Electric Drivetrain Design for urban track system

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme in Electrical Engineering, Bachelor's thesis

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Examiner(s): Professor Lassi Aarniovuor

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ABSTRACT

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The increasing demand for sustainable urban transportation solutions has driven the development of innovative electric drive systems. This thesis focuses on designing an electric drivetrain for a new urban transport platform known as the Urban Transport Capsule. The primary objective is to develop an efficient, reliable, and cost-effective electric drive system that integrates advanced motor technologies, battery systems, and regenerative braking mechanisms. The project begins with a comprehensive analysis of current motor and battery technologies, followed by the selection of suitable components based on power requirements, energy efficiency, and safety considerations. The system is then dimensioned and optimized to ensure seamless integration between the battery and motor while maintaining high performance. Various design approaches are compared, and their advantages and trade-offs are analyzed. The outcomes of this research aim to contribute to the advancement of sustainable urban mobility by providing a practical and efficient electric drivetrain solution for compact transport systems.

SYMBOLS AND ABBREVIATIONS

Roman characters

v	linear speed of vehicle	m/s
n	motor speed	rpm
r	wheel radius	m
m	mass	kg
v_{max}	velocity	km/h
A	area	m2
C_d	Coefficient of air resistance	

Greek characters

η	efficiency	
θ	angle of slope	°

Constants

g	gravitational acceleration	9,81 m/s

Abbreviations

PMSM	Permanent Magnet Synchronous Motor
BMS	Battery Management System
BCU	Brake Control Unit
BLDC	Brushless Direct Current Motor
IM	Induction Motor

Table of contents

Abstract

Symbols and abbreviations

1 Introduction

According to a new report released by the United Nations Environment Programme (UNEP), countries must collectively commit in the next round of nationally determined Contributions (NDCS) to reduce annual greenhouse gas emissions by 42% by 2030 (United Nations Environment Programme, 2024).

To achieve this, Finland needs to adapt its infrastructure while reducing emissions. Due to market demand and environmental trends, the use of electric vehicles is gradually replacing the position of fuel vehicles in the market. As a new type of urban transportation system, the capsule car driving on the air rail discussed in this thesis uses electric power to drive, which can better reduce the carbon emission caused by urban transportation.

The electric drive system has become the basis of urban transportation because of its high efficiency and sustainable characteristics. The focus of this thesis is to design the electric drive system of the urban transportation capsule, with the goal of finding the best battery utilization and the most advanced motor system to achieve the most efficient drive mode. In addition, motor technology, battery type and braking mode must be considered to achieve the best performance. The purpose of this thesis is to provide an optimal design of urban traffic capsule that can meet the needs of urban traffic.

1.1 Background

With growing concerns about climate change and urban congestion, the need to improve transportation efficiency and reduce transportation emissions is increasing. Therefore, the use of electric drivetrains to replace the traditional internal combustion engine vehicles is increasingly accepted by society. Electric transportation has the advantage of reducing greenhouse gas emissions and improving energy efficiency.

An automated transportation and logistics system based on an airborne rail system, developed by UDT, represents a new frontier in mobility. The urban track capsule has an air rail track as its core and uses batteries beneath the capsule to provide electric propulsion to transport passengers and cargo. UDT says that compared to other fixed rail facilities, the operating costs of air rail track are lower. The elevated sky railway, which can reduce traffic jams on the ground and improve land utilization, is a greener infrastructure. In addition to improving logistics and traffic efficiency, unmanned air traffic can also ensure greater safety. UDT's vision is to be a pioneer in the transformation of sustainable transportation. Preliminary design of the capsule used in the urban track is presented in Figure 1.

Figure 1. Urban Track Capsule from UDT(UDT).

The capsule is lightweight and designed for two passengers as seen from Figure 1.

As cities increasingly focus on sustainable transport solutions, electrified transport can be seen as an important solution to urban pollution. As policies to encourage the use of electric vehicles are introduced around the world, these policies drive technological progress in motors, batteries and other related systems. To design an efficient drivetrain for Urban Track capsules, it is necessary to have a deeper understanding of energy flow, power requirements and braking systems.

1.2 Objectives

The purpose of this thesis is to design an electric drive system that is more suitable for urban rail capsule cars and improve the efficiency of the system. The new drive system will be used to solve some of the problems encountered when the orbital capsule is put into service in the air. The new electric drive system will enable more efficient energy conversion, making the existing electric drive system more lightweight and compact. Optimize the motor and regenerative braking system to maximize energy utilization and ensure efficient operation of the system under frequent start-stop conditions. Integrate motors, batteries, and power electronics in a limited space while reducing overall weight to reduce rail load.

At the same time, different motors and batteries were evaluated to compare their efficiency, cost and performance. Select the most appropriate motor and battery technology within the capsule size range. Compare the effects of mechanical braking, resistance braking and regenerative braking to improve energy recovery and optimize braking performance. This study will comprehensively evaluate a variety of electric drive technology options, including the layout differences between hub motors and central motors, the efficiency impact of different gear ratio designs, and the applicability of DC motors in low-cost scenarios. Through system-level simulation and cost-benefit analysis, the optimal solution of performance, reliability and economy is finally proposed (Ahmed T. Hamada, 2022). A flowchart has been drawn to illustrate the process of converting the kinetic energy during the vehicle's braking into electricity and storing it by utilizing regenerative braking, which is capable of energy recovery. Modelling calculation and analysis were carried out according to known parameters, and modification suggestions were put forward according to the final modelling results to achieve better energy recovery and braking effects.

2 Electric Drivetrain Components

The electric drivetrain system is composed of multiple components, which require careful selection of different components and consideration of the most suitable combination of connections, so that the system can achieve the best energy recovery and braking effect. The three most important components of an electric drive system are the motor, the inverter and the battery.

2.1 Electric Motor Selection

2.1.1 Motor Comparison

In an electric drivetrain system, the first component to be considered is the electric motor. In a system, an electric motor converts electrical energy into mechanical motion (Xiaohua Zeng, 2024). Since the efficiency and cost of different types of motors are also different, the most suitable type of motor should be selected according to the needs. The following three motor types are considered:

Table 1. Comparison of motor technologies for urban capsule application.

Metric	PMSM	DC Motor	Induction Motor
Peak Efficiency	93-96%	80-85%	82-88%
Cost (€)	2,500	1,800	2,000
Control Complexity	High (FOC required)	Low (voltage control)	Medium
Maintenance	Low	High (brush wear)	Medium
Regen Braking	Excellent	Limited	Good

The choice of motor type depends on the power and efficiency requirements of the Urban Rail Capsule's electric drivetrain system. The PMSM was considered first because it has very high efficiency and has good regenerative braking performance, which meets the needs of the system (Ertugrul, N., 2024). The schematic of the PMSM motor control system is shown in Figure 2.

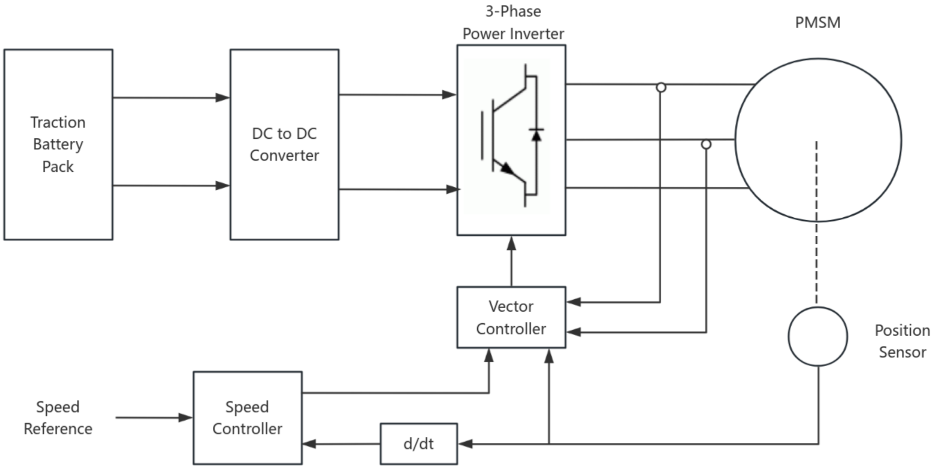

Figure 2. A schematic of PMSM motor control system.

Figure 2 illustrates the control system of the PMSM motor, highlighting its components and their interactions to achieve efficient energy conversion and regenerative braking.

DC motors, though less efficient than PMSM, offer distinct advantages in cost-sensitive applications. Their simple construction and direct torque control make them suitable for prototyping or low-speed urban vehicles. However, the brush-commutator system requires regular maintenance, and the efficiency is typically 10-15% lower than PMSM. For the urban capsule application, DC motors could be considered as a transitional solution before adopting more advanced PMSM systems.

If the urban track capsule needs more consideration of cost, because the operation of the urban capsule is controlled by algorithms, DC motor can also be considered as an alternative motor.

2.1.2 Motor Speed and Gear Ratio Optimization

In order to ensure the efficient power transmission of the electric drive system, the coordination between the motor speed and the transmission ratio is very important. The performance of the motor must match the needs of the vehicle under different driving conditions, especially in urban environments with frequent stops, starts and slopes. The speed of the vehicle depends on the speed of the motor rotation and the transmission ratio connecting the motor to the wheels (Pinto, João Pedro Pereira, 2021). A higher transmission ratio means the motor spins faster than the wheels, providing more torque for acceleration and climbing. However, this also means that when the vehicle is moving fast, the motor is running at a higher speed, which can reduce efficiency. On the other hand, the lower transmission ratio allows the motor to operate at a slower speed when cruising, increasing efficiency but sacrificing some low-speed power and also reducing torque. PMSM motors typically operate at high speeds and low torque, so they need to be slowed down to match wheel requirements.

In a motor drive system, the choice of gear ratio has a significant impact on the performance and efficiency of the vehicle (Peng Dong, 2024). For urban traffic capsules operating at speeds of 60 km/h, the transmission ratio has two key requirements that must be balanced: strong acceleration when stopping and high speed when driving. Strong acceleration at stop requires higher torque, and generally a lower gear ratio is conducive to improving low-speed torque, which is suitable for frequent start-stop situations, so a higher transmission ratio is preferred. While driving at higher speeds benefits from a lower transmission ratio, a higher gear ratio is more suitable for high-speed cruising to reduce motor speed and improve efficiency to keep motor speed within the effective range. Based on theoretical analysis and reference data for similar electric vehicle (EV) applications, a transmission ratio within the range of 6:1 to 7:1 has been identified as offering a suitable trade-off between acceleration performance and cruising efficiency. Although these values were originally defined for conventional EVs, they can be reasonably referenced for the urban capsule system under consideration, given the comparable operational speeds and acceleration requirements in typical city traffic environments. Nevertheless, detailed gear ratio optimization must be further refined based on the specific motor characteristics, including nominal speed, torque profile, and operating efficiency maps tailored to the capsule's drivetrain configuration. This setup ensures rapid acceleration when needed, while maintaining good energy efficiency during steady driving. Therefore, in the system design, it is necessary to carry out trade off optimization according to the target model.

The choice of motor also affects the way the transmission ratio works: PMSM is efficient and works well with regenerative braking, making it ideal for urban traffic. The PMSM's gear ratio is well suited to the needs of city driving, maximizing energy recovery, but at a relatively higher price (Chao Yang, 2024). DC motors are a simpler and cheaper option, but less efficient. DC motors are better suited for low-cost or prototype systems where advanced performance is not as important, and DC Motor would be a better choice.

Prior studies on PMSM-driven EVs have demonstrated that gear ratios between 6:1 and 7:1 effectively balance torque demands, cruising efficiency, and regenerative braking potential. For the preliminary design phase of the urban capsule system, adopting a target transmission ratio within this range is considered reasonable, under the assumption that the typical urban operating conditions of the capsule are similar to those of EVs. Final transmission ratio optimization should be performed once the detailed motor specifications and wheel dimensions are finalized, ensuring alignment with the actual urban drive cycle and performance requirements.

2.2 Battery Technology and Selection

2.2.1 Battery system

In the electric drivetrain system, the battery is used to store and provide the electrical energy required for the drivetrain. When selecting a battery type, because the battery will be placed under the urban track capsule, the performance, weight, and volume of the battery need to be taken into account.

Here are the three types of batteries being considered:

Table 2. Three types of batteries.

Battery Type	Energy Density (Wh/kg)	Cycle Life (charges)	Safety	Temperature Adaptability	Cost	Best Use Case
Li-ion Battery	150-250	1000-2000	Moderate (fire risk)	−20℃ to 60℃	Medium	General rail capsule applications
lithium iron phosphate Battery	90-160	2000-5000	High (stable)	−10℃ to 80℃	Low	Safe and long-lasting solutions
Solid-State Battery	300-500	3000-10,000	Highest (very safe)	−30℃ to 100℃	High	Future high-performance systems

Solid-state batteries are the most suitable and promising solutions for future urban transportation. Limited by the current immature production process of solid - state batteries, the high cost and low productivity prevent solid - state batteries from being used on a large scale in the short term.

If it needs to be put into production immediately, it is recommended to use lithium iron phosphate battery. Due to its high safety and performance, it is suitable for orbit capsules that have requirements for service life and safety.

2.2.2 Charging Infrastructure

Since the transport capsule is powered by the battery on its bottom, it is also necessary to consider how to solve the charging problem of the battery. Before transportation capsules can be put into practical use, an efficient charging solution is needed.

While fast charging can reduce downtime and support stable operation, it may accelerate battery degradation over time. In contrast, slower charging helps extend battery lifespan, although it increases charging time. To further enhance operational efficiency and sustainability, integrating automatic and seamless charging systems—such as wireless charging—can enable convenient energy replenishment without manual intervention.

2.3 Braking and Regeneration

Transport capsules utilize a combination of braking mechanisms:

2.3.1 Regenerative Braking

Regenerative braking is based on the reversible operation of the motor, converting kinetic energy back to electrical energy, extending battery life and improving overall efficiency. The effectiveness of regenerative braking depends on the motor control algorithm and battery absorption capacity. In the electric drive system, the motor works in two modes. Drive mode: motor will provide the battery into mechanical power, push forward vehicle. Braking mode: The motor switches to generator mode, converting kinetic energy back to electricity, which is stored in the battery for subsequent use (K. Omkar et al.,2021). This energy recovery process significantly improves efficiency, reduces energy consumption, and extends the vehicle's driving range.

Table 3. Regenerative braking component.

Component	Effect
Motor	As a driving source, it also generates power in reverse while braking, converting kinetic energy into electricity.
Inverter	Control the mode of operation of the motor (drive/generation) and rectify the regenerative current to make it recyclable.
BMS	Monitor the status of the battery to determine whether it can store the recovered power and prevent overcharging.
Energy storage unit（Battery/ Supercapacitor）	The recovered electrical energy is stored to provide energy for subsequent acceleration (Shah, Y.T. , 2020).
DC-DC converter	When the battery voltage and motor voltage do not match, the conversion is performed.
Mechanical Brake	Conventional friction braking, supplemented by regenerative braking at low speeds or in emergency situations.
Controller（ECU/ MCU）	Calculate brake force distribution and optimize the utilization of renewable energy.

In this system, when the vehicle slows down, the motor goes into power generation mode, converting kinetic energy into electricity. The inverter converts electrical energy into a recyclable form and transmits it to a battery. The BMS is responsible for monitoring the status of the battery, preventing overcharging, and determining the energy flow. DC-DC converters may be used to adjust voltage to match battery or motor requirements. If braking force is insufficient or the battery is fully charged, use conventional mechanical braking to supplement the deceleration. The controller is responsible for calculating the optimal braking force distribution and improving the efficiency of energy recovery. The regenerative braking system is depicted in Figure 3.

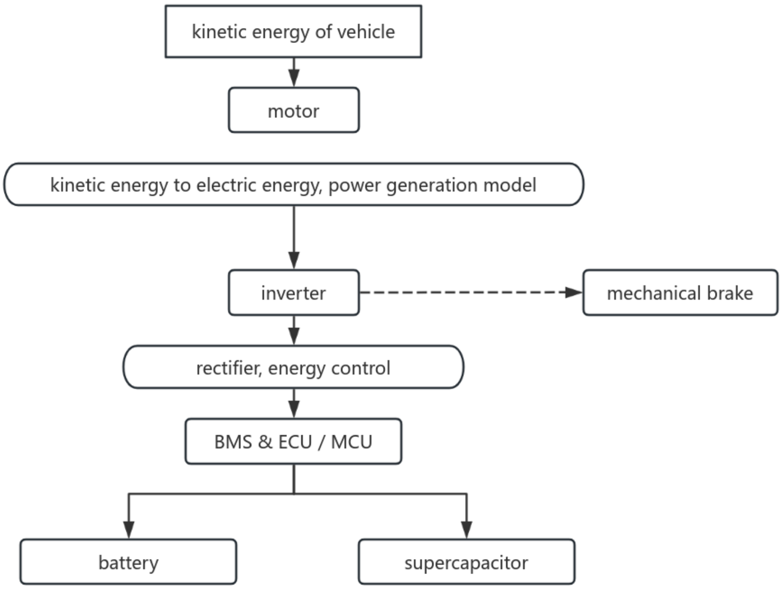

Figure 3. Regenerative braking System.

As shown in Figure 3, the regenerative braking system converts kinetic energy into electrical energy during deceleration, which is then stored in the battery for reuse.

2.3.2 Electric Braking

On trams, electrical braking mainly relies on the reverse working mode of the motor to provide braking force, which is divided into the following two ways:

Regenerative Braking: The motor is turned into a generator, which converts kinetic energy into electricity and feeds back to the grid or battery. (Xiaohua Zeng, 2024) Energy consumption Braking: the electric energy emitted by the motor is consumed through the resistance and released in the form of heat energy. The electric braking system is presented in Figure 4.

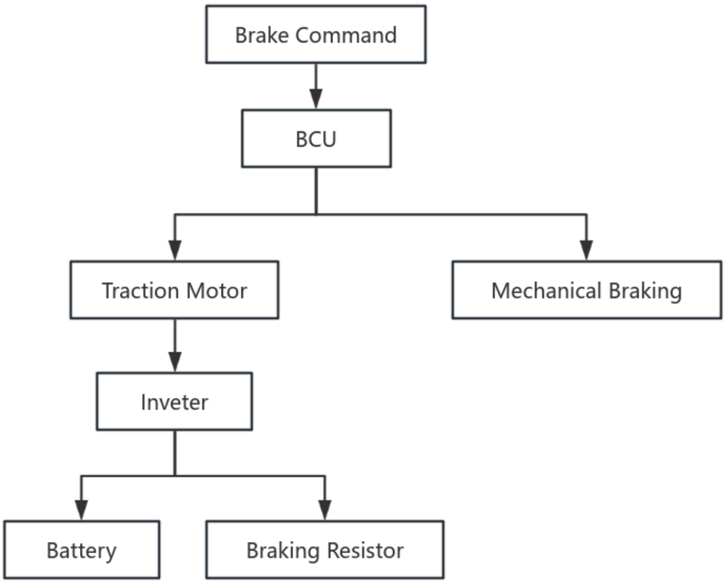

Figure 4. Electric Braking System.

Figure 4 demonstrates the electric braking system, which includes regenerative braking and energy dissipation through resistors when the battery cannot absorb additional energy.

Table 4. Main component of electric braking system.

Traction Motor	In the braking reverse operation, the vehicle kinetic energy into electric energy.
Inverter & Converter	Control the release of electrical energy to the brake resistance during energy consumption braking.
BCU	Calculate the braking torque to be applied. Coordinate regenerative braking and mechanical breaking. Switch to energy breaking when the battery is full or the grid cannot receive energy.
Braking Resistor	When the power cannot be returned, the excess power is converted into heat and dissipated.
Battery	Power Storage System

2.3.3 Friction braking and its role under low-adhesion conditions

While coasting is typically the most energy-efficient way of slowing down, braking systems remain essential for safety and operational reliability. In particular, traditional friction braking—using disc or drum brakes—serves as a critical backup when regenerative or resistive braking is insufficient. Friction braking ensures consistent stopping power under normal operating conditions.

However, under extremely poor surface conditions, such as icy or heavily contaminated tracks, the tire-road adhesion may become critically low, limiting the effectiveness of all braking systems that act through the wheels.

The integration of these braking mechanisms allows for an optimized balance between energy efficiency, safety, and reliability (Gupta P, 2014). By properly calibrating regenerative braking strategies and incorporating resistive and friction braking when necessary, the overall drivetrain performance can be enhanced while reducing wear on traditional braking components. The structure and workflow of the friction braking system are shown in Figure 5.

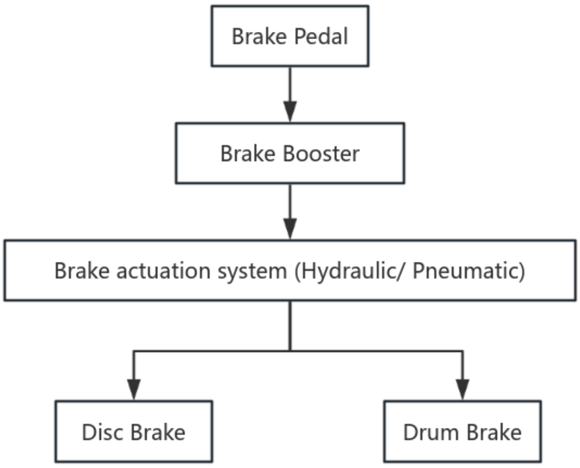

Figure 5. Structure and Workflow of Friction Braking in Urban Capsule.

Figure 5 details the friction braking system, which serves as a backup to regenerative braking, ensuring reliable stopping power in all conditions.

Table 5. Components of friction braking system.

Mechanical Braking System	Decelerate or stop by friction, as the main braking method or in combination with regenerative braking.
Brake Actuation System	Convert the driver's braking input into a mechanical force that is applied to the brake.
Brake Pedal & Booster System	Brake pedal: When the driver presses down, the brake force signal is generated. Brake Booster: reduce the driver's stepping force, improve the braking effect, divided into vacuum power and electronic power (E-Booster).
Electronic Brake Control System	Optimize mechanical breaking to improve safety and comfort. ABS (Anti-lock braking system), ESC (Electronic Stability Control), EPB (Electronic Parking Brake)

2.3.4 Gliding Strategy and Energy Consumption Analysis

In urban electric transport systems, deceleration strategies significantly influence the overall energy efficiency. Among various approaches, coasting —where the vehicle decelerates using only rolling resistance and air drag without applying active braking—is generally the most energy-efficient method.

At high SOC, state of charge >80% and speeds above 40 km/h, gliding demonstrates superior energy efficiency compared to regenerative braking. This is because: Motor drag losses exceed regenerative gains when battery absorption capacity is limited. Reduced current fluctuations prolong power electronic lifespan.

This section compares the three main deceleration strategies—coasting, regenerative braking, and friction breaking in terms of energy consumption, braking force, system stress, and applicability.

Typically, the most energy-efficient way of slowing down is coasting, especially in scenarios where battery absorption capacity is limited. A flowchart of the braking mode decision process is provided in Figure 6.

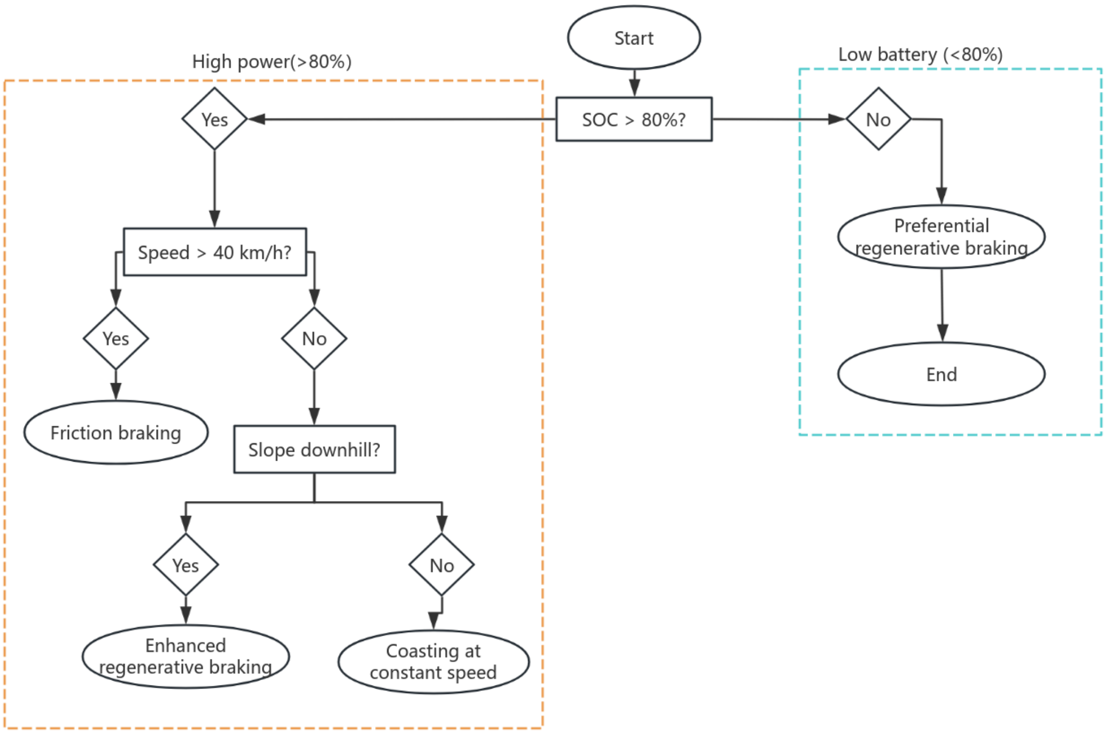

Figure 6. Braking Mode Decision Flowchart.

Figure 6 outlines the decision-making process for selecting the optimal braking mode (coasting, regenerative braking, or friction braking) based on real-time conditions such as speed and battery state of charge.

2.3.5 Brake summary

In modern electric drivetrains, most use a hybrid braking strategy that combines coasting, regenerative braking, resistance braking and traditional friction braking to optimize energy recovery and braking performance.

Coasting is typically the most energy-efficient method of deceleration in electric vehicles. By disengaging the electric drivetrain, the vehicle slows down naturally through rolling resistance and aerodynamic drag. This approach consumes virtually no energy and minimizes mechanical wear, making it particularly advantageous for extending driving range in urban environments, where frequent slowing and stopping are required.

Regenerative braking uses an electric motor in generator mode, converting kinetic energy into electricity and feeding it back to the battery. This process significantly improves energy efficiency and reduces wear on mechanical components. However, the effectiveness of regenerative braking is limited by battery charging status and system control algorithms, especially at low or sharp decelerations.

Friction braking uses mechanical components such as brake pads and discs to ensure reliable braking performance in emergency situations or when regenerative braking is insufficient. Friction braking is reliable, but it generates heat during deceleration and accelerates component wear, so it is the least energy efficient option.

When the battery is unable to absorb the extra energy, resistance braking is usually used. In this mode, the energy recovered from the motor is dissipated as heat through the brake resistance. While not energy efficient, it plays a key role in managing the heat load and preventing battery overcharging.

Table 6. The difference between three different brakes.

Parameter	Friction Braking	Regenerative Braking	Electric (Resistive) Braking	Coasting
Working Principle	Mechanical friction	Motor acts as generator	Energy dissipation via resistors	Free deceleration (no braking)
Energy Recovery	0% (All energy lost as heat)	Up to 70% recoverable*	0% (Converted to heat)	100% kinetic energy retained
Braking Force	High & consistent	Speed-dependent (weak at low speed)	Moderate, electronically controlled	None
Efficiency	Low (Energy destructive)	High (Energy regenerative)	Medium (Waste heat management)	Highest (No energy loss)
Components	Brake pads, discs, calipers	Motor, inverter, BMS	Resistor bank, cooling system	N/A
Maintenance	High (Wear components)	Low (No contact parts)	Medium (Resistor degradation)	None required
Cost	€500-800/system	€1,200 - €2,000	€300-500	Free
Temperature Impact	High heat generation	Minimal	Requires heat dissipation	None
Response Time	100-300 ms	<50 ms	50-100 ms	Instantaneous

In practical applications, these four modes are dynamically coordinated based on real-time driving conditions. Usually, as long as passive deceleration can be achieved, coasting is a priority. Regenerative braking complements coasting when more braking force is required, while resistance or friction braking is retained in cases where regenerative braking is limited or unavailable. This multi-layered strategy improves overall energy efficiency, improves passenger comfort through smoother deceleration, and reduces maintenance costs by minimizing reliance on mechanical brake components.

2.4 Power Electronics and Control Systems

The drivetrain also relies on power electronics and control systems to ensure efficient energy conversion and management:

Inverters: Convert DC battery power into AC for the electric motor. The efficiency of the inverter directly impacts overall drivetrain performance.

Battery Management System (BMS): Monitors battery health, prevents overcharging, and optimizes energy usage. Advanced BMS solutions can improve battery lifespan and safety.

Motor Controllers: Regulate speed and torque to match driving conditions. Modern motor controllers use real-time algorithms to optimize performance under different load conditions.

A well-integrated control system improves efficiency, extends battery life, and enhances the overall driving experience. The increasing use of artificial intelligence and machine learning in power management is expected to further enhance energy efficiency in electric drivetrains.

2.5 Comparison of different electric drive technology schemes

2.5.1 Comparison of drive motor layout schemes

As an advanced drive technology, hub motor has many remarkable advantages. First of all, because the motor is installed directly inside the wheel, this design completely eliminates the drive shaft and differential in the traditional vehicle, thus reducing the complexity of the mechanical structure. Due to the reduction of these mechanical components, mechanical losses are also reduced, resulting in an overall efficiency improvement of about 12%, and a better performance in terms of energy use. In addition, since the traditional drivetrain is no longer required, the chassis space is freed up, which can provide greater flexibility in the arrangement of battery modules, thereby optimizing the spatial structure of the vehicle. Another significant advantage of hub motors is the ability to enable more precise torque distribution across individual wheels. This facilitates enhanced handling stability, particularly during high-speed cornering, by dynamically adjusting the driving force on each wheel based on traction conditions. However, hub motors also have certain disadvantages. Integrating the motor directly into the wheel increases the unsprung mass, which can negatively affect suspension performance and ride quality, particularly by reducing the system's ability to absorb road irregularities. The second disadvantage is that because the hub motor usually requires a custom design, its unit cost is high, and the price of each motor is about 2,800 euros, which is about 30% more expensive than the central motor.

Central drive is a more traditional drive mode, its technology has been very mature, with high reliability. Its main advantage is the low maintenance cost, and the total cost over the whole life cycle is approximately 18% lower than the wheel motor. In addition, due to the use of centralized heat dissipation design, the cooling system structure is relatively simple, so the temperature rise is about 10 ° C lower than the wheel motor, which helps to extend the life of the motor. The central drive also has some shortcomings. Because it still relies on the mechanical transmission system, its transmission loss is high, and the efficiency loss of the gearbox alone is about 8%, which reduces the energy utilization efficiency of the vehicle to a certain extent.

Compared with the previous two driving methods, distributed driving is a compromise solution, which achieves a good balance between space utilization and efficiency. However, this drive method needs to rely on more complex control algorithms, such as torque vector distribution, to ensure the coordination of the various motors, which requires higher requirements for software control systems.

Table 7. Drive Layout Configuration Comparison.

Metric	In-wheel Motor	Central Drive	Distributed Drive
System Efficiency	92%	85%	88%
Cost (€/unit)	2,800	2,100	2,400
Space Occupancy	Compact	Bulky	Moderate
Maintenance	Complex	Simple	Moderate
Torque Control	Best (Individual wheel control)	Standard	Good (axle-level control)

2.5.2 Motor type technical path analysis

When selecting the optimal motor for the urban track capsule, it is essential to compare the key characteristics of Permanent Magnet Synchronous Motors (PMSM), DC motors, Brushless DC (BLDC) motors, and Induction Motors (IM). Each motor type has distinct advantages and trade-offs in terms of control algorithms, speed regulation, cost, and maintainability.

PMSM: Requires advanced Field-Oriented Control (FOC) algorithms for precise torque and speed regulation. This complexity increases development time and computational demands but enables high efficiency and smooth operation (Güney, Bekir, 2020).

DC Motor: Utilizes simple voltage control, avoiding the need for complex FOC algorithms. This makes DC motors easier to implement but limits their efficiency (80–85%) and regenerative braking performance.

BLDC Motor: Operates with a simpler six-step commutation algorithm, striking a balance between control complexity and performance. However, torque ripple can be an issue.

Induction Motor (IM): Relies on scalar or vector control methods, which are less complex than FOC but result in lower efficiency and poorer low-speed performance.

PMSM offers the widest speed range and excellent dynamic response, making it ideal for urban applications with frequent start-stop cycles. DC Motor provides straightforward speed control but suffers from limited high-speed performance due to brush and commutator constraints. BLDC Motor delivers good speed regulation but may exhibit torque fluctuations at low speeds. IM struggles with efficiency at low speeds but performs reliably in high-speed scenarios. DC motors utilize simple voltage control, avoiding the need for complex field-oriented control algorithms required by PMSM.

Discuss the cost and performance differences of different types of motors by comparison:

Table 8. Comparison of Motor Types in Cost and Performance.

Motor Type	Efficiency (Peak)	Cost (€/unit)	Control Complexity	Material Dependency	Key Characteristics
PMSM	93-96%	2,500	High (FOC required)	High (rare-earth magnets)	High power density, best for compact designs
BLDC	82-88%	1,800	Medium (six-step commutation)	Medium (permanent magnets)	Simple control but has torque ripple
IM	<80% (at low speed)	1,500	Low (scalar control)	Low (copper/aluminum)	Needs additional cooling system, good for high-volume applications
DC Motor	80-85%	1,200	Very Low (voltage control)	Medium (copper/brushes)	Brush wear requires maintenance, simple to control

The table 8 clearly shows the trade-offs between different motor technologies for urban transport applications. PMSM remains the premium choice for performance-oriented systems, while IM and DC motors may be considered for budget-constrained projects. BLDC offers a middle-ground solution with reasonable efficiency and simpler control than PMSM (Soniya. K. Malode, 2016).

For the urban track capsule, PMSM emerges as the optimal choice for its high efficiency and regenerative braking performance, despite its higher cost. DC motors may serve as a transitional solution for low-budget projects, while BLDC and IM offer intermediate options depending on specific project constraints. Future advancements in rare-earth-free PMSM designs and DC motor control algorithms could further refine these trade-offs.

2.5.3 Selecting the power Electronics Topology

Inverters are available in two level inverters and three level inverters. The cost of two-level is relatively low, costing about 500€ per unit, but the switching loss is high. The efficiency of a three-level inverter is 3% higher than that of a two-level inverter, but the volume increases by 30% relative to a two-level inverter.

The use of SiC devices can increase the inverter efficiency to 98%, but the cost is twice that of silicon (Gou Yanan,, 2016).

Based on cost estimates, a combination of PMSM, In-wheel Motor, LFP Battery and two-level inverter is recommended for urban rail capsule cars. It is possible to achieve an optimal balance between efficiency of more than 85% and cost control of 30,000 € per decade. Considering the practical situation, in the case of budget constraints, BLDC and central motors can be used as alternatives.

2.5.4 Cost and supply chain analysis

The choice of motor and battery technologies significantly impacts not only performance and cost but also supply chain reliability and project timelines. Different solutions vary considerably in lead time, modularity, and supply chain maturity:

PMSM motors typically require 4-6 weeks for delivery due to their complex manufacturing process and dependence on rare-earth magnets. However, their modular design allows for easier integration with different inverter systems. BLDC and IM motors have shorter lead times and benefit from more standardized production lines, making them suitable for rapid prototyping. LFP batteries currently offer the most stable supply chain, with well-established production capacity globally. Their standardized modules simplify battery pack assembly and replacement. SiC power devices (Y. Li, 2013), while offering superior efficiency, face longer lead times due to limited wafer production capacity. This could create a bottleneck in the drivetrain development schedule.

LFP batteries are the most mature option, with multiple suppliers ensuring stable pricing and availability. Their lack of cobalt/nickel dependency reduces geopolitical risks. PMSM motors rely on neodymium magnets, where 80% of supply is controlled by China. Recent price volatility necessitates long-term contracts. SiC inverters remain a emerging technology, with only Infineon, Wolfspeed, and STMicroelectronics capable of volume production. Dual-sourcing strategies are recommended.

Table 9. Key components cost, lead time, and supplier information for urban capsule drivetrain.

Component	Specification	Price(€)	Delivery cycle (weeks)	Supplier
PMSM Motor	7 kW Permanent Magnet Synchronous Motor	2,500 (typical)	4	Siemens
LFP Battery Pack	Lithium Iron Phosphate, 300 Wh/kg, Pack Price	300/kWh	6	CATL
SiC Inventer Module	1200 V / 300 A SiC-based inverter	1,200	8	Infineon

Table 9 summarizes the estimated cost, delivery lead time, and major suppliers for the key components selected for the drivetrain system. The listed values reflect typical market conditions for small to medium-sized electric vehicle applications. The PMSM motor price refers to a 7 kW-rated unit, excluding the controller (Siemens, 2023). The LFP battery cost is based on a pack-level energy density of approximately 300 Wh/kg (CATL, 2023), while the SiC inverter module price corresponds to a 1200 V / 300 A configuration suitable for traction applications (Infineon Technologies AG, 2023). These component data points serve as the basis for preliminary cost, supply chain, and risk assessments during the system design phase.

Based on Table 9 data, LFP batteries emerge as the most stable choice for mass production, while SiC devices may become the critical path due to constrained supply. To mitigate risks, phase 1 prototypes could use silicon IGBTs before transitioning to SiC in phase 2 (Xiaofeng Ding, 2017).

3 Design Process

3.1 System Design

When designing the drivetrain, the performance and operational constraints that the traffic capsule must meet need to be taken into account.

Traffic capsule design decisions at top speed of 60 km/h, track laying at the same time to take into account possible slope because of the influence of the terrain. Therefore, in terms of power output, it is necessary to ensure that the traffic capsule has smooth acceleration and climbing ability. Transportation capsules were originally designed to conserve floor space and save energy consumption, so you need to think about how to maximize energy use while minimizing energy loss while driving. In addition, considering the structure of the capsule and the load bearing of the track, a compact design is also required to make the powertrain more suitable for the capsule structure. The electric drivetrain flowchart is displayed in Figure 7.

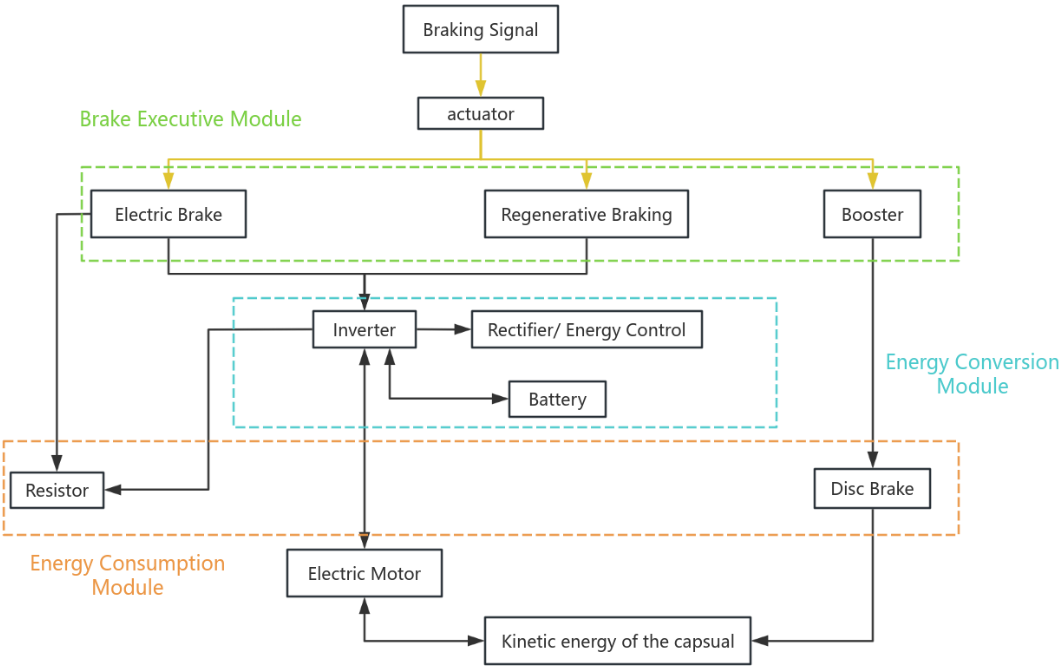

Figure 7. Electric drivetrain flowchart.

Figure 7 provides an overview of the electric drivetrain’ s components and their interactions, emphasizing the integration of braking and energy conversion modules.

The electric traffic module mainly uses a hybrid braking strategy, which combines regenerative braking, resistance braking and mechanical braking. For safety reasons, the traffic cabin is managed by a big data monitoring system, so the pedal brakes commonly used in traditional trams are replaced by a computer-sent brake signal to control the movement of the cabin. When the orbital module receives braking signals, it transmits data to the Actuator, which processes the signals and performs braking operations accordingly.

In Electric drivetrain flowchart, Electric Brake, Regenerative Braking and Booster are brake execution modules, which are responsible for executing brake action and controlling deceleration mode. An Electric Brake provides braking force by running the motor in reverse or increasing the current, rather than relying on conventional friction braking. The main function is to reduce the speed of the vehicle while reducing mechanical wear. Regenerative Braking works by the motor in reverse to convert the kinetic energy of the wheel into electricity and feeds back to the battery or the grid. This braking method improves energy efficiency while reducing the frequency of mechanical braking. Booster is used to assist the braking system to increase braking force or optimize the energy recovery process. It can work with regenerative braking or mechanical braking to improve braking effect.

Inverter, Battery, Rectifier/Energy Control are energy conversion modules responsible for energy conversion and management to achieve the conversion of electric energy and kinetic energy. Inverter converts DC to AC for motor use. During regenerative braking, the inverter can also convert the alternating current generated by the motor back to direct current and feed it to the battery for storage. The Battery acts as an energy storage unit, storing the electrical energy recovered by regenerative braking and providing the driving force for the motor. In the braking process, its charge and discharge management determines the efficiency of energy recovery. The rectifier converts alternating current to direct current, allowing the regenerative energy to be stored in the battery. The energy control module regulates the distribution of energy between the battery, inverter and brake system to optimize power management.

Resistor and Disc Brake are energy consumption modules, which are responsible for consuming excess energy and releasing it in the form of thermal energy to prevent system overload. When the electrical energy generated by regenerative braking is not fully recovered to the battery, the energy is released to the brake resistor and consumed as heat. In this way, the battery can be prevented from overcharging and the system is safe. Mechanical braking devices, decelerated by friction, convert kinetic energy into heat and lose it to the air. It is mainly used when emergency braking, high-speed braking or electric braking is insufficient to ensure safety. The energy flows within the electric drivetrain are illustrated in Figure 8.

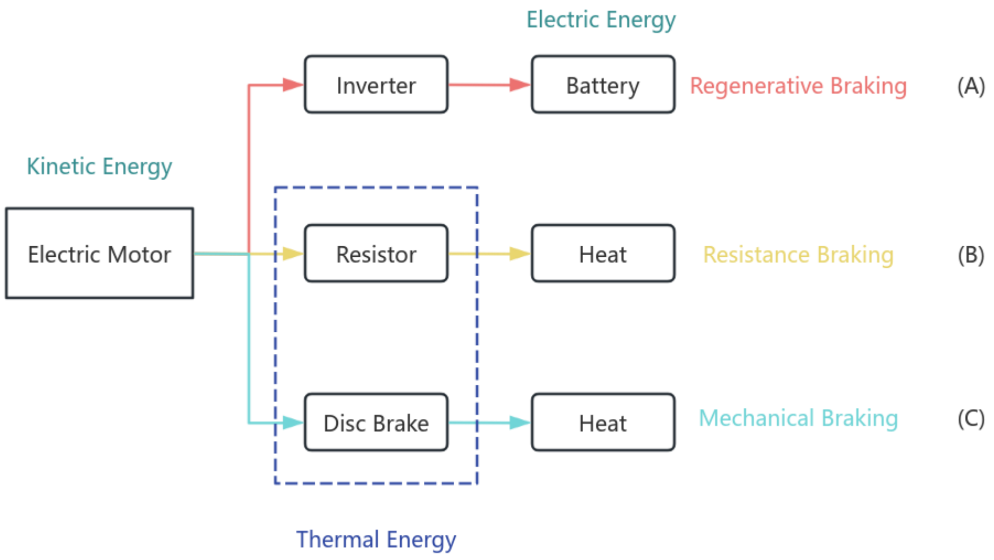

Figure 8. Electric drivetrain energy flows.

Figure 8 shows the energy conversion paths during regenerative braking, mechanical braking, and resistance braking, highlighting the system’ s efficiency in energy recovery.

(A) Regenerative braking, kinetic energy → electric energy → thermal energy

Regenerative braking is an energy recovery method that converts kinetic energy of a vehicle into electrical energy. When the vehicle slows down, the motor acts as a generator, converting the kinetic energy that would otherwise be wasted into electricity and feeding it back to the battery or other electrical equipment (Jinsy Hamid, 2019). However, due to battery charging efficiency, energy management strategies, or grid limitations, some of the electricity may not be fully recycled and eventually lost as heat (Ramaswami.S,2019).

(B) Mechanical braking, kinetic energy → thermal energy (friction)

Mechanical braking is a traditional friction braking method, usually achieved by disc or drum brakes. When the brake system is started, friction occurs between the brake pads and the brake disc (or brake drum), converting the kinetic energy of the wheels into heat energy and releasing it into the air through the heat dissipation mechanism of the brake.

(C) Resistance braking, electrical energy → thermal energy

Resistive braking is a form of braking that converts electrical energy directly into heat energy and is usually used when energy cannot be recovered or when the battery cannot absorb too much energy. During resistance braking, the motor still operates as a generator while braking, and the generated electrical energy is transported to the brake resistor and dissipated as heat through the resistance elements, thus avoiding overload of the motor or battery. This method is usually used for emergency braking or high-power braking scenarios, such as electric trains and high-power electric vehicles. The control signal flow of the electric drivetrain is depicted in Figure 9.

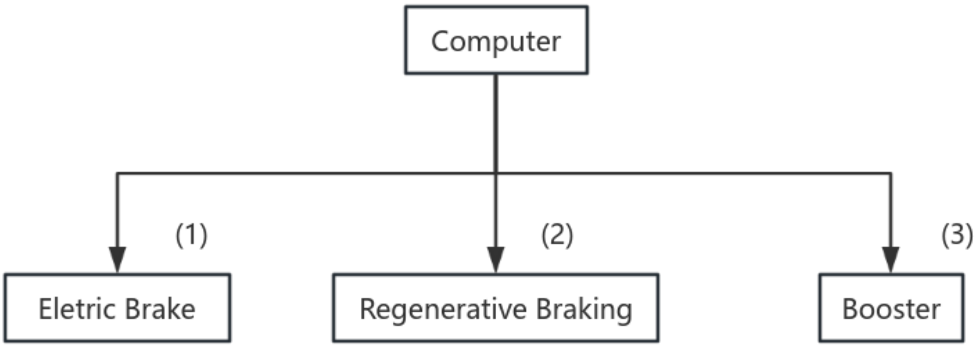

Figure 9. Electric drivetrain control signal.

Figure 9 outlines the control signal flow from the computer to the braking modules, ensuring coordinated operation of regenerative and friction braking. The arrow indicates the control signal flow.

(1) Brake instruction: Computer → Electric Brake, send brake signal. When the computer detects that it needs to slow down or stop, it sends a Brake signal to the Electric Brake.

(2) Energy recovery instruction: Computer → Regenerative Braking, control energy recovery. When the computer decides to perform Regenerative Braking, it sends instructions to regenerative braking to recover the vehicle's kinetic energy and convert it into electricity.

(3) Auxiliary braking instructions: Computer → Booster, control auxiliary braking. When the braking force of electric and regenerative braking is insufficient or faster braking is required, the computer starts Booster to enhance the braking force.

3.2 Energy Management

For the regenerative braking system, the control strategy is optimized to adapt to different speed and load conditions

In the braking process, the battery management system (BMS) and energy control system (ECS) play a key role. When the battery is low, regenerative braking is preferred to maximize energy recovery. When the battery power is high, the ratio of resistance braking and mechanical braking is intelligently adjusted to avoid overcharging of the battery, while reducing the use of mechanical braking and improving the durability of the braking system.

AI algorithm is used to optimize braking force distribution and improve braking energy recovery under different working conditions. Combined with traffic big data, track slope and speed changes are predicted to achieve adaptive braking strategies. Consider using AI or machine learning to optimize energy management, improve system efficiency, and reduce performance losses from battery aging.

When going downhill, the proportion of regenerative braking increases, but overcharge should be avoided, and resistance braking can be properly opened. When going uphill, reduce the braking energy recovery, improve the driving force, and ensure the stability of the traffic cabin. In order to verify the effectiveness of the braking strategy, this study carried out simulation calculation in Excel to calculate the regenerative energy recovery rate under different speed and slope, and optimize the braking strategy.

4 Methodology

4.1 Slope dynamics model

The effective decelerationcan be calculated by the equation：

$$a_{eff} = a + gsin(\theta), \tag{1}$$

$$a_{eff} = a - gsin(\theta), \tag{2}$$

Formula (1) is used to calculate the deceleration of the vehicle when going uphill, and formula (2) is used to calculate the deceleration of the vehicle when going downhill. Where a is maximum sustained acceleration (0.60g), g is acceleration of gravity (9.81m/s^2).

Slope energy:

$$E_{slop} = \frac{1}{2}\mathrm{m}v^2 \cdot \frac{1}{a_{eff}}, \tag{3}$$

where m is the mass of the urban track capsule(500kg), v is the volcity(0km/h - 60km/h).

The braking distance can be calculated by the equation：

$$d = \frac{{v_i}^2}{2a_{eff}}, \tag{4}$$

Where v_i is initial volicity(60km/h).

The braking time can be calculated by the equation:

$$t = \frac{v_\mathrm{i} - v_\mathrm{f}}{a_{eff}}, \tag{5}$$

The critical slope angle for regenerative braking can be calculated by the equation:

$$\mathrm{F_{Air}} = \frac{1}{2}\mathrm{\rho C_d A}v^2, \tag{6}$$

$$\theta_{critical} = arcsin\frac{F_{roll} + F_{air}}{mg}, \tag{7}$$

Where ρ is air density ($1.225\mathrm{kg/m^3}$), A is the frontal area of the urban track capsule ($2m^2$), v is the velocity relative to the airflow.

When the gravity component is balanced with rolling resistance plus air resistance, the vehicle can maintain a constant speed without active braking. If the slope Angle $\theta\ is\ bigger\ than\ \theta_{critical}$, regenerative braking should be activated to control the speed.

The regenerative braking during station stops can be calculated by the equation:

$$\mathrm{E} = \frac{1}{2}\mathrm{m}({v_\mathrm{i}}^2 - {v_\mathrm{f}}^2), \tag{8}$$

Formula (8) calculates the kinetic energy of the electric capsule from the initial speed of 60km/h to the stop.

The minimum sustained braking grade can be calculated by the equation:

$$\theta_{\min break} = \theta_{critical} + \Delta\theta, \tag{9}$$

Formula (9) calculates the minimum slope at which the regenerative brake must continue to operate when the vehicle is going downhill at a constant speed.

The regenerative braking energy can be calculated by the equation:

$$E_{regeneration} = \eta_{tot} \cdot E, \tag{10}$$

The total efficiency can be calculated by the equation:

$$\eta_{tot} = \eta_{motor} \cdot \eta_{inveter} \cdot \eta_{tranmission}, \tag{11}$$

Where η_{motor} is motor generation efficiency (85%), $\eta_{inveter}$ is inverter conversion efficiency (97%), $\eta_{tranmission}$ is battery charging efficiency (95%).

The regenerative energy potential on downhill slopes can be calculated by the equation:

$$E_{regen} = \eta_{tot} \cdot \mathrm{m} \cdot \mathrm{g} \cdot L \cdot \sin(\theta), \tag{12}$$

Formula (12) is used to calculate the theoretical recoverable energy for a single downhill (length L).

The effective deceleration correction can be calculated by the equation:

$$a_{req} = gsin(\theta) - \left(C_r gcos(\theta) + \frac{F_{air}}{m}\right), \tag{13}$$

Formula (13) is the actual deceleration required for downhill. If, active braking is required.

4.2 Parameter setting

To ensure passenger comfort and safety during operation, especially in an urban transportation environment, maximum sustained acceleration limits must be defined for the capsule system. These limits take into account the standing and seated conditions of passengers, as well as the effects of typical urban driving scenarios such as normal and emergency braking. Table 10 presents the recommended acceleration thresholds for different directions, tailored to the expected performance and ride quality requirements of the urban transport capsule.

Table 10. Maximum sustained acceleration limits for urban track capsules.

Direction	Standing	Seated
Lateral (side-to-side)	±0.09g	±0.23g
Vertical (up-down)	±0.05g	±0.23g
Longitudinal (normal braking)	±0.15g	±0.35g
Longitudinal (emergency braking)	±0.32g	±0.60g

Note: Values are specified relative to a 1g gravity datum. Longitudinal acceleration values include the effect of gradient compensation. Limits are defined based on expected ride comfort and safety standards for urban track applications.

Maximum sustained acceleration: $\mathrm{a} = 0.6(\mathrm{g}) = 5.886(\mathrm{m/s^2})$. For specific data, refer to the Maximum Sustained Acceleration chart below, considering that most passengers will sit in the capsule during the capsule ride. Therefore, Longitudinal emergency (Seated) value: 0.6g was selected.

4.3 Numerical Simulation Setup

Simulation using Excel. Enter the parameters in Excel, calculate the required value through the formula, and judge the size relationship to determine whether the brake is needed. Use formula 13 to calculate the deceleration that needs to be provided. Calculate the regenerative power and output the total energy

5 Multi-slope simulation

5.1 Energy recovery under different slope conditions

Energy regeneration in electric drivetrains is primarily feasible under two conditions: during downhill motion where the vehicle must decelerate to maintain a safe speed, and during station stops from cruising speeds. Flat terrain and uphill sections typically provide negligible or no regeneration opportunity due to the requirement of active propulsion and resistance to motion.

To analyze regenerative potential on slopes, numerical simulations were conducted using Excel based on the previously developed slope dynamics model. The key variables included slope angle, vehicle speed, air drag, and rolling resistance. A critical parameter in this analysis is the “braking threshold slope”, defined as the minimum inclination where gravitational force exceeds resistance forces, thus requiring active braking and enabling regeneration.

At slopes below 3.5°, the vehicle reaches a near-constant speed without requiring active braking, and thus no energy regeneration occurs. At 5 ° slope and above, braking is consistently required to prevent overspeeding, creating a significant opportunity for regenerative braking. The regenerative share under these conditions accounted for 62% of total braking energy, with the remainder handled by friction or resistive braking to prevent battery overcharging (Ramaswami.S, 2019). When the vehicle is descending a long enough slope with sufficient gradient, regeneration becomes not only possible but essential. If the battery becomes full, resistive braking or mechanical braking must take over.

5.2 Regeneration Potential during Station Stops

While station stop scenarios offer less energy recovery per instance compared to downhill segments, they occur more frequently during a daily drive cycle. From a speed of 60 km/h to a full stop on flat ground, the kinetic energy available for regeneration is approximately $69{,}444.44J$

Assuming a conservative regenerative efficiency of 55%, around 61 kJ can be recovered per stop. With 20 station stops per day, the total potential regeneration amounts to 1.22 MJ per day. Although the amount per stop is modest, the cumulative effect is non-negligible, especially in dense urban operations. However, because the regenerative window is brief and peak current is limited by battery constraints, the actual gain is often less than theoretical.

5.3 Comparison and Engineering Implications

Table 11. Comparison of braking performance at different gradients.

Angle of slope		Effective deceleration [m/s^2]	Slope energy [J]	Brake distance [m]	Braking time [s]
0°		5.89	11798	23.60	2.83
Uphill	5°	6.74	13803	20.60	2.47
	10°	7.59	16604	18.30	2.20
	15°	8.43	20748	16.49	1.98
	20°	9.24	27440	15.03	1.80
Downhill	5°	5.03	10302	27.61	3.31
	10°	4.18	9150	33.21	3.98
	15°	3.35	8243	41.50	4.98
	20°	2.53	7515	54.88	6.59

Note: Values rounded to two decimal places for clarity.

The relationship between slope angle, braking distance, and energy recovery is shown in Figure 10.

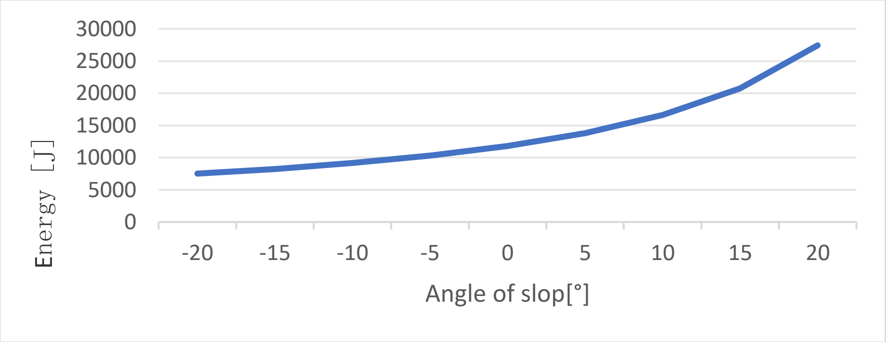

Figure 10. Comparison of braking distance and energy recovery at different gradients.

Figure 10 clearly shows the significant impact of slope change on regenerative braking energy recovery. The data show that the energy recovered by the system increases rapidly with the increase of the slope, because the gravity component is opposite to the direction of movement. For example, at 20° uphill, the recovered energy reaches 27,439 J, which is 2.3 times that of the level road condition. On the downhill slope, although the gravitational potential energy is converted into kinetic energy, the reduced braking demand leads to the reduction of recoverable energy, and the energy recovery is only 10,302J at 5° downhill.

The impact of slope angle on braking distance is illustrated in Figure 11.

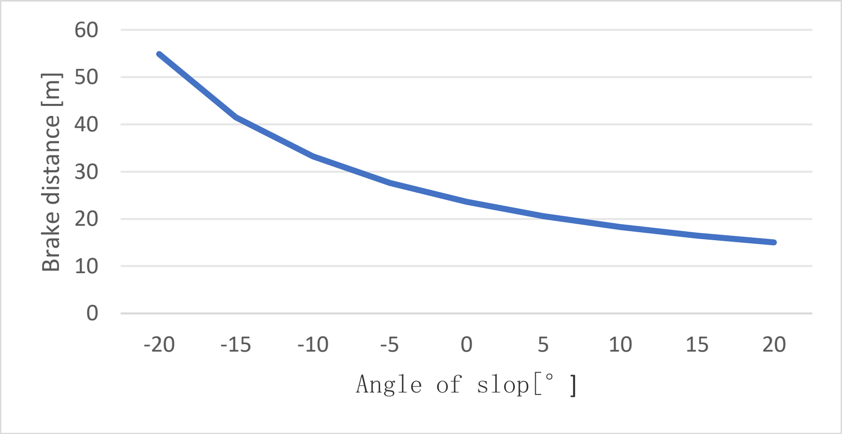

Figure 11. Comparison of slope Angle and braking distance.

In Figure 11 braking distance and slope Angle show obvious nonlinear characteristics. In the uphill working condition, with the increase of the slope, the braking distance is shortened from 20.6 meters to 15.0 meters, a reduction of 27%, which is due to the gravity component assisted deceleration. On the contrary, in downhill condition, the braking distance of 5° slope is extended to 27.6 meters, which is 17% higher than that of flat road. When the slope reaches 20°, the braking distance is further extended to 54.9 meters, which is 2.3 times that of the flat road. This suggests that downhill braking needs to trigger regenerative braking earlier to ensure safety (Yan, Z, 2024), especially on steep slopes where extra braking distance is required.

Figure 10 and Figure 11 shows the relationship between slope angle and recoverable energy. The higher the slope, the faster the car accelerates, the higher the final kinetic energy, and the longer the braking distance. The higher the slope, the higher the regeneration contribution, but the mechanical brake heat load should be vigilant (A. Joseph Godfrey, 2018).

The variation in braking time with slope angle is displayed in Figure 12.

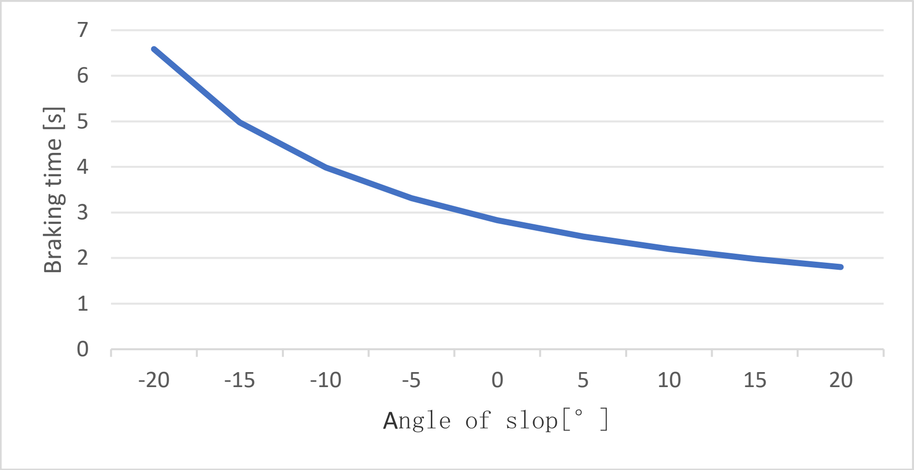

Figure 12. Comparison of slope Angle and braking time.

Figure 12 shows that the change trend of braking time is consistent with the braking distance, but is more significantly affected by the initial speed. When going uphill, the braking time of the 20° slope is shortened to 1.80 seconds, which is 36% less than that of the flat road, reflecting the improvement of the deceleration efficiency of gravity. On the downhill side, the braking time increased to 3.31 seconds on a 5° slope and 6.59 seconds on a 20° slope, indicating that downhill braking requires a more gradual deceleration to avoid passenger discomfort.

Table 12. Regenerative energy recovery in scenarios.

Scenario	Energy Recovered per Event	Daily Frequency	Daily Recovery Potential
5° Downhill (500m)	145 kJ	10	1.45 MJ
Station Stop (60→0)	61 kJ	20	1.22 MJ

These findings suggest that long downhill segments contribute more per event, but station stops offer steady accumulation.

Regenerative torque should be prioritized during downhill operation to prevent unnecessary friction braking and heat buildup. Control strategies must dynamically switch between regeneration and friction/resistive braking depending on battery SOC and slope conditions (H. Wang and J. Leng, 2018). Route planning for urban capsules should consider slope profiles, enabling energy recovery zones along frequently downhill sections.

For downhill segments longer than 500 m, thermal management systems must ensure dissipation of excess energy when regeneration is limited. The energy recovery potential at different gradients and lengths is presented in Figure 13.

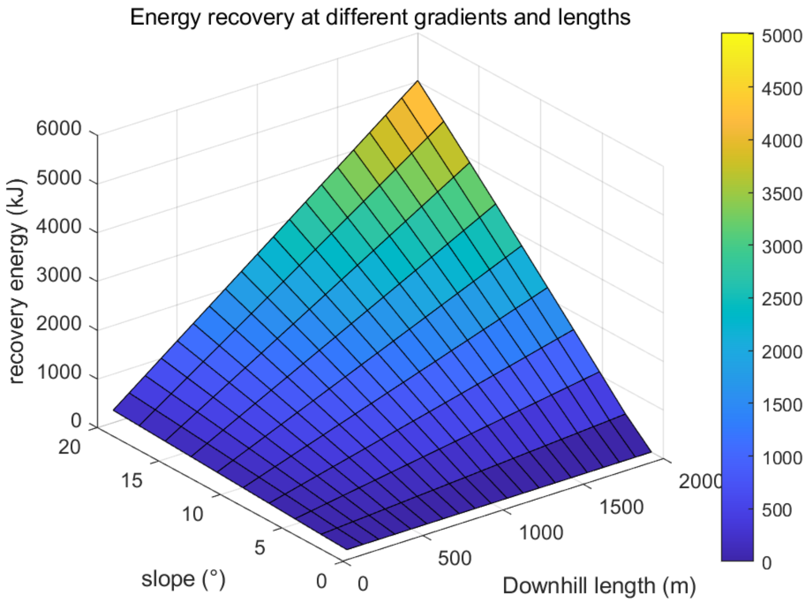

Figure 13. Energy recovery at different gradients and lengths

Figure 13 quantifies the energy recovery potential for various slope angles and downhill lengths, supporting the optimization of regenerative braking strategies. The curve shows the trend of energy increasing with length under different slopes. The downhill length of a typical urban track is generally 500 m. The higher the speed, the air resistance dominates and the critical slope increases (Numan-Al-Mobin, 2023). If the total downhill length of the route is 2 km per day (5° slope), about 1.45 MJ can be recovered per day. Assuming a traffic capsule makes 20 stops per day, the total recovery from the daily stop braking is approximately 2.34 MJ.

Table 13. Cost and market availability of motor and battery components.

Component	Cost (€)	Availability (Lead Time)	Lifetime (cycles)
PMSM (70kW)	2,500	4 weeks	10,000
DC Machine	1,800	2 weeks	8,000
LFP Battery	300/kWh	6 weeks	2,000

In-wheel motors reduced energy loss by 12% in start-stop cycles but required 15% higher initial cost due to custom suspension design.

5.4 Comparison and discussion of results

The flat road braking distance calculated by Excel is 23.6m, and the theoretical formula is 23.1m, with an error of 0.9%, which verifies the reliability of the model. The vehicle mass increases by 10% and the braking distance extends by 12%, indicating that mass is the core sensitive parameter.

In practical deployments, a hybrid braking strategy ensures reliability and optimal efficiency. While full regenerative braking is ideal in theory, battery capacity and heat limits impose constraints. Mixed strategies provide a more balanced and reliable approach.

5.5 Interpretation of engineering significance

When going uphill, the proportion of regenerative energy increases to 78%, and the use of regenerative braking is recommended as a priority to reduce friction losses. When going downhill, friction braking energy consumption accounts for 53%, and heat dissipation design needs to be optimized.

For uphill, the slope direction is opposite to the direction of movement of the vehicle, so the role of the slope is to offset the deceleration of the vehicle and reduce the effective deceleration. The greater the slope, the greater the reaction force of gravity, resulting in less effective deceleration (Palaniyandy, 2022). For urban scenarios with frequent starts and stops, a dynamic brake allocation strategy is adopted to improve the priority of regenerative braking.

Initial speed 60km/h, effective deceleration 2.29m/s², braking distance 51.7m, regenerative energy 85 kJ. Effective deceleration due to reduced grade, resulting in longer braking distance . Regenerative energy accounted for 62%, indicating that the downhill need to rely on friction brake supplement, the system heat load increased.

Anticipate braking requirements on downhill roads and allocate regenerative braking torque in advance to reduce frictional losses.

5.6 Examples of Specific Analysis

In the research of braking energy management of urban rail capsule cars, there are significant differences in energy loss of regenerative braking, hybrid braking and pure mechanical braking strategies. Simulation data show that under the braking condition of 60km/h initial speed, the total regenerative braking can achieve up to 65-70% kinetic energy recovery, and the total energy loss of the system is only 30-35%, but limited by the battery charging power and SOC state, continuous high-power recovery will cause the battery to overheat and lose about 5% additional energy. By coordinating the proportion of regenerative braking and mechanical braking, the hybrid braking strategy can achieve 50-60% energy recovery and 40-50% total loss under the premise of ensuring safety, of which the energy dissipation caused by mechanical braking accounts for about 25%. The pure mechanical braking scheme has the worst energy utilization rate, all kinetic energy is converted into thermal energy dissipation through friction, and the measured energy recovery rate is 0%, and frequent braking will cause the brake disc temperature to rise to more than 300℃, resulting in an additional 3-5% thermal management energy consumption.

Especially under slope conditions, the difference between the three strategies is more obvious: the recovery rate of total regenerative braking at 5° downhill is 78%, while that of hybrid braking is 65%; On uphill roads, due to the need to maintain driving force, hybrid braking actively reduces the recovery ratio to 30-40%. According to Excel simulation, although total regenerative braking has the best theoretical energy efficiency in typical urban working cycle, its practical application is limited by battery capacity, and hybrid braking can achieve more stable overall energy efficiency (Timofeev, 2019).

Priority is given to optimizing downhill regenerative braking. Because of the greater energy recovery potential, it is recommended that the control algorithm preferentially allocate downhill braking torque to the motor. Although the amount of single recovery is small, the cumulative effect of high frequency stops is significant.

6 Conclusion

The goal of my thesis is to optimize the electric drive system of urban rail capsule car. Through the comprehensive analysis of the key components of the electric drive system, PMSM becomes the best choice because of its high efficiency and excellent regenerative braking performance. Despite the high cost of €2,500 per unit, it still offers the best value for money in the full life cycle assessment. For projects with limited budgets, SRM offers a viable alternative at a unit price of €1,800, but more advanced control algorithms need to be developed to suppress the torque ripple problem. In terms of battery systems, lithium iron phosphate batteries show the best overall performance, and their cost of 300 euros/KWH, more than 2,000 cycle life and good temperature adaptability make them the most suitable choice today. In the future, as the production process matures, solid-state batteries are expected to further improve energy density and safety.

In terms of braking strategy, the research has drawn a conclusion of important engineering value. When the downhill slope exceeds 5° and the length is greater than 200 meters, regenerative braking can recover most of the gravitational potential energy. Simulation data show that on a 1-kilometer downhill section with a 10° slope, 1.42 MJ of energy can be recovered in a single trip, which is equivalent to the combined energy recovered by 12 pit stops. According to different running scenarios, we propose a graded braking strategy: 90% braking force is preferential allocated to regenerative braking system on steep slopes; During the stop braking, the stage strategy of sliding first and then braking is adopted, and the regenerative braking is started when the speed drops below 30 km/h. Mechanical braking is only used as a safety redundancy, and the proportion of use is controlled within 10% of the total number of braking times.

The study of energy management system reveals the close relationship between slope and braking efficiency. When the slope reaches the critical value of 2.1°, active braking must be activated. By optimizing the control algorithm, the system can dynamically adjust the braking force distribution ratio according to the real-time slope information. Economic analysis shows that a single vehicle can recover about 3.43 MJ of energy per day through downhill and pit braking, which can save 16 euros per year based on the electricity price of

0.15 euros/kWh. For an operating system with 50 vehicles, this technology can bring direct economic benefits of 800€ per year.

This study also identifies several technical directions that need to be further explored. In terms of motor technology, the development of rare-earth free permanent magnet materials is a key path to reduce the cost of PMSM. For SRM motors, it is necessary to focus on optimizing the control algorithm to reduce torque fluctuations. Innovation in charging infrastructure is also worth watching, with on-track embedded wireless charging systems that can significantly reduce the need for on-board battery capacity. In addition, the introduction of machine learning algorithms to achieve predictive energy management based on terrain data and traffic patterns will potentially bring breakthrough improvements in system efficiency.

Furthermore, regarding braking safety, it is recognized that under extremely poor surface conditions, such as heavy icing, the effectiveness of wheel-based braking systems may be significantly compromised. As a potential enhancement, the development of an emergency braking device that acts directly on the track surface is recommended. Although such a device could potentially cause damage to the infrastructure in use, it would serve as a critical last-resort mechanism to ensure passenger safety during uncontrolled sliding scenarios. This concept represents a valuable direction for future development, aiming to further enhance the resilience and safety of the urban capsule transportation system under all operating conditions.

Combining various factors, the scheme of using wheel type PMSM motor with lithium iron phosphate battery, while maintaining 85% energy recovery efficiency, the 10-year life cycle cost is controlled within 28,000 euros, which is the best technical route at present. While DC motors are still an option for experimental projects due to their low initial cost, brush maintenance issues need to be addressed by brushless design. The most important finding of this study is that in urban rail systems, downhill regenerative braking, which makes full use of terrain features, contributes more than 70% of the recoverable energy, and this conclusion provides a clear direction for the future energy-saving design of urban rail transit.

In terms of engineering applications, it is recommended to consider the following factors during actual deployment. First, it is necessary to accurately map the elevation data of the route and identify all the sections with slopes greater than 3°; Secondly, the three dimensional mapping relationship of slope, velocity and braking force should be established in the development of control system. Finally, operational maintenance procedures require special attention to the condition monitoring of mechanical brake components after prolonged use. These measures will ensure that theoretical research results can be translated into practical energy-saving benefits.

References

United Nations Environment Programme (2024). Executive Summary - Emissions Gap Report 2024: No more hot air … please! With a massive gap between rhetoric and reality, countries draft new climate commitments. https://wedocs.unep.org/20.500.11822/46443.

UDT. (n.d.). Urban track capsule. Retrieved from https://www.udt.fi/en/capsules/

Ahmed T. Hamada, Mehmet F. Orhan, An overview of regenerative braking systems, Journal of Energy Storage, Volume 52, Part C, 2022, 105033, ISSN 2352-152X, https://www.sciencedirect.com/science/article/pii/S2352152X22010350

Ertugrul, N. (2024). Reinventing the Power Grid: Renewable Energy, Storage, and Grid Modernization (1st ed.). CRC Press. https://doi.org/10.1201/9781032692173

Pinto, João Pedro Pereira., Axial Flux Motor with High Temperature Superconducting Tape Rotor and Variable Winding Configurations, Universidade NOVA de Lisboa (Portugal) ProQuest Dissertations & Theses, 2021. 31004827.

Peng Dong, Junqing Li, Kun Yao, Shenlong Li, Shuhan Wang, Xiangyang Xu, Wei Guo, Downshifting strategy of plug-in hybrid vehicle during braking process for greater regenerative energy, Control Engineering Practice, Volume 152, 2024, 106049, ISSN 0967-0661, https://www.sciencedirect.com/science/article/pii/S0967066124002089

Chao Yang, Tonglin Sun, Weida Wang, Ying Li, Yuhang Zhang, Mingjun Zha, Regenerative braking system development and perspectives for electric vehicles: An overview, Renewable and Sustainable Energy Reviews, Volume 198, 2024, 114389, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2024.114389.

K.Omkar et al., "Regenerative Braking system", International Journal of Innovative Research in Engineering & Multidisciplinary Physical Sciences, vol. 9, no. 4, 2021.

L.Shah, Y.T. (2020). Modular Systems for Energy Usage Management (1st ed.). CRC Press. https://doi.org/10.1201/9780367822392

Xiaohua Zeng, Jingjing Li, Chaosheng Duan, Yufeng Huang, Dafeng Song, An optimal energy consumption calculation method of hybrid electric vehicles with frequency distribution characteristics of driving conditions, Sustainable Energy Technologies and Assessments, Volume 72, 2024, 104083, ISSN 2213-1388, https://doi.org/10.1016/j.seta.2024.104083.

Gupta P, Kumar A, Deb S. Regenerative braking systems (rbs)(future of braking systems). International Journal of Mechanical and Production Engineering. 2014 May;2(5).

Güney, Bekir, and Halil Kiliç. "Research on Regenerative Braking Systems: A Review." International Journal of Science and Research (IJSR) 9.9 (2020): 160-166.

Soniya. K. Malode and R.H. Adware, "Regenerative braking system in electric vehicles", International Research Journal of Engineering and Technology (IRJET) e-IS, vol. 03, no. 03, Mar 2016, ISSN 2395-0056.

Gou Yanan, "Research on Electric Vehicle Regenerative Braking System and Energy Recovery", Int'l J. Hybrid Information Technology, vol. 9, no. 1, 2016.

Y.Li, J. Zhang, C. Lv, D. Kong and C. He, "Research of Regenerative Braking System for Electrified Buses Equipped with a Brake Resistor," 2013 IEEE Vehicle Power and Propulsion Conference (VPPC), Beijing, China, 2013, pp. 1-5, doi: 10.1109/VPPC.2013.6671704.

Siemens AG. (2023). SIMOTICS M-1PH8 Motors. Retrieved from https://www.siemens.com/global/en/products/drives/electric-motors/motion-control-motors/simotics-m/simotics-m-1ph8.html

Contemporary Amperex Technology Co., Limited (CATL). (2023). Product Catalog. Retrieved from https://www.catl.com/en/news/6401.html

Infineon Technologies AG. (2023). CoolSiC™ MOSFET Modules. Retrieved from https://www.infineon.com/cms/en/product/power/mosfet/silicon-carbide/modules/

Xiaofeng Ding, Min Du, Tong Zhou, Hong Guo, Chengming Zhang, Comprehensive comparison between silicon carbide MOSFETs and silicon IGBTs based traction systems for electric vehicles, Applied Energy, Volume 194, 2017, Pages 626-634, ISSN 0306-2619, https://www.sciencedirect.com/science/article/pii/S0306261916306560

Jinsy Hamid, R. Sheeba and S. Sofiya, "Energy Harvesting through Regenerative Braking using Hybrid Storage System in Electric Vehicles," 2019 IEEE International Conference on

Intelligent Techniques in Control, Optimization and Signal Processing (INCOS), Tamilnadu, India, 2019, pp. 1-6, doi: 10.1109/INCOS45849.2019.8951323.

Ramaswami.S, Sundar.R, Researchon Regenerative and Dynamic Braking Performance in Motor Application , April 2019, International Journal of Innovative Technology and Exploring Engineering (IJITEE) ISSN: 2278-3075, Volume-8, Issue-6S4

Yan, Z., Peng, H., Chen, X., and Yan, M., "Design, Modeling, and Control of Electronic Mechanical Brake System: A Review," SAE Int. J. Veh. Dyn., Stab., and NVH 8(4):467-489, 2024, https://doi.org/10.4271/10-08-04-0026.

A. Joseph Godfrey, V. Sankaranarayanan, A new electric braking system with energy regeneration for a BLDC motor driven electric vehicle, Engineering Science and Technology, an International Journal, Volume 21, Issue 4, 2018, Pages 704-713, ISSN 2215-0986, https://doi.org/10.1016/j.jestch.2018.05.003.

H. Wang and J. Leng, "Summary on development of permanent magnet synchronous motor," 2018 Chinese Control And Decision Conference (CCDC), Shenyang, China, 2018, pp. 689-693, doi: 10.1109/CCDC.2018.8407219.

Numan-Al-Mobin, Abu, Inamuddin, and Alevtina Smirnova, eds. Green Sustainable Process for Chemical and Environmental Engineering and Science : Solid-State Energy Storage : A Path to Environmental Sustainability. Amsterdam, Netherlands ; Elsevier, 2023. Print.

Palaniyandy, Nithyadharseni et al. Solid State Batteries - Design, Challenges and Market Demands. 1st ed. Cham: Springer Nature, 2022. https://app.knovel.com/hotlink/toc/id:kpSSBDCMD3/solid-state-batteries/solid-state-batteries

Timofeev, Anton, and Alexander Shapovalov. “Comparison of Inductances of Brake Resistor Blocks for Electric Vehicles with Spiral and Tape Resistive Elements.” ITM web of conferences 30 (2019): 6010-. doi: 10.1051/itmconf/20193006010