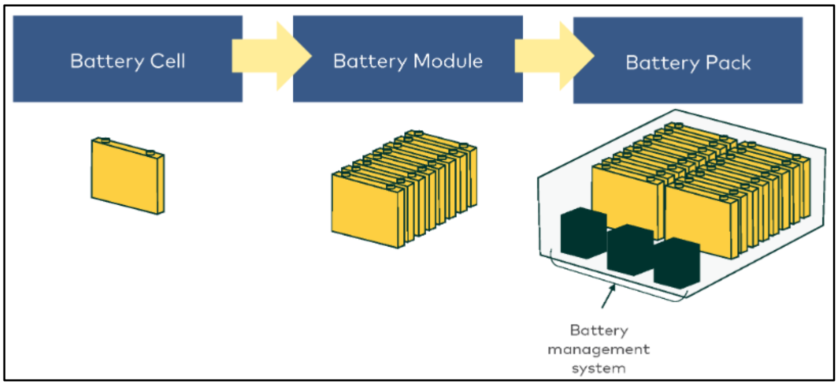

Figure 13 Battery cell, module and battery pack [28]

There are certain requirements that the battery pack must fulfil to meet the application needs and demands. These are:

- High specific energy
- High specific power
- Low cost
- Fast charging
- Life span
- Safety

This section covers how these specific requirements play an important role in determining the most suitable battery type for a powertrain. These factors are essential, as they directly influence the performance, efficiency, and reliability of the powertrain system, making them important in the battery selection process.

Specific energy

The specific energy of a battery, also referred to as gravimetric energy density quantifies the amount of electrical energy a battery can store per unit of its mass and is denoted by watt-hours per kilogram (Wh/kg). This is an important parameter, especially for applications, where minimizing weight is paramount. This gives the understanding about how energy-dense a battery is.[29][30] Batteries with higher specific energy are lighter in weight as compared to batteries with low specific energy storing same amount of energy. This advantage allows to achieve extended driving ranges and improves overall efficiency due to the reduced mass.[31]

Specific power

Specific power refers to the amount of power a battery can deliver per unit of mass, measured in watts per kilogram (W/kg). It indicates how quickly a battery can supply electrical power, which is essential for achieving rapid acceleration in vehicles. Additionally, batteries with high specific power can typically accept energy at a faster rate, enabling quicker charging times. [32]

Cost

Battery constitutes a significant portion of cost an electric powertrain. This significant cost proportion is largely driven by innovation and pricing dynamics within the raw materials sector. Consequently, instability in the cost of raw material costs and along with the sourcing complexities impacts the battery manufacturing expenses. The yearly trend for the battery cost from the year 2022 to 2025 can be analysed with the Figure 14. [33]

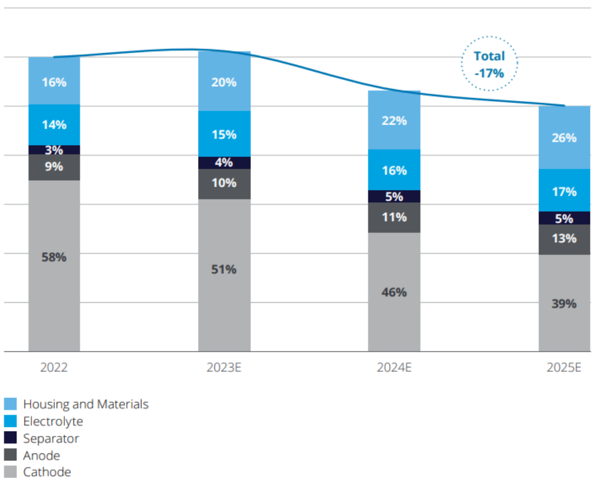

Figure 14 Cost of EV battery materials [33]

Lifespan

A battery should be robust to sustain multiple charge -discharge cycles before coming to its end of life. A battery with a lower lifespan will result in increase of operational cost of the application. Hence, a battery with long lifespan is important for a cost-effective application. Figure 15 shows the influencing factors of battery life.

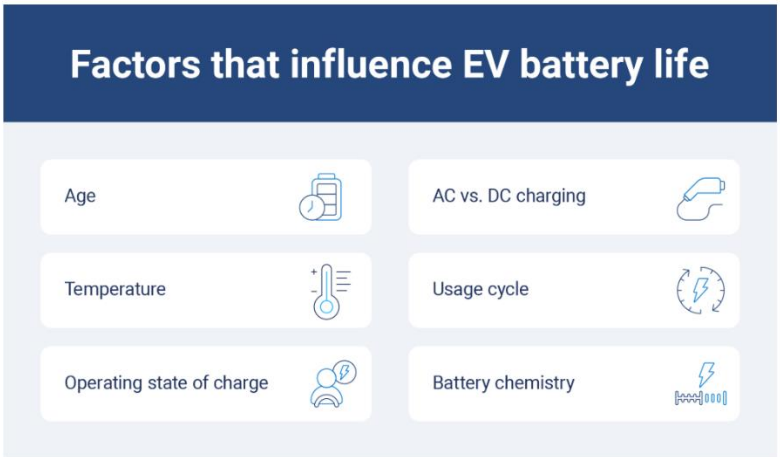

Figure 15 Factors affecting battery life [34]

Safety

Safety is a critical aspect of battery systems, as failures can result in severe damage or safety hazards. These failures may originate from internal sources, such as thermal runaway or material degradation, or from external conditions like mechanical impact, overcharging, or extreme temperatures. To reduce the risk of such failures, battery packs are equipped with protective components, including fuses, pressure-relief vents, and current-interrupting devices. Continued innovation in both materials and system design is essential to addressing the complex challenges of battery safety. [35]

Choosing the right traction battery for an application is about finding the best balance between several important parameters. Some factors, like cost or weight, can be adjusted or compromised depending on the use case, while others such as safety or energy density are usually given higher priority. In the following section, a comparative evaluation of various battery chemistries is presented to illustrate how these trade-offs influenced battery selection for this traction application.

Various types of electro chemical batteries are powering the vehicles today. The traction batteries support the entire vehicle unlike the auxiliary batteries which only provides the energy needed to start the vehicle. [36]

The most prominent electro chemistries used in the vehicles are:

- Lead- Acid (LA)
- Nickel-Cadmium (NiCd)
- Nickel- Metal hydride (NiMh)
- Lithium ion (Li-ion)
- Lithium-metal (Li-metal)

Lead acid batteries

LA batteries were the first commercially available rechargeable batteries for automotive applications.[36] These batteries are less expensive but have low specific energy (typically 30–50 Wh/kg), low energy density (approximately 80–100 Wh/L), and limited travel range. [31] These characteristics resulted in large and heavy battery packs that significantly increased the vehicle's curb weight, adversely affecting efficiency and driving range. As a result, they have largely been replaced by more advanced battery chemistries.

Nickel cadmium batteries

NiCd battery is a type of rechargeable energy storage device which is characterized by its use of nickel oxide hydroxide and metallic cadmium as electrode materials. [37] These batteries were supposed to replace LA batteries used in the vehicles in Europe, however their market adoption remained limited.[36] This was primarily due to a complex disadvantageous characteristics such as its relatively low energy density, significant self-discharge rate, susceptibility to the memory effect, high manufacturing costs, and the environmental toxicity associated with its constituent metals (nickel and cadmium).[37, 38]

Nickel metal hydride batteries

NiMH batteries use hydrogen inserted metallic alloys instead of cadmium at the negative electrode offering a more environmentally friendly and advanced solution than NiCd batteries.[39] These batteries offer higher specific energy (60–120 Wh/kg) and energy density (140–300 Wh/L) than NiCd batteries.[31] NiMH batteries have a safety advantage due to their use of an aqueous electrolyte, which is less flammable than the organic solvents used in other batteries. They offer good overall lifespan, particularly with durable nickel electrodes.[40] While NiMH batteries dominated the hybrid vehicle market in the early 2000s, they were eventually replaced by lithium-based batteries due to better performance and efficiency. [31]

Lithium-ion batteries

Li-ion batteries are currently the most widely used battery systems, particularly in EV applications, due to their high specific energy and favourable weight-to-performance ratios. Li-ion batteries offer a significant reduction in weight compared to earlier battery chemistries, making them widely used as traction batteries [36]

A graphical representation as shown in the Figure 16 is known as the Ragone plot. It is commonly used in battery research to compare and evaluate the most important performance parameters of various battery chemistries specifically, specific energy and the specific power. It facilitates the selection of an appropriate energy storage technology by clearly illustrating the trade-offs between energy density and power density under practical operating conditions. The plot underscores why Li-ion batteries are a preferred choice for electric powertrains, as they offer an optimal balance of both energy and power, two parameters essential for an efficient vehicle performance.

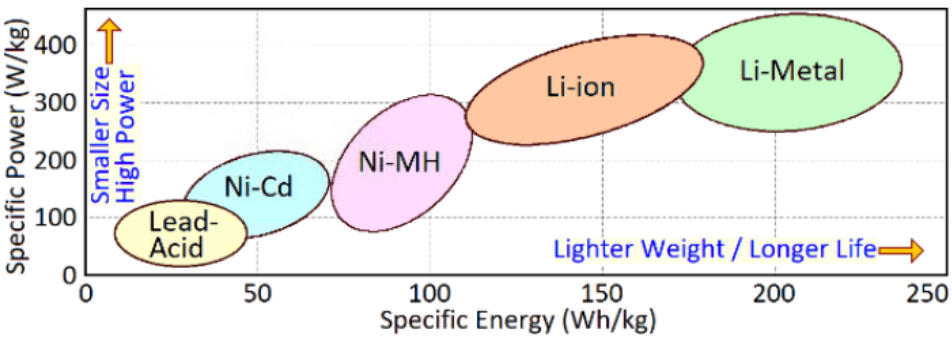

Figure 16 Ragone plot for battery chemistries [31]

While the diverse battery chemistries evaluated above have their unique advantages and disadvantages, the significant recent advancements in Li-ion technology have positioned Li-ion batteries as the leading solution for electric powertrains. Considering these essential parameters, Li-ion chemistry has been strategically selected for ASINO. The following section will thus explore the various Li-ion chemistries to identify the most appropriate option for this specific application.

Li-ion Battery chemistries

The cathode in a Li-ion battery is the main source of active lithium ions. Most commercial Li-ion batteries use cathode materials which are either lithiated metal oxides or lithiated metal phosphates. [41]

The Li-ion battery chemistries most frequently used for traction applications are: [42]

- Lithium iron phosphate ($LiFePO_4$, LFP)
- Lithium titanate ($Li_4Ti_5O_{12}$, LTO)
- Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$, NMC)
- Lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$, NCA)

There is no single Li-ion chemistry which possesses all the desired specifications rather each of these chemistries offers a unique balance of energy density, safety, lifespan, and cost, allowing them to be tailored for different application.

- **Lithium iron phosphate ($LiFePO_4$, LFP)**

LFP represents one of the more recent advancements in Li-ion battery chemistries. The use of phosphate-based compounds instead of metal oxides in the cathode enhances both the safety and reliability of the battery compared to materials such as Lithium Manganese Oxide (LMO) or Lithium Cobalt Oxide (LCO).[41] Phosphate compounds contribute to improved thermal stability by resisting degradation during overcharging and maintaining structural integrity at elevated temperatures. As a result, LFP batteries exhibit a broad operational temperature range from approximately −30°C to +60°C, and have a significantly lower risk of thermal runaway.[43] The cathode's olivine crystal structure enhances its resistance to oxidation and corrosive environments. It is less toxic and costly than other cathode materials but a key drawback of LFP cells is their relatively higher self-discharge rate, which may lead to cell imbalance over time, particularly as the battery ages.[41, 43]

- **Lithium titanate ($Li_4Ti_5O_{12}$, LTO)**

This is the most preferred chemistry to be used commercially with LTO as an anode material. LTO has high operating voltage which is beneficial in not allowing the growth of lithium dendrites even if the cell is temporarily overcharged, which leads to a better safety. Therefore, even at negative temperatures LTO provides high charge capability.

It is thermally more stable than chemistries with graphite as anode like LFP at above 200℃ [44] [45]

- **Lithium nickel manganese cobalt oxide ($LiNiMnCoO_2$, NMC)**

These are most effective Li-ion systems and high-in demand batteries for the traction application. These chemistries use nickel-manganese-cobalt as the cathode active material and offers high specific energy. Most commonly used NMC batteries are NMC-111, NMC-532, NMC-622. The number combination following, represents the relative quantity of the metals used as shown in the Figure 17. Adding these metals in different proportions affects the battery performance. [46]

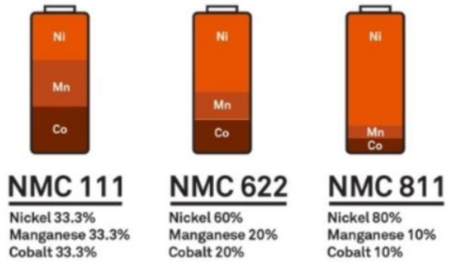

Figure 17 NMC battery types based on proportion of metals [47]

- **Lithium nickel cobalt aluminium oxide ($LiNiCoAlO_2$, NCA)**

These batteries use lithium nickel cobalt aluminium oxide as cathode. It is similar to NMC battery in terms of specific energy and specific power. NCA batteries are less safe in comparison to the above chemistries and also requires special safety measures. High manufacturing costs limits their use in different applications.[43]

The radar chart presented in the Figure 18 provides a visual comparison of the previously evaluated battery chemistries, illustrating how each one performs relative to the key parameters essential for electric powertrain applications.

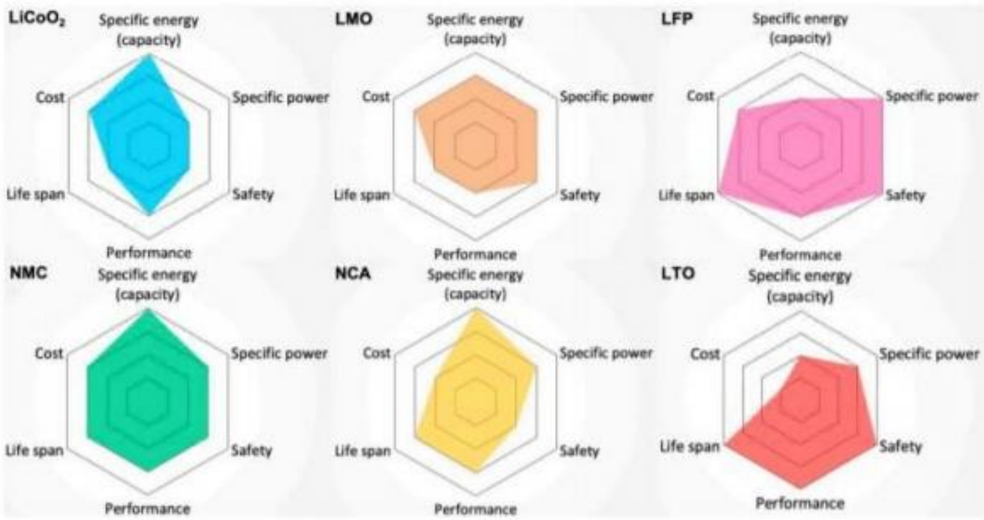

Figure 18 Radar chart for battery comparison [36]

Selection for Li-ion battery chemistries

Weight and volume of battery

A key parameter for assessing the suitability of a battery chemistry for a specific application is energy density, which refers to the amount of energy stored per unit of weight or volume. This plays an important role in determining the overall efficiency and feasibility of a battery system.[42] Among Li-ion chemistries, NMC batteries exhibit a wide range of energy densities from approximately 140 Wh/kg for NMC-111 cell types to around 300 Wh/kg in more advanced cell types such as NMC-811. Similarly, NCA batteries demonstrate high energy density, ranging between 200 to 322 Wh/kg, making them suitable for applications requiring extended range. In contrast LFP cells typically offer lower energy density but still comparable to NMC, generally in the range of 90 to 190 Wh/kg.[46] LTO batteries have the minimum energy density values compared to the other chemistries.

Economic aspect of batteries

The decision-making process on the traction battery selection heavily depends on economic aspect. The research suggests that global average battery prices decreased slightly from $153 per kilowatt-hour (kWh) in 2022 to $149 in 2023. The prices could even reach around $80 per kWh by 2026, indicating nearly a 50% drop from 2023. [48] The drop in battery prices along the years can be seen in the Figure 19. There are two major reasons for the price slash: one being the technological innovation and other being the reduction in the battery metal prices which contributes approximately 60% of the cost of batteries. The cost for NMC-532 cells may go around 110 to 130 EUR/kWh to 30 EUR/kWh for NMC-811 cells. The cost for LFP cells may go around 70 to 110 EUR/kWh and for NCA it goes around 80 to 130 EUR/kWh.[46] The cost of LTO batteries is considerably higher than other chemistries because of use of titanium as anode material.

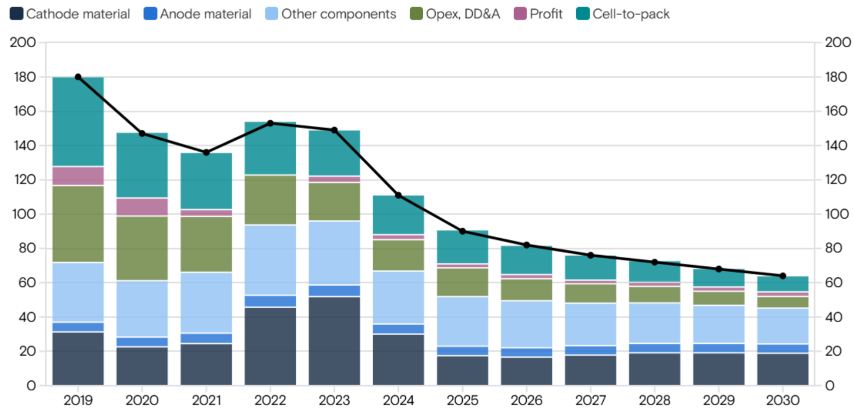

Figure 19 Trend for the battery prices [48]

Safety and Lifecycle

Another important consideration in selection parameters are safety and lifecycle. As per the experts, NCA batteries have lifecycle of 1 000 to 1 500 cycles, but at elevated temperatures these batteries are more prone to thermal runway and also loss of capacity due to strange reactions, leading to rapid ageing of the battery. NMC batteries also have similar lifecycle as that of NCA which is also around 1 000 to 1 500 cycles. On the other hand, LFP batteries show excellent thermal stability along with high structural and cyclic stability. They have a service life of 2 000 to 4 000 lifecycles. In LTO cells the lithium extraction and insertion occurs highly reversibly which leads to no significant change of volume resulting in long lifespan which can go up to 15 000 to 60 000 full cycles based on test conditions. LTO have very low risk of thermal runaway and is considered amongst the safest chemistries. [46, 49]

Beyond the battery technologies discussed above, a number of next generation battery technologies such as solid state and sodium-ion batteries, are actively being researched and developed in an effort to commercialise them. In solid state batteries an ion-conducting solid is used instead of a liquid organic electrolyte. These batteries use three different categories of solid electrolytes namely polymeric, hybrid and ceramic. The choice of electrolyte is based on the trade-off between cycle life, operating temperature safety etc. Although, these batteries are currently expensive due to their developmental stage but are promising as the next generation energy storage.[46]

On the other hand, sodium-ion batteries are potentially low-cost alternative to the Li-ion batteries due to the wide availability of sodium. These batteries have the advantage of being free from lithium and retaining 90% of its operational performance event at temperatures of -20℃. These batteries are less flammable than LFP's and also shows high temperature resistance.[46]

The battery is to be used in the powertrain of ASINO which is a commercial application that requires a chemistry capable of withstanding multiple charge and discharge cycles. It should be able to support frequent regenerative braking, which results in high instantaneous charging currents, and has safety-critical constraints. LTO chemistry is the preferred choice by trading off low energy density and high cost against safety, longer lifecycle, and fast charging capability. In the section5 discussed ahead, other chemistries are also taken into consideration for comparison, keeping in mind the cost and spatial constraints.

4.2 Traction inverter

Inverters are a type of power electronics, which is a group of devices that regulate the flow of electricity. [50] The term 'traction' means pulling something over a surface. So basically, it is device utilised to provide motion over a surface in coordination with an electric motor. In the context of EV's, a traction inverter is an essential power electronic device that converts the DC supply from the batteries to the AC supply required for the motor. In an AC motor, the direction of current flow in each phase must be reversed between positive and negative at the proper times, based on the motor shaft position and the required torque. As the speed increases, current alternation becomes more rapid. This frequency and the exact timing of the phase currents is managed by a traction inverter, which continuously tracks the shaft angle and calculates the appropriate current needed to generate the desired torque at each instant. Figure 20 shows the detailed schematic view of inverter used in traction application. [51]

To choose an inverter for railway freight applications, it is important to consider electrical, mechanical, and environmental factors. Electrical considerations include the acceptable DC voltage range, peak and continuous power requirements, and the inverter's AC output current capacity. Mechanically, factors such as the inverter's mass, physical dimensions, mounting provisions, and cooling system specifications, including coolant temperature range and flow rate, must be evaluated. Additionally, environmental requirements are determined based on the mounting location within the vehicle.[52] Figure 21 shows the image of a vehicle inverter with assembly of its different components.

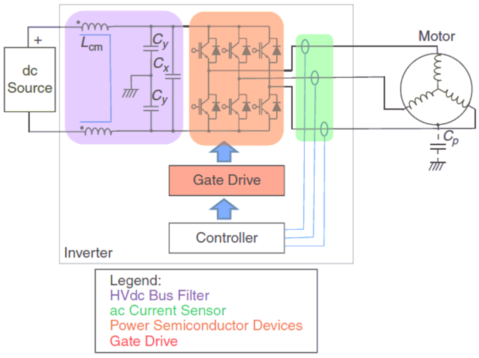

Figure 20 Schematic of an inverter [52]

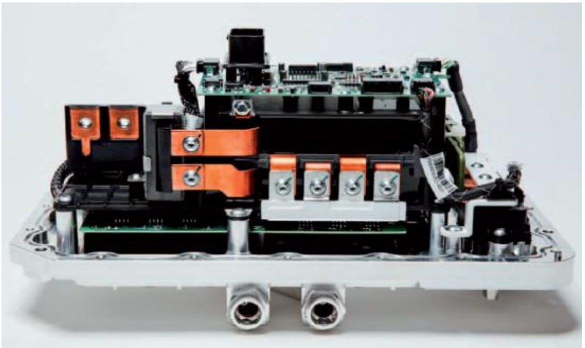

Figure 21 Vehicle inverter [52]

The 2 major types of inverters based on input source are:

- Voltage source inverter (VSI)
- Current source inverter (CSI)

Voltage source inverters (VSI's) are the industry standard for modern railway traction and EVs, thanks to their control flexibility, efficiency, and compact design. VSI's can be further classified into is sub-types as shown in the Figure 22.

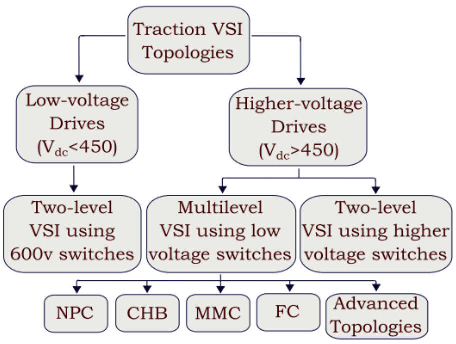

Figure 22 Classification of VSI's [53]

By optimizing the Inverter configuration higher operating voltages can be achieved. Hence, inverters can further be classified according to voltage level-wise as:

- Two-level inverter
- Multi-level inverter

In recent years, there has been a noticeable shift toward increasing battery voltage levels in electric traction drives, particularly in passenger EV's.[53] For this to be accepted by the inverter the structure must be changed in order to withstand higher voltages. Each inverter level, whether 2-level or multilevel, presents distinct advantages and disadvantages that must be evaluated when selecting the appropriate topology for a specific application. Figure 23 presents the traction application of different topologies of inverter. The decision largely depends on factors such as circuit complexity, physical size, cost, and the control techniques required.

Application	DC Voltage (V)	Structure	Switching Devices
Electric Ships	1.5 kV to 15 kV	Two-level or Multilevel	GTO, Thyristor, or IGBT
Trains and Tramways	up to 3 kV	Two-level or Three-level	GTO, Thyristor, or IGBT
Buses, Trucks	up to 900 V	Two-level	IGBT, MOSFET
Passenger EVs	up to 900 V	Two-level	IGBT, MOSFET

Figure 23 Topologies of inverter for different traction application [54]

Multilevel inverters are increasingly considered as alternatives to traditional 2-level inverters in high-voltage electric drive applications. In contrast, using 2-level inverters at elevated voltages can lead to increased electromagnetic interference emissions (EMI), higher voltage stress across switching devices, and power quality degradation. [55] Given that cost and size are constraints in EV design, these factors must be carefully considered when evaluating and selecting among different inverter topologies. Multilevel inverters generally require a larger number of capacitors, which are often the bulkiest and heaviest components in the inverter system. This results in increased system volume and weight compared to their 2-level counterparts. Furthermore, the higher number of semiconductor switches used in multilevel designs contributes to increased cost. [54] The inclusion of additional elements such as pre-charging circuits and voltage sensors further impacts system reliability in multi-level inverters.[53] Moreover, the implementation of advanced motor control strategies like direct torque control (DTC) and field-oriented control (FOC) tends to be more complex in multilevel inverter systems, as compared to 2- level inverters.[55] Since for our application with cost and spatial constraints 2- level inverters would be the feasible choice.

Power semiconductor devices form the core of the inverter and plays the fundamental role of switching and converting within power control systems.[56] Their primary function is to rapidly switch the high-voltage DC output from the battery on and off to synthesize an AC waveform that drives the electric motor. This application is particularly demanding due to the high voltages, large current flows, and elevated operating temperatures experienced.[57] Key performance parameters of these devices include voltage and current ratings, conduction and switching losses, as well as short-circuit tolerance, all of which significantly influence inverter efficiency and reliability.[52]

Figure 24 shows the classification of power semiconductors based on their operation.

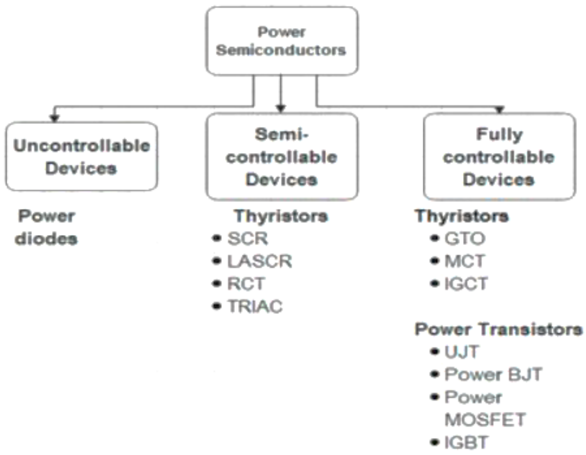

Figure 24 Classification of power semiconductors [56]

Since the introduction of EV1 - the first modern and mass-produced EV from General Motors in 1996, silicon (Si) insulated-gate bipolar transistor (IGBT) has been the dominant switching device in EV power converters and inverters.[52] However, with Si-based IGBTs and metal-oxide-semiconductor field- effect transistor (MOSFET) nearing their material performance limits, silicon carbide (SiC) MOSFETs have emerged in recent years as alternatives. SiC devices offer key advantages over conventional silicon counterparts, like significantly lower conduction and switching losses, faster switching speeds, reduced voltage drops, and the ability to operate at higher temperatures. These benefits are due to the intrinsic material properties and device structure of SiC. Hence, as a result SiC based devices are more efficient and power dense compared to their Si counterparts. Additionally, they facilitate a more sinusoidal phase current waveform, reducing harmonic content which results in getting benefited from high motor efficiency. [52][58] Figure 25 shows the radar chart comparing the important properties of Si IGBT and SiC MOSFET's.

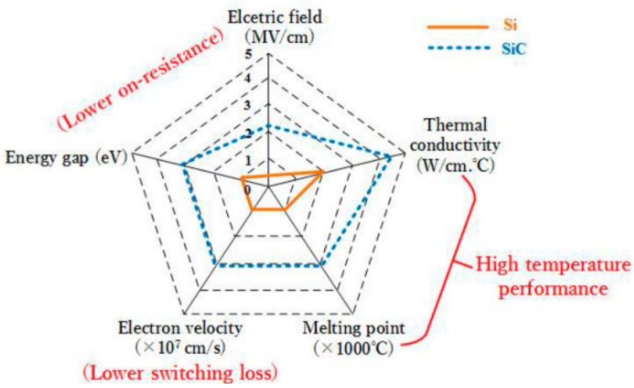

Figure 25 Radar chart - Si v/s SiC [58]

Despite these clear advantages, Si-based IGBTs remain the most widely used in traction inverter applications today, primarily due to their technological maturity, widespread availability at required voltage and current ratings, and cost-effectiveness.[54] Based on the advantages discussed in the section above inverter with Si IGBT power semiconductor is the preferred choice for ASINO.

4.3 Electric motor

One of the key components of the powertrain responsible for propulsion is the traction motor, which derives its power from the battery system. In electric powertrains, electrical energy serves as the primary energy source. This energy is stored in the battery and subsequently converted into mechanical energy by the electric motor to drive the vehicle.[59] The motor plays a central role in vehicle dynamics, as it delivers torque directly to the wheels in traction applications. Consequently, the performance of EV is largely governed by the torque-speed characteristics of the traction motor.[60] Traction motors must be capable of providing high torque at low speeds while also maintaining operational efficiency across a broad speed range. The selection of an appropriate electric motor for traction applications is demanding step in powertrain design.

Key requirements for a traction motor include: [61][62]

- High instant power and power density
- High torque at low speed and high power at high speeds
- Faster torque response
- Regenerative braking capacity
- Lower moment of inertia
- High performance to price ratio
- Reduced weight & smaller size

Considering these requirements, the selection of a suitable electric motor for traction applications poses a substantial engineering challenge as different types of motors exhibit unique advantages and limitations.[63] Figure 26 represents the different motor types used for the traction application.

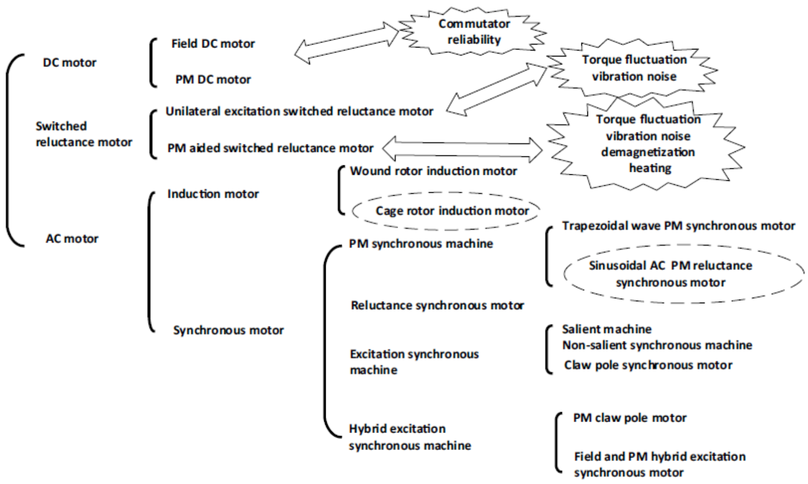

Figure 26 Motor types for traction applications [62]

The commonly considered motor types for the traction application are:

1) Direct current motors
    - Permanent magnet brushed DC motors (PMDC's)
    - Permanent magnet brushless DC motors (PMBLDC's)
2) Alternate current motors
    - Synchronous motors (SM's)
        - Permanent magnet synchronous motors (PMSM's)
3) Induction motors (IM's)
4) Switched reluctance motors (SRM's)

Brushed DC motor drive

These motors have been employed as traction motors since the late nineteenth century due to their ability to deliver high torque at low speeds, a key requirement for traction applications. Their speed can be controlled effectively by adjusting the supply voltage, and they are typically designed with two, four, or six poles, depending on the required power output and operating voltage. However, despite these advantages, such motors are characterized by significant drawbacks. They tend to have a large mass and relatively low efficiency, and the use of brushes and a mechanical commutator leads to increased maintenance demands. Furthermore, the mechanical commutation process also restricts the motor's maximum speed. Taken together, these limitations make them less viable for current electric traction demands. [59, 60] Construction of the brushed DC motor is shown in the Figure 27

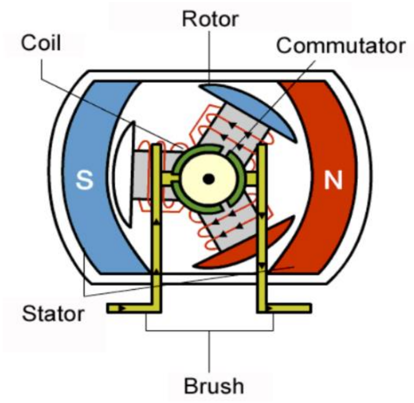

Figure 27 Schematic Construction of a Brushed DC Motor [64]

Permanent magnet brushless DC motor

PMBLDC is a specialised form PMSM characterised by the use of permanent magnets on the rotor as shown in the Figure 28. This design eliminates the need for energy to produce magnetic poles, thereby improving efficiency compared to PMDC motors, IMs, and SRMs. The absence of a commutator-brush system removes mechanical speed limitations, however in inner-rotor configurations, the strength of the magnets may constrain maximum speed. Despite its efficiency advantages and good thermal performance, the PMBLDC motor faces several drawbacks. The use of rare-earth magnets increases cost and also limits their scalability for high-torque applications because of its mechanical strength. Torque ripple and acoustic noise are common during electronic commutation, and it also suffers from limited field weakening capability, limiting its high-speed performance. Additionally, increased switching frequency at high speeds leads to elevated switching losses and reduced efficiency.[62, 60]

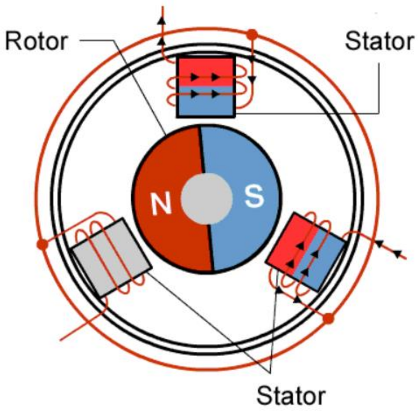

Figure 28 PMBLDC Motor [64]

Permanent magnet synchronous motor

This motor is employed in most of the EV's in the market. PMSM belongs to the AC synchronous motor category and the excitation windings of the traditional SM are replaced by permanent magnets.[62] The stator windings are supplied with three phase AC generating a rotating magnetic field reacting to the constant magnetic field of the rotor causing swirling.[65]

PMSM's are classified based on the position of permanent magnets:

1. Surface-mounted PMSM (SPMSM): Magnets are mounted on the rotor surface
2. Interior embedded PMSM (IPMSM): Magnets are embedded inside the rotor

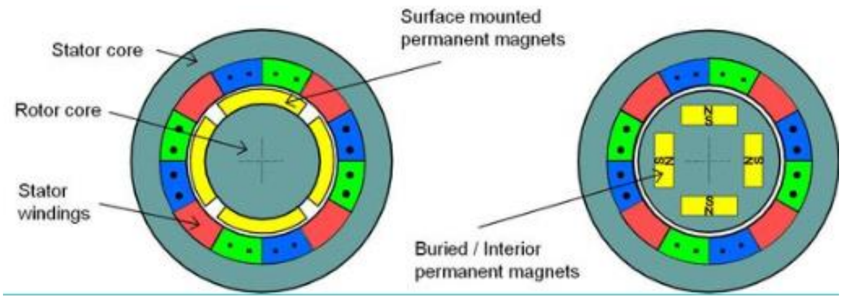

Figure 29 Cross section - SPMSM V/S IPMSM [66]

Figure 29 shows the difference between SPMSM and IPMSM in cross sectional view.Figure *29*

IPMSM's are more widely considered in traction applications because of high torque density, mechanical strength and efficiency reasons compared to surface mounted PMSM.

The use of PMSM offers advantages such as:

1. The airgap magnetic field and rotor rotate synchronously, resulting in no rotor losses[63]
2. Use of high-energy, high-coercivity rare-earth magnets enables PM machines to achieve high torque density[63]
3. PMSM offers high power density allowing for the design of smaller and lighter electric motors[67]
4. Advanced power electronics allow precise control, enabling rapid acceleration, deceleration, and smooth regenerative braking[67]
5. PMSM motors typically operate with lower noise and vibration than many other motor types.[67]

Reluctance torque, which boosts the machine output power is dependent on the placement of magnets.[63]

Because of all these benefits IPMSMs have become dominant in traction motor applications. Despite their impressive performance there are some limitations of PMSM motors, like the excitation torque generated by the permanent magnets is reduced during field weakening therefore it has high torque ripple.[63] Also, due to the use of permanent magnets PMSM motors are more expensive to manufacture. High temperatures and excessive heat can demagnetize the permanent magnets and impact motor performance.[67] Difference between output current profiles of BLDC and PMSM is shown in the Figure 30.

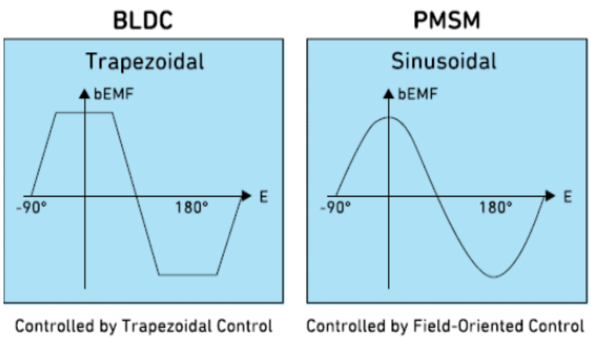

Figure 30 Output Current Profiles - BLDC v/s PMSM [68]

Induction motors

These are also the most widely used traction motors. Since any machine with brushes or commutators are not preferred because of their high maintenance, squirrel cage induction motors are most preferred.[62, 61] From its construction point of view, stator and rotor cores are built from laminated sheets of silicon steel. The rotor conductors are bars of copper or aluminium, which are placed in the parallel slots of the rotor and brazed to the end rings, and the windings are integrated with the lamination stack of the stator.[62] These motors have simple and rugged construction and are also cost effective and reliable.[59] They are operated with a vector control drive allowing them for a wide speed range variation. IMs are less power dense and efficient in comparison to PMSMs and also has complex control which leads to reduction of its contribution in the global market.[62] A detailed cross section of the IM is represented in the Figure 31.

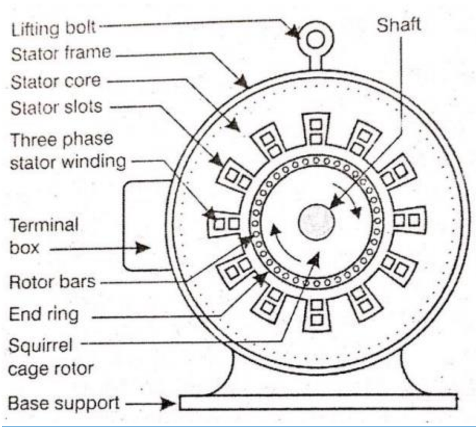

Figure 31 Induction Motor [69]

Switched reluctance motor

These were the primary motors employed in the first EV prototypes.[65] There are simple concentrated windings on the stator. The rotor is made from a stack of laminated iron sheets of ferroelectric material and does not include windings and permanent magnets which makes this motor suitable for high speed operations.[62, 70] The absence of permanent magnets and windings makes thermal management simple and also makes it suitable for short time overloading operation which is beneficial in electric traction applications.[71] Advanced control methods allow for high speed operation with high starting torques, making it suitable for its use in gearless powertrain operations. [70, 60] These motors have a single source of excitation and a salient pole structure, which makes vibration a constraint while achieving higher power densities. Its low cost and robust construction characteristics makes it suitable for EV traction.[63] Figure 32 shows the construction of SRM.

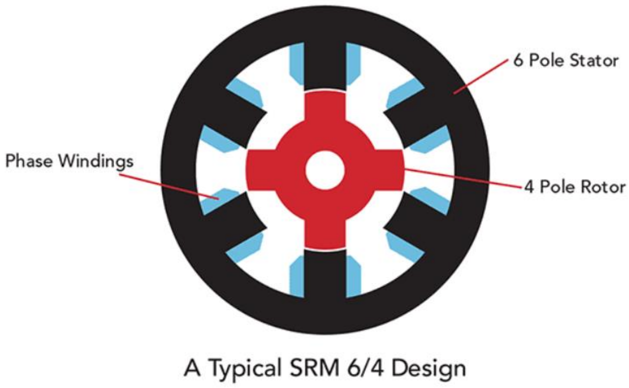

Figure 32 Switch Reluctance Motor [72]

The selection of appropriate motor technology is an important aspect of powertrain development, particularly in traction applications. Although several motor types may be applicable to the same use case but the identification of most suitable motor technology requires a detailed analysis. Discussed the specific performance attributes required for traction applications, a comparative analysis of various commercially available motor technologies has been presented in the section above.

Based on the comparative analysis and aligned with the key performance requirements outlined in this thesis, motor technologies such as IPMSMs, IMs, SRMs emerge as the primary candidates for railway freight traction applications. Brushed DC motors are excluded from consideration due to their bulky construction, lower efficiency, and high maintenance demands associated with mechanical commutators and brushes. While PMBLDC motors offer high efficiency and power density, they are not preferred in this context due to their limited field weakening capability resulting from trapezoidal control, which further contributes to undesirable acoustic noise and torque ripple. In spite of having all the desired characteristics IM is not considered for the application because of the rotor copper losses limiting their application in high torque operation which is an essential requirement of the application and also because of the weight constraints. In contrast, IPMSMs are favoured over IMs due to their comparatively higher power density, efficiency, and better fault tolerance. SRMs are currently not viable for this application owing to their pronounced torque ripple, acoustic noise, and lack of commercial maturity in the railway sector. Therefore, PMSMs represent the most appropriate choice for the proposed traction system.

4.4 Gearbox

Gearbox is used to transmit the power to the wheels. This helps in reduction of speed and increase of torque at the wheels. It has set of gears which helps in achieving the reduction of speed. Freight application gearboxes are designed for heavy duty use and they offer high load bearing capacity.

5 Design of Powertrain System

System integration

The objective of this thesis was to design and integrate an electric powertrain that fulfils defined performance specifications while adhering to strict spatial and economic constraints. To achieve this, component selection was guided by a thorough evaluation of electrical, mechanical, and thermal compatibility. In parallel, a comprehensive thermal management strategy was also developed to ensure component operation in its optimal operating temperature range, improving overall efficiency and ensuring the system's reliability.

System integration is not just about assembly of components, but it is also about ensuring that the components work seamless and efficient after integration.

This integrated design methodology enabled the development of a compact and cost-efficient powertrain architecture. The following section describes the inter-dependencies between the battery system, power electronics, motor, and mechanical transmission. It discusses how these dependencies were identified and addressed in the overall system design.

The first component to be selected for the powertrain is the electric motor and its selection ensuring optimal compatibility with other components. Given that ASINO to be used in last-mile shunting operations require high torque at low speeds, the motor must deliver both high continuous and peak torque. For ASINO the continuous and peak torques are 6 350 Nm and 12 400 Nm respectively which are very high for the motor to deliver individually, hence there is a need for the integration of gearbox with the motor to amplify torque at the wheels. To minimize the gearbox ratio a motor with the highest possible torques was sought. This combination of highest possible torque motor and lowest possible gearbox fits well within the available space. The selection was done through the detailed understanding of the datasheets and possible technical discussions with the suppliers. Table 2 shows the detailed technical comparison of motors considered for selection.

	AMXE200L - 3GLX203583-BFA [73]	AMXE250L - 3GLX253582-BFA [74]	iM-425 Motor inverter Module [75]	Unit
Manufacturer	**ABB**	**ABB**	**Cascadia Motion**	-
Motor Type	3ø - PMSM	3ø - PMSM	3ø - PMSM	-
Continuous Power @Nominal speed	127	118	280	kW
Nominal RPM	1 500	750	-	RPM
Max.Permissible RPM	5 000	3 500	6 000	RPM
Nominal Voltage	750	750	750	V
Continuous Torque	811	1 500	1 580	Nm
Peak Torque	2 813	3 353	2 700	Nm
Continuous Current	241	257	-	A
Inertia	0.417	1.22	1.09	$kg.m^2$
Dimensions (L x ø)	655 X 404	635 X 510	495 X 574 X 547 (L X W X H)	mm
Weight	287	490	190	kg
Efficiency	96		98 (Combined)	%
IP rating	IP67	IP66	-	-
Thermal Management	Liquid Cooled	Liquid Cooled	Liquid Cooled	-

Table 2 Specifications of motors

The ABB AMXE250L motor offers the highest peak and continuous torque among the motors considered, resulting in the lowest possible gearbox ratio for integration. However, its substantial size and weight exceed the system’s design space, making it unsuitable for the available space. Additionally, its comparatively high inertia is a drawback for the ASINO application's last-mile shunting operations, where frequent starts and stops demand manoeuvrability and energy efficiency. The greater inertia means more energy is required during acceleration and more is dissipated during deceleration, reducing overall system efficiency, hence not considered for the application.

The Cascadia iM-425 is a lightweight motor-inverter integrated module weighing 190 kg, eliminating the need for a separate inverter and thus reducing system complexity. Its high peak torque allowing for a low gear ratio of 4.57, enabling a more compact gearbox. However, logistical constraints of shipping this motor from the United States will incur expenses and also is complex, which makes this module unsuitable for the application.

The ABB AMXE200L-3GLX203583-BFA motor satisfies the functional requirements while being compact enough to fit within the available space. Its inertia and weight are significantly lower than those of the AMXE250L, enhancing system efficiency and making it a more optimal choice for weight-sensitive applications. Although its continuous torque is nearly half that of the AMXE250L, resulting in a higher gear ratio of 7.83 and a comparatively larger gearbox. However, the trade-off between size and energy efficiency favours the latter. Also, the motor revolutions per minute (RPM) during individual bogie operation remains within its nominal rating.

$$i = \frac{T_{wheel}}{T_{motor}} = \frac{6350}{811} = \ 7.83 \tag{1}$$

Where,

i = Gear ratio

T_{wheel} = Required torque at wheels in Nm

T_{motor} = Motor output torque in Nm

The calculation below illustrates the wheel and motor RPM at bogie speed of 25 km/h under self-propelled conditions:

$$\text{Circumference} = 2\pi r = 2\pi \cdot 0.42 = 2.64\ \text{m} \tag{2}$$

$$\text{Wheel RPM} = \frac{\text{Vehicle speed (m/min)}}{\text{Wheel circumference (m)}} = \frac{416.66}{2.64} = 158\ RPM \tag{3}$$

Worn wheel diameter of 840 mm was considered for the calculation to represent the worst-case scenario.

$$\text{Motor RPM} = \text{Wheel RPM} \cdot \text{Gear ratio} = 158 \cdot 7.83 = 1\ 237.1\ \text{RPM}$$

To ensure optimal motor performance, DC link voltage should match the motor's rated value of 750 V.

The motors also have characteristics curves for power, speed and torque which indicates motors performance and are helpful in selection of the motor for a particular application as explained below:

- **Motor torque curve** – It helps to understand the motor performance under different load conditions. It helps in the selection of motor based on the required torque for the application.
- **Motor power curve** – It indicates the range, where the motor operates more efficiently delivering the required power for the application. It helps in selection of motor based on power required for a range of speed.

Analysis of the motor's continuous torque and speed characteristics from the Figure 33 indicates that, even with a 600 V battery, the motor can deliver more than 820 Nm up to 1 500 RPM, which are higher than 811 Nm torque and 1 237.1 RPM at which the motor should rotate while delivering continuous torque. Although operating below the nominal voltage can result in earlier onset of field weakening and some performance degradation, but not impacting the system performance of ASINO.

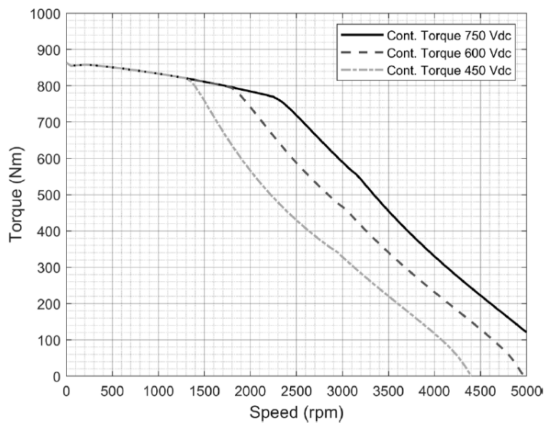

Figure 33 Torque v/s Speed characteristics [73]

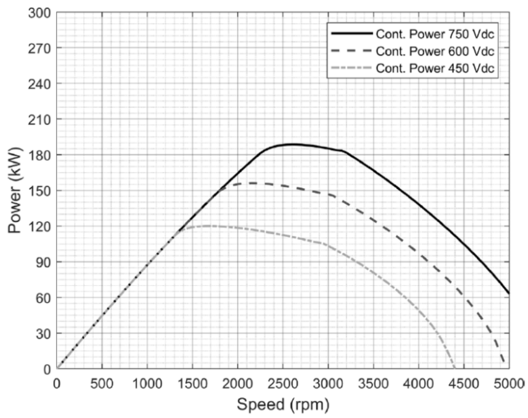

Figure 34 Power v/s Speed characteristics [73]

The continuous power and speed characteristics as seen in the Figure 34 also confirm that the selected motor can deliver the required system power at a bogie speed of 25 km/h with motor running at 1 237.1 RPM. These performance criteria's collectively support the selection over alternative motor options.

Gearbox integration

Given the motor selection and the required gear ratio of 7.83, it is necessary to use a gearbox with a hollow shaft diameter of at least 180 mm to accommodate the 22.5 t axle load and the wheelset shaft dimension. Existing metro and suburban train gearboxes do not meet the demanding requirements of the self-propelled freight bogie, particularly concerning axle diameter, size, and weight constraints. Therefore, a new gearbox must be developed, or an existing design must be significantly modified, to provide the necessary shaft bore, compactness, and reduced weight for optimal integration in this application. Table 3 shows the requirements of gearbox for ASINO.

Additional information about the gearboxes and the design modifications which could be done to match the requirements of ASINO was gathered by contacting and initiating the technical discussions with different gearbox manufacturers.

Specification	Values	Unit
Gear Ratio	7.83	-
Axle Load	22.5	t
Continuous Torque	6 350	Nm
Max. Starting Torque	12 350	Nm
Wheelset Shaft Diameter	180	mm
Max Speed (Driving alone)	25	km/h
Max speed in convoy	120	km/h

Table 3 Gearbox requirements

AKB Antriebstechnik, specializing in customer-specific gearbox solutions, and AKIM AG have both proposed developing new gearboxes tailored to the specified requirements, as no suitable standard options exist. Alternatively, PULSGETRIEBE Gear Systems offers the V400 and VV400 parallel shaft gearboxes, which can be extensively customized for the self-propelled freight application. A preliminary gearbox concept, including a rough hand-drawn sketch, was provided by PULSGETRIEBE as shown in Figure 35. Also an estimated budget from the supplier presented in Table 4 is available for reference.

Description	Cost
Engineering	€20k
Production	€15 000 (1 Piece)
Development Lead Time	6 Months

Table 4 Details of supplier quotation [76]

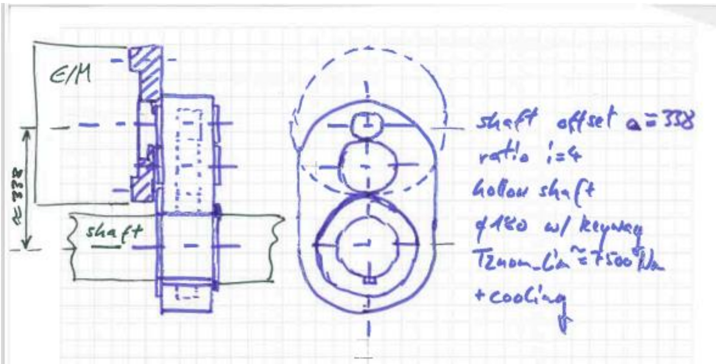

Figure 35 Gearbox conceptual sketch [76]

Another customised gearbox solution would be from Gmeinder. As per the discussion with the supplier the gearbox with the disengagement mechanism would be the more suitable for application in ASINO. They recommended the ELH-Scheuchzer gearbox, specifically designed for the Y25 freight bogie, and the GGT 210 S/922 type gearbox. However, since these gearboxes are originally designed for hydrostatic motors, modifications are required for compatibility with electric motors. Considering the supplier discussions and the lack of readily available gearboxes meeting the specifications, developing a new gearbox tailored to the application remains necessary.

Clutch

A clutch is required to decouple the motor and transmission from the axle when the bogie is coupled with a locomotive. During high-speed towing operations (up to 120 km/h), continuous rotation of the motor and gearbox induces significant mechanical drag losses and accelerates component wear, leading to heat generation and reduced system efficiency. For PMSM motors, remaining coupled at high RPMs is particularly disadvantageous as prolonged high-speed rotation causes the motor to act as a generator, producing back electromotive force (back-EMF) that, if not actively managed by the inverter, can damage power electronics. Additionally, uncontrolled electrical losses generate heat in the stator windings, risking rotor magnet demagnetization and consequent performance degradation or failure. Hence, decoupling the motor during towing is important to prevent these detrimental effects.

To enable regenerative braking while maintaining efficiency at higher speeds, a switchable clutch is proposed. This clutch can be engaged at low bogie speeds to facilitate energy recovery and recharge the battery, and disengaged once the battery is fully charged. This approach supports both efficient regeneration and high-speed operation.

Battery

As previously highlighted, battery selection is important in electric powertrains because the battery acts as the primary power source directly influencing the drivetrain's performance, range, and efficiency. For this application, a fundamental requirement was that the battery must deliver sufficient power to the wheels, taking into account all system losses, and provide adequate energy storage capacity to meet operational demands. Additionally, since the inverter and motor are arranged in series, the battery's nominal DC voltage also ensures their optimal performance. Consequently, selecting the battery based on its voltage rating is a crucial aspect alongside the power delivery and energy capacity. Technical parameters of the battery pack under consideration are described in Table 5 and Table 6 .

	XMP 96P High Power [77]	Flat Pack Battery System [78]	Cubic Pack Battery System [78]	Unit
Manufacturer	**Freudenberg e-power systems**	**BorgWarner - AKASOL**	**BorgWarner - AKASOL**	-
Cell Chemistry	**NMC**	**LFP**	**LFP**	-
Type	Sub-Pack	Battery Pack	Battery Pack	-
Nominal Energy	9.6 (67.2@Battery Pack)	50/100	100	kWh
Power Output	42.1 (Subpack)	100.05/200.1	200.1	kW
Required DC Link Voltage		600		V
Nominal Voltage	88.6 (Sub-Pack)	338/676	676	V
No. of Sub-Packs Required	7	-	-	-
Nominal Capacity	108	148	148	Ah
Discharge Rate (Cont)	4.4	2	2	C
ChargingRate (Cont)	2.0	2	2	C
Dimensions (L x W x H)	Sub-Pack – 753 x 303 x 282	2 000 x 660 x 140	1 155 x 660 x 585	mm
Weight of Sub-Pack	77.6	-	-	kg
Weight of Battery Pack	543.2	-	-	kg

Table 5 Technical comparison of batteries- 1

	PRO 8C-800 [79]	PRO 8C – 850 [80]	LiTrac	Unit
Manufacturer	**ABB**	**ABB**	**HOPPECKE**	**-**
Cell Chemistry	**LTO**	**LTO**	**LTO**	-
Type	Battery Pack	Battery Pack	Module	-
Nominal Energy	30.5	33	3.7	kWh
Power Output	125	140	-	kW

Required DC Link Voltage	600			V
Nominal Voltage	662	718	32.2	V
No. of Modules Required	-	-	19	-
Nominal Capacity	-	-	115	Ah
Discharge Rate (Cont.)	-	-	-	C
Charging Rate (Cont.)	-	-	-	C
Dimensions (L x W x H)	1 870 x 674 x 298	1 870 x 764 x 298	852 x 242 x 147	mm
Weight				
Module			47	kg
Battery Pack	485	525	893	kg
Lifecycles	20 000 cycles at 35°C, 10-90 % SOC, 2C/2C		-	cycles

Table 6 Technical comparison of batteries - 2

The formula used to calculate power output from the battery is:

$$I = \text{C-rate} \cdot \text{Battery capacity (Ah)} \tag{4}$$

$$P = V \cdot I \tag{5}$$

I = Discharge current in Amps

P = Power in Watts

The minimum voltage for the battery has been kept as 600 V based on the motors performance characteristics which allows the system to perform optimally. Based on the battery voltage, the effective output voltage to the motor via inverter is calculated as:

$$V_{AC(RMS)} = \frac{V_{DC}}{\sqrt{2}} = \frac{600}{\sqrt{2}} = 424.26\ V \tag{6}$$

V_{DC} = DC Link voltage, specifically called as battery voltage

$V_{AC(RMS)}$ = Effective output voltage to the motor

With this effective output voltage, the motor can still effectively perform to give the desired output based on its performance characteristics curves as represented by the Figure 33 and Figure 34 . Based on the available data sheets and meetings with the potential suppliers the data has been gathered for the battery selection.

The battery system from Freudenberg e-Power Systems, requiring an assembly of 7 subpacks to achieve the specified battery voltage, results in a configuration that is too large to be accommodated within the available installation space. While a design with fewer subpacks integrated with compact DC-DC converters might have been feasible but the primary limitation is the use of NMC cell chemistry.

Despite its high energy density, NMC cells with their relatively short service life and the necessity of a relatively complex thermal management system would significantly increase the overall installation cost, thereby constraining the suitability for this application. This battery pack also needs some design changes in the battery pack which is discussed in the later section of the thesis.

The battery packs offered by Akasol-BorgWarner utilize LFP cell chemistry. However, the Cubic battery pack was not considered suitable for the application due to its height which is too large as compared to the available clearance for underfloor installation. The Flat pack configuration provides a more space-efficient option compared to the Cubic pack but has integration challenges. This 338 V unit would necessitate the use of a DC-DC converter to match system voltage, introducing losses, added system complexity, and increased costs. The 676 V variant meets voltage requirements but significantly overshoots the application's power and energy targets leading to unnecessary over dimensioning. Additionally, accommodating the pack within the available space would require design modifications to the mounting tray in a way that will create practical challenges during assembly and disassembly of the battery pack. Hence, these options were excluded from further consideration.

The LiTrac modules from **Hoppecke**, based on LTO chemistry, require an assembly of 19 modules as per their technical specifications outlined in Table *6*. Such a configuration is practically infeasible due to the excessive size, which exceeds the constraints of the available installation space.

Both **ABB** battery systems fulfil the application's energy and power requirements without the need for a DC-DC boost converter. The 8C-800 Pro variant offers a weight advantage over the 8C-850, which is beneficial in our application with weight constraints. There is also an 8C-800 Max variant of battery pack which shares similar electrical specifications with the 8C-800 Pro model however, its greater height and weight make it less suitable for the available installation space. Considering the trade-offs in technical parameters and to avoid the selection of an oversized component, the **8C-800 Pro** is selected as the most suitable option for integration.

With the battery system defined and selected for the application, the next component in the powertrain architecture is inverter. The selection of inverter also plays an important role in ensuring the optimal performance and efficiency of the powertrain. A detailed technical analysis of the inverters under consideration is described in Table 7 and Table 8.

	VP600-18W340 [81]	VP600-18W360 [81]	ACH65M30 [82]	Unit
Manufacturer	**ARADEX**	**ARADEX**	**InMotion**	-
Topology	2-level	2-level	2-level	-
Switching Device	Si-IGBT	Si-IGBT	Si-IGBT	
Nominal Voltage	720	720	650	V
Continuous Current	180 @4kHz PWM	250 @4kHz PWM	225 – 1hr. rating at 4kHz PWM	A_{rms}
Continuous Power	159	220	179	kW
Peak Current	400, 1min@2kHz PWM	488, 1min@2kHz PWM	320, 1min@4kHz PWM	A_{rms}
Peak Power	-	-	255	kW
PWM Frequency	Min -1 Max -8	Min -1 Max -16	-	kHz
Cont.Power Loss	1.5	2.5	-	kW
Electrical rotational frequency	599	599	0-599	Hz
Efficiency	>98%	>98%	>97%	%
Dimensions (W x L x H)	266 x 421 x 131	266 x 421 x 131	362 x 421 x 122	mm
Weight	19	19	18	kg
Thermal Management	Liquid Cooling	Liquid Cooling	Liquid Cooling	-
IP Class	IP67	IP67	IP6K9K	

Table 7 Comparative Analysis of Inverters - 1

	HES580-104-0400 [83]	EC-C1200-45-L+MC180 [84]	Unit
Manufacturer	**ABB**	**Danfoss**	**-**
Topology	3-level	-	-
Switching Device	Si-IGBT	Si-IGBT	
Nominal Voltage	800	750	V_{DC}
Continuous Current	300	180	A_{rms}
Continuous Power	-	150	kW
Peak Power	-	300	kW
PWM Frequency	1-12	8	kHz
Cont. Power Loss	-	-	kW
Electrical rotational frequency	-	0 – 580	Hz
Efficiency	98.5% - 99%	>98%	%
Dimensions (W x L x H)	406 x 119 x 413	244 x 482 x 109	mm
Weight	20	14	kg
Thermal Management	Liquid Cooling	Liquid Cooling	-
IP Class	IP67 6K9K	IP6K9K, IP67	

Table 8 Comparative Analysis of Inverters - 2

Optimal system efficiency is achieved when all powertrain components are seamlessly integrated, therefore inverter selection is also inherently linked to the characteristics of other components:

1. Battery

This defines the DC input side of the inverter. The nominal voltage rating of the inverter must be equal to or exceed the maximum battery voltage to ensure safe and reliable operation.

2. Motor

The inverter's continuous power, peak power and current capacities must be greater than or equal to the motor rated capacities. Also, the inverter's electrical and switching frequencies must be equal to or exceed the motor's rated frequencies to ensure efficient and reliable operation.

Since the battery with 662 V as the nominal voltage is selected, the DC current input from the battery to the inverter can be calculated as:

$$P = \frac{3 \cdot V_{battery} \cdot I_{rms}}{\sqrt{3} \cdot \sqrt{2}} \tag{7}$$

$$I_{rms} = \frac{P \cdot \sqrt{3} \cdot \sqrt{2}}{3 \cdot V_{battery}} = \frac{125 \cdot \sqrt{3} \cdot \sqrt{2}}{3 \cdot 662} = 154.17\ A$$

where,

P = Power to be delivered in Watts (considered max system power)
$V_{Battery}$ = Battery Nominal Voltage
I_{rms} = Inverter DC current input
The required motor phase current to deliver the required power is calculated as:

$$I_{phase} = \frac{P}{\sqrt{3} \cdot V \cdot \cos(\phi) \cdot \text{efficiency}} = \frac{125 \cdot 1000}{\sqrt{3} \cdot 468 \cdot 0.95 \cdot 0.96} = 169.1\ A \tag{8}$$

V= Motor Line to Line voltage (Based on 662V DC Link)

$\cos(\phi)$ = Power Factor, assumed as 0.95

η = Motor efficiency

As per the selected voltage of the battery, all the inverters under consideration have considerably high nominal voltage ratings, which will impact the inverter's ability to deliver power. The continuous current is assumed to be constant based on the power electronics of the inverter. Table 9 below shows the power capability differences based on the calculation as per formula:

$$\left(\frac{P_{cont,new}}{P_{cont,nominal}}\right) = \left(\frac{V_{dc,new}}{V_{dc,nominal}}\right) \tag{9}$$

Inverter Type	$V_{dc,\ nominal}$ (V)	$P_{cont,\ nominal}$ (kW)	$V_{dc,\ new}$ (V)	$P_{cont,\ new}$ (kW)
VP600-18W340	720	159	662	146.19
VP600-18W360	720	220	662	202.2
ACH65M30	650	179	662	182.3
HES580-104-0400	800	-	662	-
EC-C1200-45-L+MC180	750	150	662	132.4

Table 9 Power Capability differences based on Nominal Voltages

Based on power capability differences each of the inverters under consideration fulfils the power transmission requirements even with the reduced DC link voltage. There are other factors for estimating the right choice of the inverter for the application as discussed ahead.

The ABB **HES580-104-0400** inverter is a 3-level, Si-IGBT-based high-efficiency inverter that very well matches the application's technical integration requirements. However, 3-Level inverters inherently require additional components and complex circuitry, significantly increasing both material and manufacturing costs compared to conventional 2-level inverters. Hence, this inverter is not considered for the application from a cost-effectiveness perspective.

The **EC-C1200-450-L+MC180** inverter offers significant advantages for the application, delivering a compact and lightweight solution well-aligned with both space and cost restrictions. Its current and power ratings closely match the system's operational requirements, minimizing the risk of overdesign selection. However, despite these technical merits, the elevated cost (approx. €10 000) as reflected by current market data and online resources makes its less feasible.

Although the system requires a peak power output of 100 kW, accounting for component efficiencies and estimated losses, the battery must deliver power of 125 kW. The **ACH65M30** inverter type from InMotion and **VP600-18W340** inverter from ARADEX, both are comparable choices for the ASINO. Considering the thermal management aspect of the flow rate interdependency of components, discussed later in the section 6.4, the selection of the inverter ACH65M30 will lead to the motor running in derated condition as per the datasheet. The nominal coolant flow rate for the motor is 20 litres per minute (lpm) and the ACH65M30 inverter type can handle up to 18 lpm making it less preferred for ASINO. Also, it is comparatively bigger in size with less efficient performance. Based on the above analysis ACH65M30 is less feasible choice than VP600-18W340.

The inverter type VP600-18W360 was not considered because of its higher power loss in comparison to 18W340 type. Ultimately, the **VP600-18W340** inverter type from ARADEX which can support the required phase current (169.1 A) for the motor along with the coolant flow rate of 20 lpm was selected as the most suitable choice for the application based on its technical specifications in integration to other components.

6 Thermal Management

Effective thermal management represents a critical challenge in electric powertrains, as various powertrain components are exposed to thermal stresses during operation. These stresses impact the efficiency, operational reliability, and service life of powertrain components.[85]

6.1 Heat Generation Mechanisms in Powertrain Components

6.1.1 Electric motor

Electric motors convert electrical energy into mechanical power, but this conversion process is not fully efficient and is accompanied by various forms of energy loss, primarily in the form of heat as shown in Figure 36. The losses can be categorised as below:

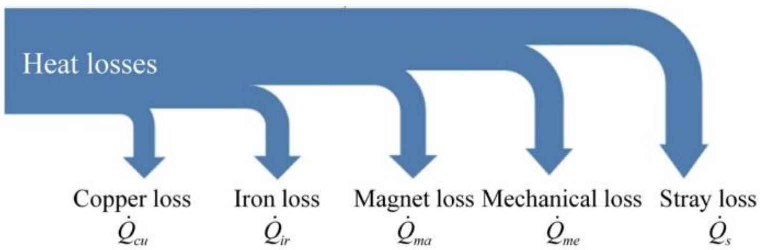

Figure 36 Losses in the electric motor [86]

Electric drive motors generate heat primarily due to resistive (I^2R) losses in the stator windings and core losses in the magnetic materials. Additionally, mechanical losses occur due to friction of the moving components. Ventilation losses are generated when air resistance is encountered by rotating parts, particularly in motors with non-circular rotors. Stray losses, though relatively smaller, result from a combination of structural imperfections, and environmental conditions.[85].

6.1.2 Inverter

Inverters require efficient cooling solutions to maintain optimal performance and ensure long-term reliability. The primary sources of heat generation within inverters are high-frequency switching losses in the semiconductor devices and resistive losses within the circuit components.[85]

6.1.3 Battery

The battery pack is a significant source of heat generation within the powertrain, primarily due to internal resistance and electrochemical activity. Heat is released due to the chemical reactions in the electrolyte because of the movement of lithium ions Additionally, internal resistance opposes current flow, and as described by Joule's law ($Q = I^2R$), this results in resistive heating.[87]

6.1.4 Gearbox

Reducers in the gearbox are responsible for the reduction of speed and conversion of torque between the motor and the wheels with the use of gears. Heat generation is caused in the process of reduction and conversion due to friction that impacts the system efficiency.[85]

6.2 Challenges of Thermal Management

Thermal management of a powertrain system is important for ensuring the optimal performance of the components but it has integration challenges with the system, such as:

1. One of the main challenges in thermal management is the management of heat generation and dissipation
2. Size and weight constraints of thermal management solutions also possess integration challenges
3. Challenge of maintaining optimal performance in mixed environmental conditions of high and low temperatures.

6.3 Thermal Management Strategies

Thermal management systems can be broadly classified into 2 categories:

1. Active Cooling Systems
2. Passive Cooling Systems

6.3.1 Active Cooling

Active cooling methods enhance heat transfer by employing external devices to increase fluid flow and boost convective heat removal. While significantly improving cooling rates, their key disadvantage is increased energy consumption and associated operational costs compared to passive systems.[88] The common types of active cooling techniques are:

1. Liquid cooling
2. Thermoelectric cooling
3. Forced air cooling
4. Phase change materials

6.3.2 Passive Cooling

Passive cooling methods utilise natural heat dissipation without external energy input, offering cost-effective and energy-efficient solutions for maintaining optimal operating temperatures.[88, 89] The common passive cooling techniques are:

1. Heat sinks
2. Heat pipes
3. Radiative cooling
4. Thermal insulation materials

For ASINO as an application the components has been selected and the feasibility of the need of active or passive cooling for components is approximated based on the power loss analysis of the components and overall system. Table *10* shows the losses of different components while power transmission.

Component	Power Input (kW)	Efficiency (%)	Power output(kW)	Losses(kW)
Battery	125	95	118.75	6.25
Inverter	118.75	98	116.4	2.35
Motor	116.4	95	110.58	5.82
Gearbox	110.58	93	102.84	7.74
Total Losses				22.16

Table 10 Power loss analysis based on efficiency

The total power loss from the system would be 22.16 kW and the calculations above are initial approximations based on the efficiency of the components and also taking into consideration the worst-case operational scenarios of the components. Based on the exact load cycle of each component the losses incurring may further vary.

Since for ASINO, which is required to be operated in changing and demanding environmental conditions, an active cooling system will be the most feasible choice of thermal management in such a demanding application.

6.4 Integrated Thermal Management – Cooling system integration

At the system-level, thermal management is a complex architecture requiring coordinated heat management. A thorough understanding of how the cooling systems of the powertrain components are interdependent is essential for an effective thermal management system design. Since each of these components has unique thermal characteristics and cooling needs, coordinated operation is essential to maintain the powertrain's efficiency, durability, and long-term reliability.[85]

Cooling every component of powertrain individually leads to a degraded thermal performance impacting the efficiency of the system. An efficient and effective way to manage the heat loss of different components is to use an integrated approach of a cooling system which addresses the challenge of space and weight constraint by eliminating the need of multiple cooling components and reducing complexity. It is also thermally efficient ensuring the lifecycle of powertrain components.[85, 89] Active liquid cooling is traditionally most preferred in the integrated cooling system approach. Although integrated cooling systems are beneficial, they still come up with challenges such as:[85]

1. Integration of the flow rates, coolant properties and temperatures of components connected in series
2. It requires intensive validation to ensure the system reliability impacting the overall performance.

Integrated cooling systems may be realised as:[89]

- **Shared Cooling loop**
  It involves a single coolant loop shared by different components of the powertrain. This reduces the system complexity by ensuring efficient heat transfer. Flow control valves and temperature sensors are necessary to ensure that cooling requirements are fulfilled.

- **Dual loop systems**

  In these kinds of systems, a dual loop is used for cooling the system components. This is beneficial when different components are exposed to varying thermal loads. This is also beneficial when components with different requirements of coolant flow rate and temperatures are integrated in a system. Usually, components matching the flow rate and coolant temperatures are integrated, but a different loop can also be dedicated, ensuring that the cooling needs are justified.

As per the specification of the components selected for selected for ASINO, a dual loop cooling system is a feasible choice. Coolant temperature and flow rate requirements for the selected components are summarised in Table 11 which are based on the component technical data sheets.[79, 73, 81]

Component	Coolant temperature (℃)	Nominal coolant flow rate (lpm)	Pressure drop(bar)
Battery	15-30	6	0.5
Inverter	Max. 65	15-20	0.5 @20lpm
Motor	Max. 65	20, <20@derated operation	0.4 @20lpm
Gearbox	-	-	

Table 11 Cooling requirements

Conditions which are needed to be met when integrating components in series for cooling are:

1. Flow rate remains same for all the components in series
2. The heat of the components is progressively transferred downstream, so the order of placement of components has to be accordingly decided based on their thermal capability
3. The pump must be able to supply pressure to overcome the cumulative pressure drop of components in series while also maintaining the flow rate.

Figure 37 depicts the conceptual cooling system architecture designed, based on technical data and initial assumptions.

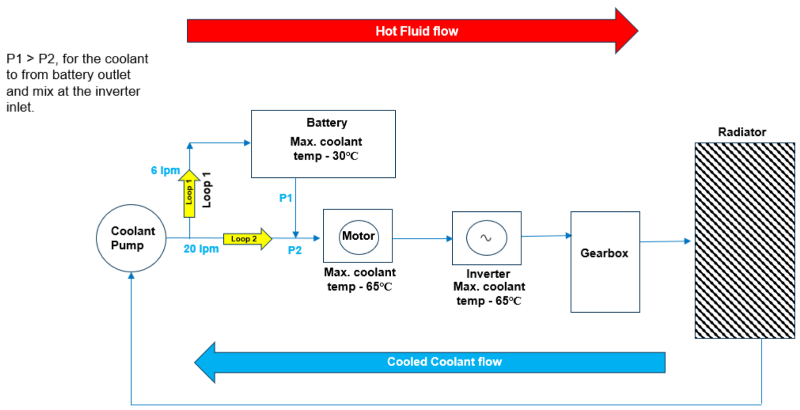

Figure 37 Conceptual cooling system architecture for ASINO

As per the cooling concept, since the battery requires a coolant flow rate of 6 litres per minute (lpm), it has to be placed in a different loop and therefore will be cooled through loop 1. As the motor requires a minimum flow rate of 20 lpm, and the inverter can also accept a flow rate of 20 lpm with a maximum coolant temperature for both components matching, the motor and inverter are series-integrated in loop 2. For the gearbox, based on further discussions with suppliers, the cooling requirements can be customised and matched. The coolant pump must be sized based on the coolant flow rate of 20 lpm and must be capable to handle pressure drop of 0.9 bar for both motor and inverter, plus the pressure drop of the gearbox.

7 Results

This chapter presents the developed powertrain system as an integrated solution composed of selected components tailored to meet the specified system performance objectives.

In the selection of these components the emphasis was on preferably selecting the components that are available in the market keeping in mind the cost constraint. Table 12 includes the technical summarisation of the components selected for the powertrain system:

Component	Type	Key Specifications	Manufacturer
Battery	Lithium-Ion Battery Pack	Cell chemistry - LTO Nominal voltage - 662 V Capacity - 30.5 kWh Power - 125 kW	ABB
Inverter	2 Level VSI with Si-IGBT Switches	Cont. current - 250 A Nominal voltage - 720 V Cont. power - 159 kW	ARADEX
Motor	3ø - PMSM	Cont. current - 241 A Nominal voltage - 750 V Cont. torque - 811 Nm Peak torque - 2 813 Nm	ABB
Gearbox	Fixed ratio	Gear ratio - 7.83	-

Table 12 Selected powertrain components

The selected components integrate effectively into a powertrain system meeting the desired functional requirements. Central to the system is the electric motor from ABB with rated continuous power of 150 kW, serving as the primary source of mechanical power. This motor's output torque is transmitted to the wheels through an integrated transmission with a fixed gear ratio of 7.83:1, providing the output torques matching the systems continuous and peak torque requirements of 6 350 Nm and 12 350 Nm. Power management is handled by inverter from ARADEX rated at 720 V, 159 kW power rating with 98% efficiency. The electrical power is drawn from the 662 V battery pack based on LTO chemistry from ABB striking an optimal balance between voltage requirements, energy capacity, and weight considerations. This integrated system achieves a balanced combination of efficiency, ease of availability, and defined technical requirements of the project

8 Construction of the freight Car bogie

This section includes the packaging concept of the powertrain with the CAD figures. The powertrain components are designed in CAD as a blackboxes to represent a space component occupies. This approach facilitates the development of the initial packaging concept, enabling the analysis of potential collisions and integration challenges within the available bogie space. Additionally, this methodology addresses the lack of detailed CAD data from suppliers, allowing the design process to progress without delay despite incomplete component information.

The battery is housed within a tray integrated beneath the cross member. This design facilitates removal of the battery tray for maintenance purposes, as it can be withdrawn laterally. The tray is fabricated from sheet metal using bending and welding processes. Figure 38 shows the structure of the battery tray.

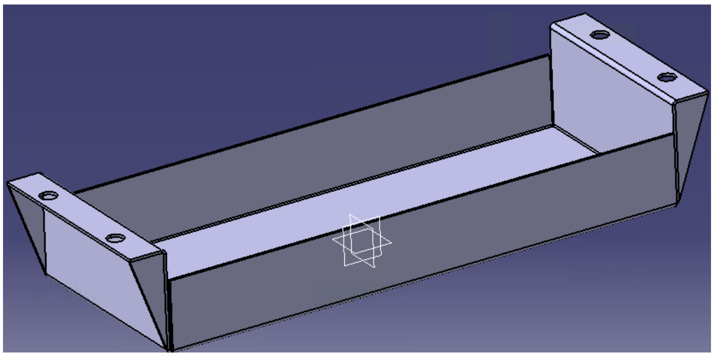

Figure 38 Structure of battery tray

Figure 39 shows the structural right view of the bogie. The red colour shows the placement of the battery in the battery tray as shown in the Figure *38*. Also, it indicates the placement of inverter in the brown colour mounted on the load bearing frame of the bogie.

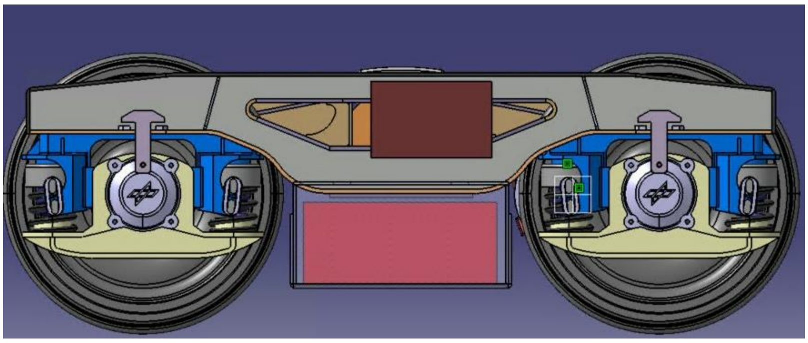

Figure 39 Structural right view showing battery tray and inverter mounting

Figure 40 shows the battery system mounting below the cross member of the of the bogie.

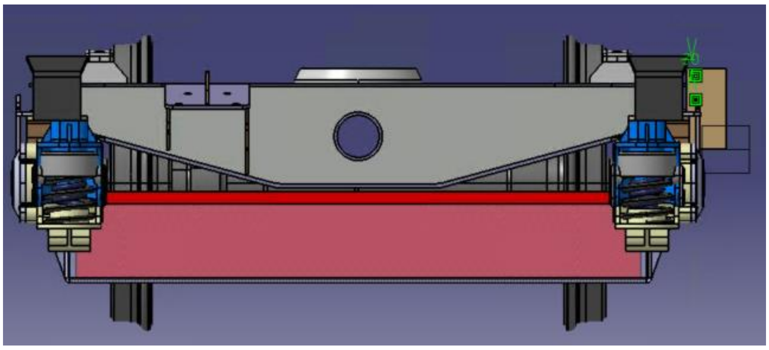

Figure 40 Sectional front view

The partly suspended drive conceptual arrangement is shown in Figure 41. As it shows the suspension of the gearbox and motor mainly on the cross member of the bogie. The CAD model still needs to be further developed to show all the suspension points of the motor and gearbox on the cross member based on the actual CAD models of the components. There is no requirement for cardanic coupling - the coupling between the outshaft of the gearbox and the wheelset shaft with this arrangement, it is also clear from the Figure 41 of the conceptual CAD model.

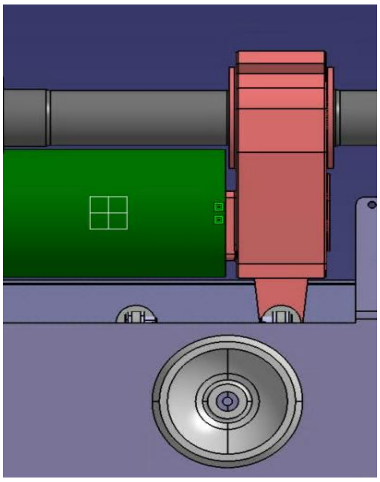

Figure 41 Partly suspended arrangement of the drive system

Figure 42 indicates all the powertrain components packaged together in the available bogie space.

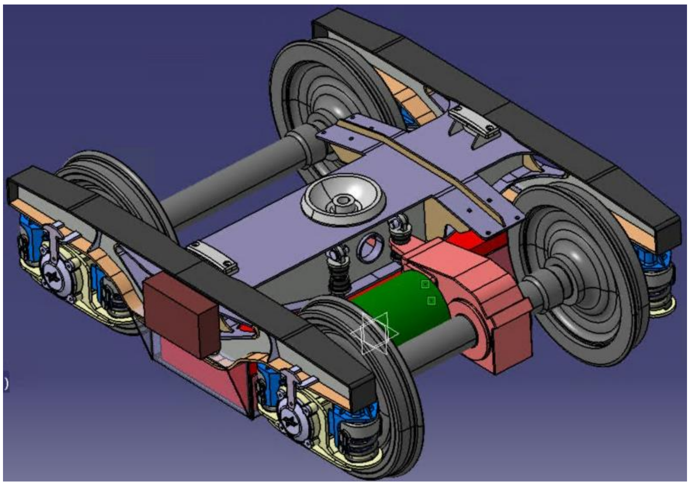

Figure 42 Powertrain Packaging

8.1 Powertrain Weight Estimation

Accurate weight estimation of the powertrain system is essential. The weight estimation was done based on the individual component masses as per manufacturers data sheets and also reference from previous thesis. Table 13 summarises the weight of overall powertrain.

Component	Weight in Kg
Battery	485
Inverter	19
Motor	287
Gearbox	300
Total Weight	1 091

Table 13 Overall Weight of the Powertrain

The total weight of the powertrain assembly is 1 091 kg for the components selected. This weight benchmark also serves as a reference for assessing future design iterations and evaluating system-level performance trade-offs.

9 Discussion

This section details the interconnected challenges encountered during the overall selection process. After providing detailed descriptions and technical justifications for individual component selection here the focus is on evaluating the collective impact of the choices on system integration, cost, complexity, and performance within the context of the initial system requirements.

The selected components align with the system's functional requirements and will translate to a fully functional system as desired. The initial focus of the development was to be cost effective in selection of components and also consider components that do not require customisation based on the requirements of ASINO. After having multiple technical discussions with different suppliers, the best available components fulfilling the functional requirements of ASINO were selected.

The battery selected from ABB, in its current packaging design is placed along the full width of the battery tray. However, the battery system can be made more compact by choosing an alternative cell chemistry or redesigning the battery pack while maintaining the existing chemistry. Discussions with the battery manufacturer BMZ group suggest that a battery pack with NMC cell chemistry could offer a more compact and cost-effective solution. Meanwhile, LTO chemistry is gaining preference for railway applications. For initial prototype testing, the existing NMC battery type from BMZ can be utilized, with the powertrain system redesigned accordingly. A more compact LTO battery pack can be custom-built and integrated into the system for series production of ASINO, which will eventually compensate for the increased battery cost.

As a part of this thesis an initial powertrain system is conceptualised based on integration of individual components, but integrated drive systems, like from Cascadia motion, could also be integrated to offer a less complex and compact integration to the ASINO, creating a space for thermal management and power electronic systems. However, thermal management for the system is an initial approximation based on literature studies, but that can be further precisely designed and optimised based on analysis of load profiles of the system components.

Based on the above discussion, it can be accounted that a further optimised design of powertrain system can be still be conceptualised fulfilling the space constraints and thermal management requirements of ASINO.

10 Conclusion

The thesis presents systematic development of electric powertrain for an advanced self-propelled fully integrated bogie – ASINO. The focus of the work was to build a powertrain system, which included component selection based on the functional requirements and technical integration of selected components to build a fully functional system. This work reflected how an entire technical system is built based on technical interdependencies of individual components and also based on research it highlighted how sizing and selection of components is done under the actual working conditions.

As a part of this work, beyond the technical assessment, discussions with component suppliers and the experts at DLR were also an important part. These discussions helped to get technical information about the component, which was not available in the component catalogues online. This also helped in validating the concept and getting technical insights on how further the performance could be improved. This all made the final system design more robust.

As a key learning, this work highlights optimised component selection which is based on meeting the performance requirements rather than selection oversized or undersized components leading to reduction of overall cost and weight aligning with the cost, weight and spatial constraints of the application.

To summarise, a powertrain system concept which is technically robust and operationally effective has been developed. This work stands as reference for further development and optimisation of the system along with integration of thermal management based on detailed analysis and simulations.

11 Outlook

Based on the performance requirements and selected motor, the transmission ratio has been defined, however final gearbox model has not yet been selected with the focus remaining on finding a compact unit. Discussions with multiple gearbox suppliers have been done to identify compact solutions, aligning with packaging constraints and performance needs. For a future work, a detailed design of the gearbox in coordination with the suppliers has to be conducted to realise a complete powertrain meeting the system requirements.

A compact battery system based on load profile analysis and NMC cell chemistry, could be developed and integrated in the system in future course of this work from BMZ. As the discussion took place at the later stages, it was not possible to fully specify the requirements. Further to this brake system from ZF could also be integrated replacing the existing to allow for a further design space optimised system.

Regarding thermal management, a preliminary assessment of the cooling system architecture has been carried out based on approximated heat losses derived from the system operating cycle and the anticipated cooling requirements of individual components. However, this is a preliminary analysis, a future work should focus on developing a fully validated thermal management architecture, including accurate heat rejection calculations, system-level integration, and comprehensive validation testing.

Addressing these design aspects will enable more accurate validation and better system optimization of the powertrain. The work completed so far provides a strong foundation to support further engineering development and collaboration with suppliers.

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